Very large liquid Argon Time Projection Chambers

CHIPP
Swiss Institute of Particle Physics

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Next Generation of Nucleon Decay and Neutrino Detectors (NNN05), 7-9 April 2005 Aussois, Savoie, France

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. 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:

- 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 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^{2}N/dEdx (β=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)**
Free electrons mobility	**0.002 cm^2/Vs**	**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)**

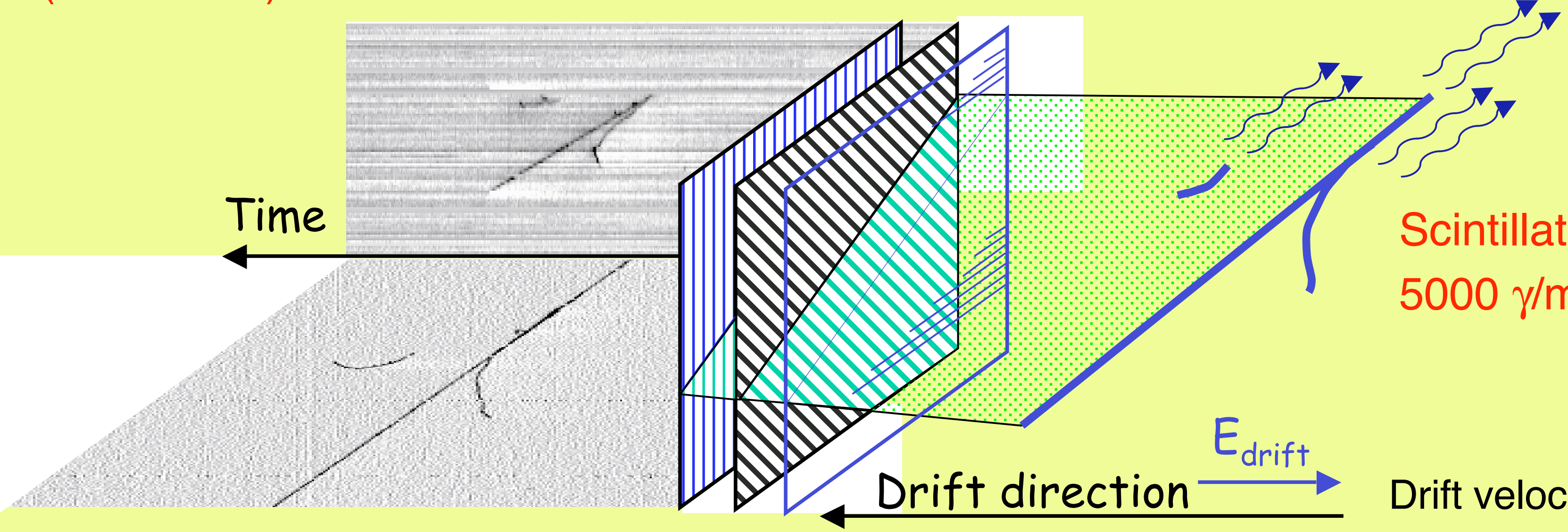
Scintillation & Cerenkov light can be detected independently !

The Liquid Argon TPC principle

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

Charge readout planes: Q

UV Scintillation Light: L



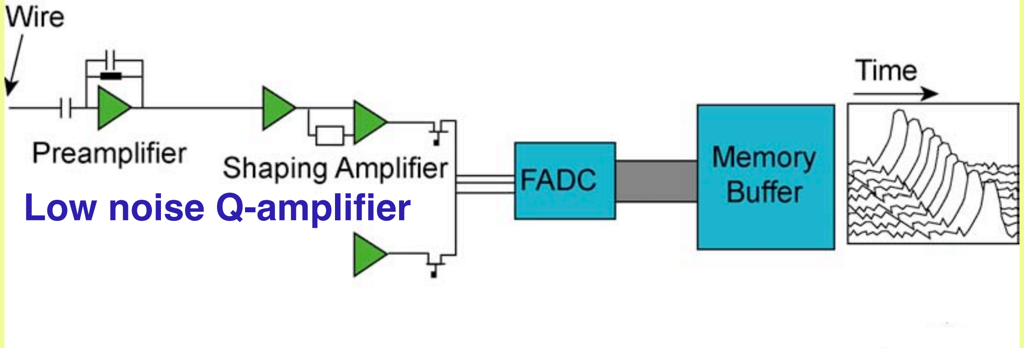
Scintillation light yield ~
5000 γ/mm @ 128 nm

Drift velocity ≈ O(1) mm/μs

Drift electron lifetime:

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

Purity < 0.1ppb O_2-equiv.



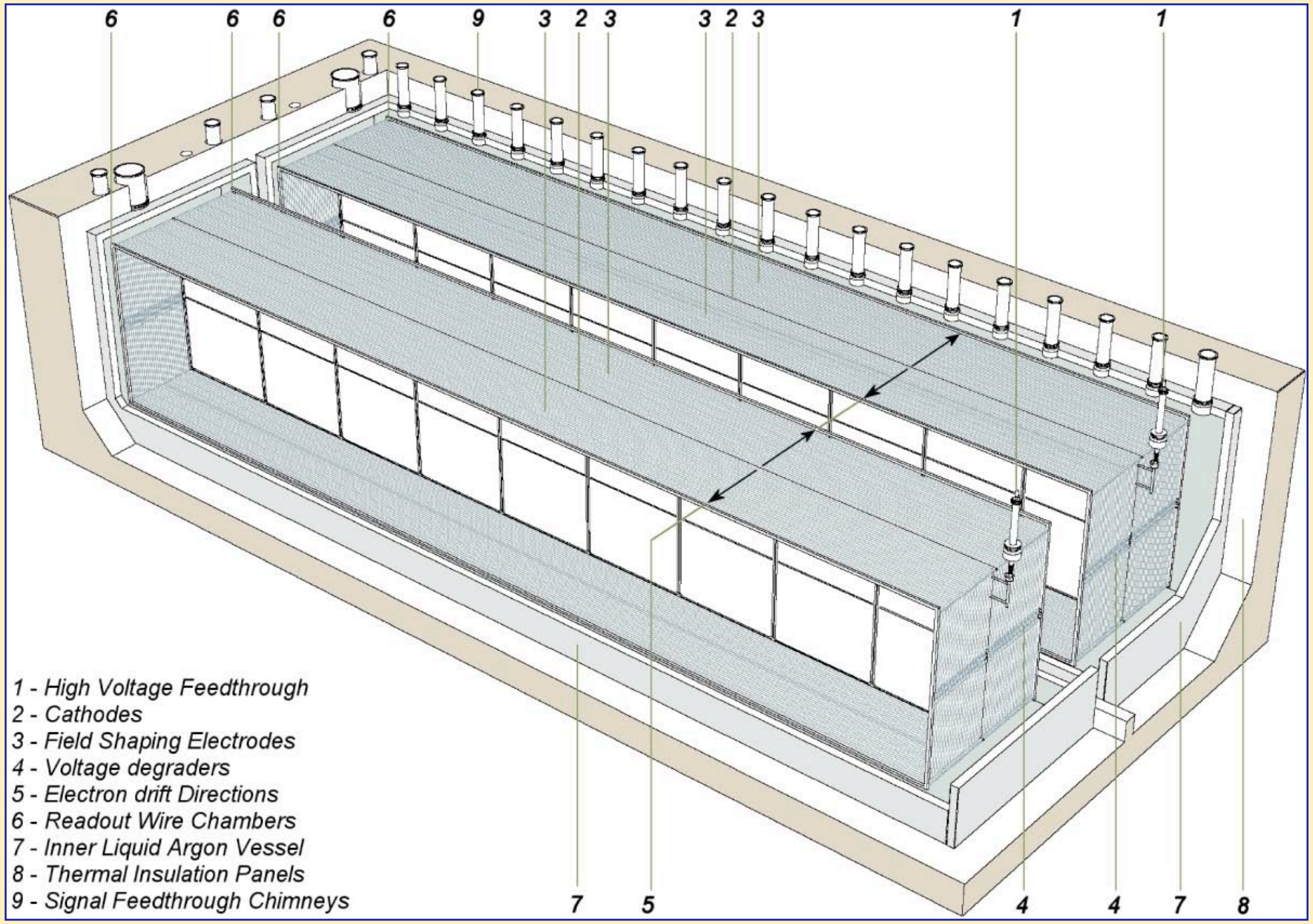
Low noise Q-amplifier

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).

Extrapolation of the technique to the ≈ kton scale

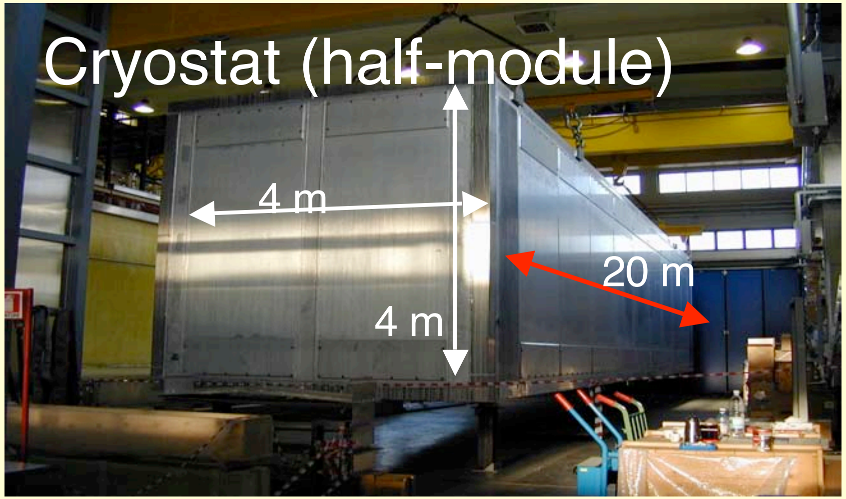
The ICARUS T600 Module: the living proof

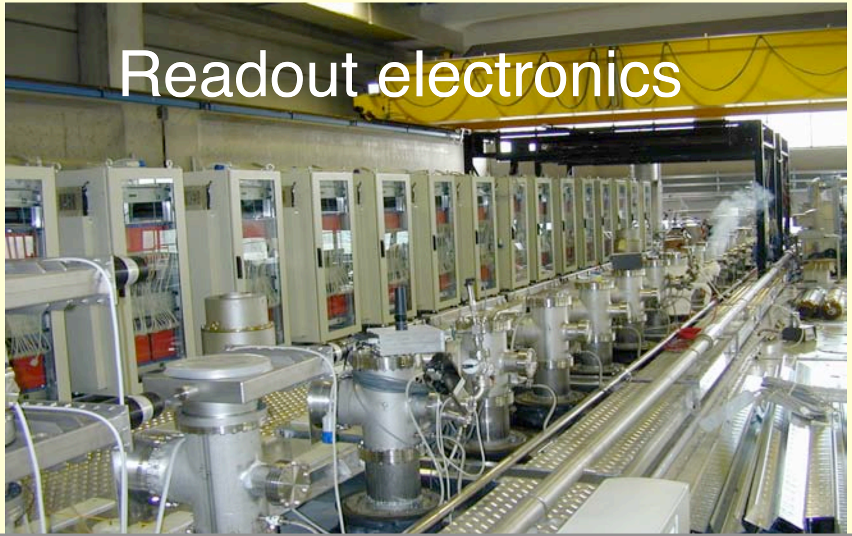


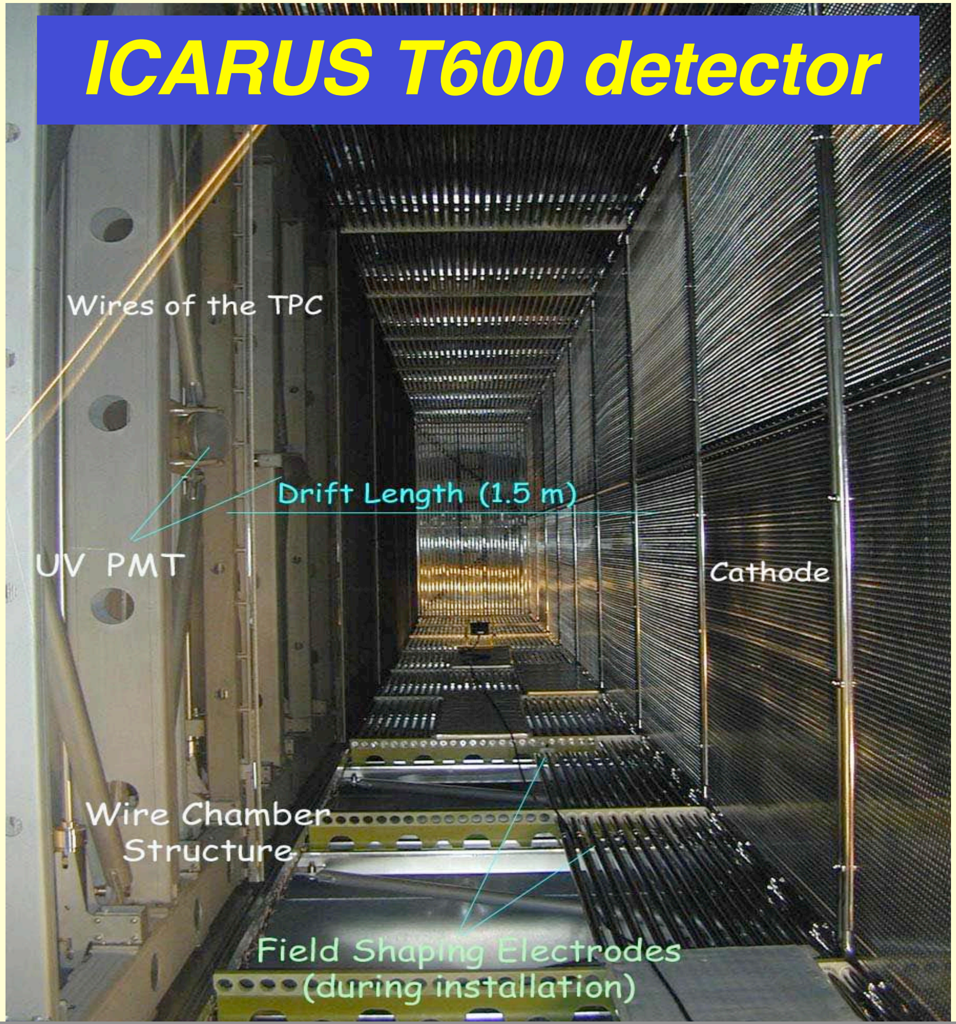
- Modular approach
- Two separate containers, each of sensitive mass = 238 ton
- 4 wire chambers with 3 readout planes at 0°, ±60° per module
- Total ≈ 54000 wires
- Maximum drift = 1.5 m
- Scintillation light readout with 8” VUV sensitive PMTs

Cryogenic system designed and assembled by Air Liquide, Italy
Inner detector design and assembly subcontracted to Breme Tecnica, Italy
Fully industrial approach

ICARUS T600 detector



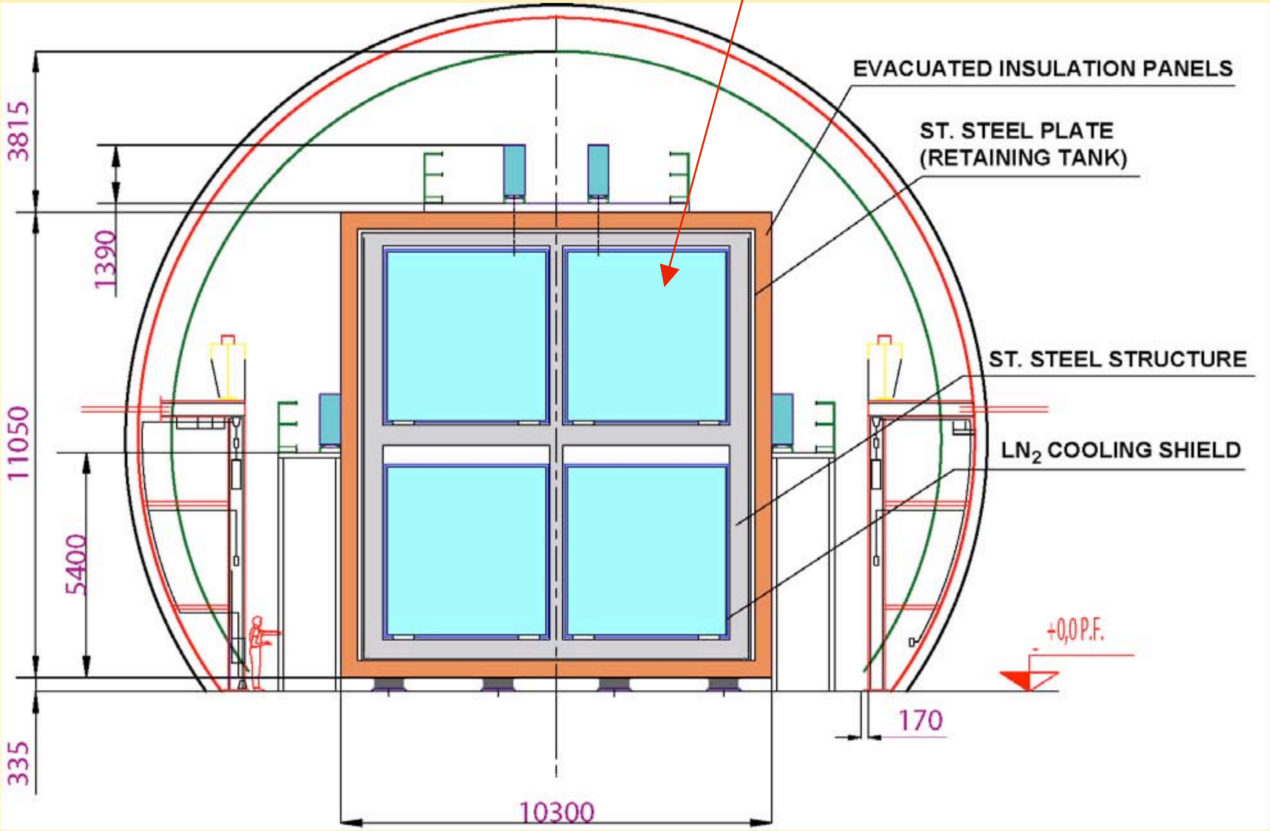




- Design, construction and tests of the ICARUS T600 detector, ICARUS Collab, NIM A527 329 (2004).
- Study of electron recombination in liquid Argon with the ICARUS TPC, ICARUS Collab, NIMA523 275-286 (2004).
- Detection of Cerenkov light emission in liquid Argon, ICARUS Collab, NIM A516 348-363 (2004).
- 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).

The ICARUS T1200 Module

Based on cloning the present T300 containers



- Preassembled modules outside tunnel are arranged in supermodules of about 1200 ton each (4 containers)
- Drift doubled 1.5 m ➔ 3 m

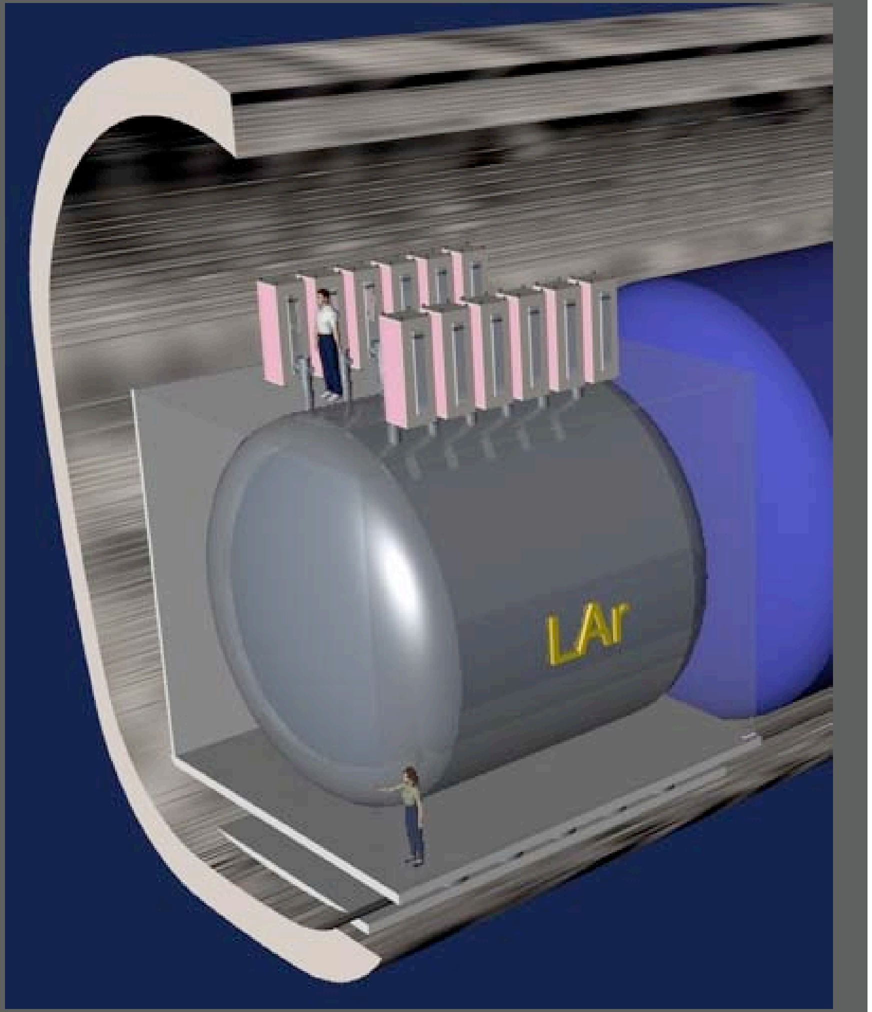
Engineering project produced by Air Liquide, Italy
Fully industrial approach

➡ *See talk by D. Duchesneau*

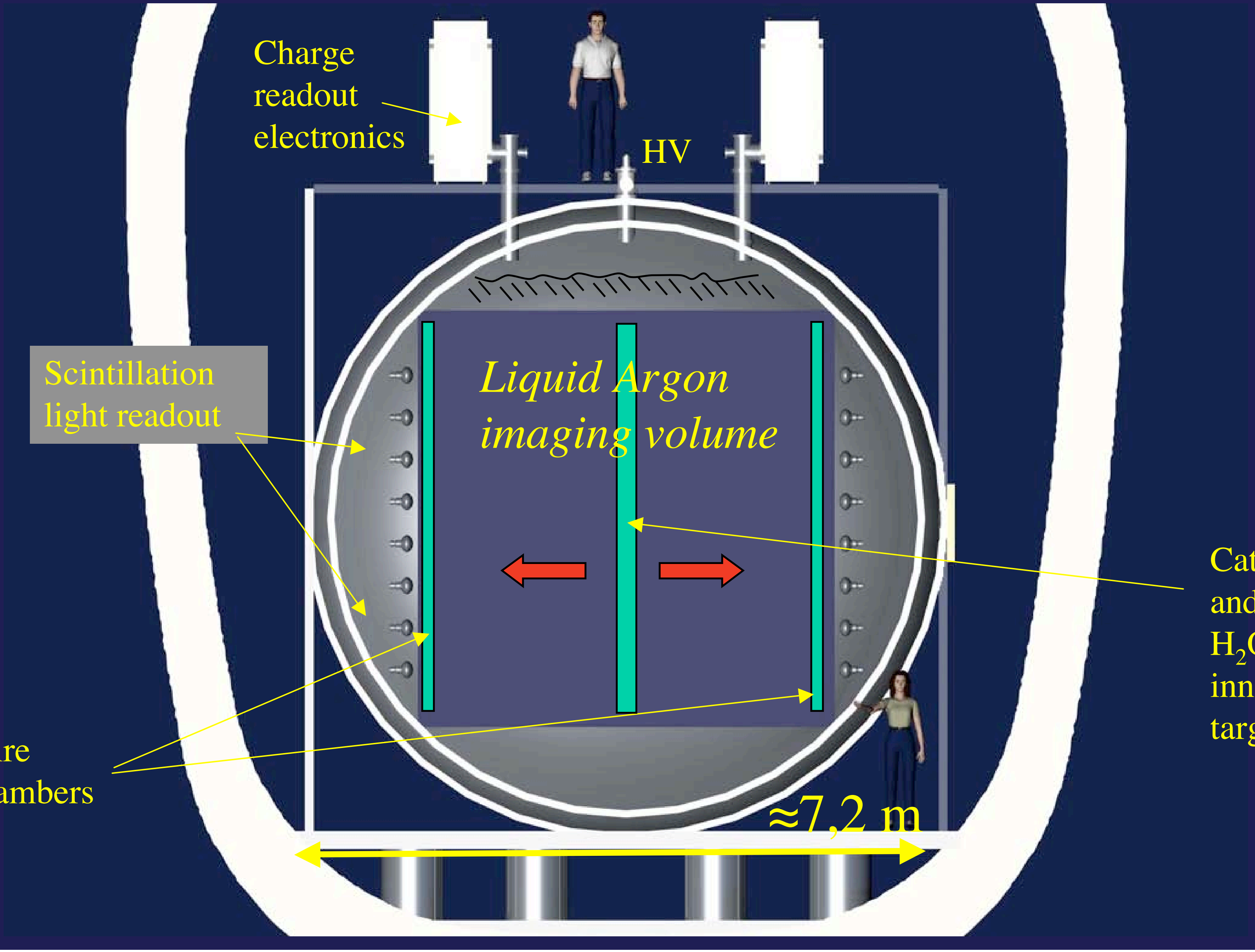
T2K-LAr: a conceptual study for the 2km position at T2K

Since November 2004 a working group including various international institutions has been formed to study a ≈100 ton LAr TPC at the 2km intermediate station

- The proposed design includes innovative features and technological advances. In particular:
  - ➥ Cryostat has a design that follows the codes of conventional cryogenic-fluid pressure storage-vessels (ASME Boiler & Pressure Vessel Code, Sect. VIII (www.asme.org)).
  - ➥ Boil-off is compensated with cooling from a heat engine with Ar as medium (avoid LN_2) combining Ar purification
  - ➥ Inner detector has an innovative and simple design (to limit complexity & cost)
  - ➥ Immersed Cockroft-Walton to generate uniform and high drift field (to exploit very high electric rigidity of LAr)
  - ➥ Inner target allows to measure events on Water / CO_2
  - ➥ Electronics based on newly designed digital part (since triggered by beam timing).



Front view



Charge readout electronics

HV

Scintillation light readout

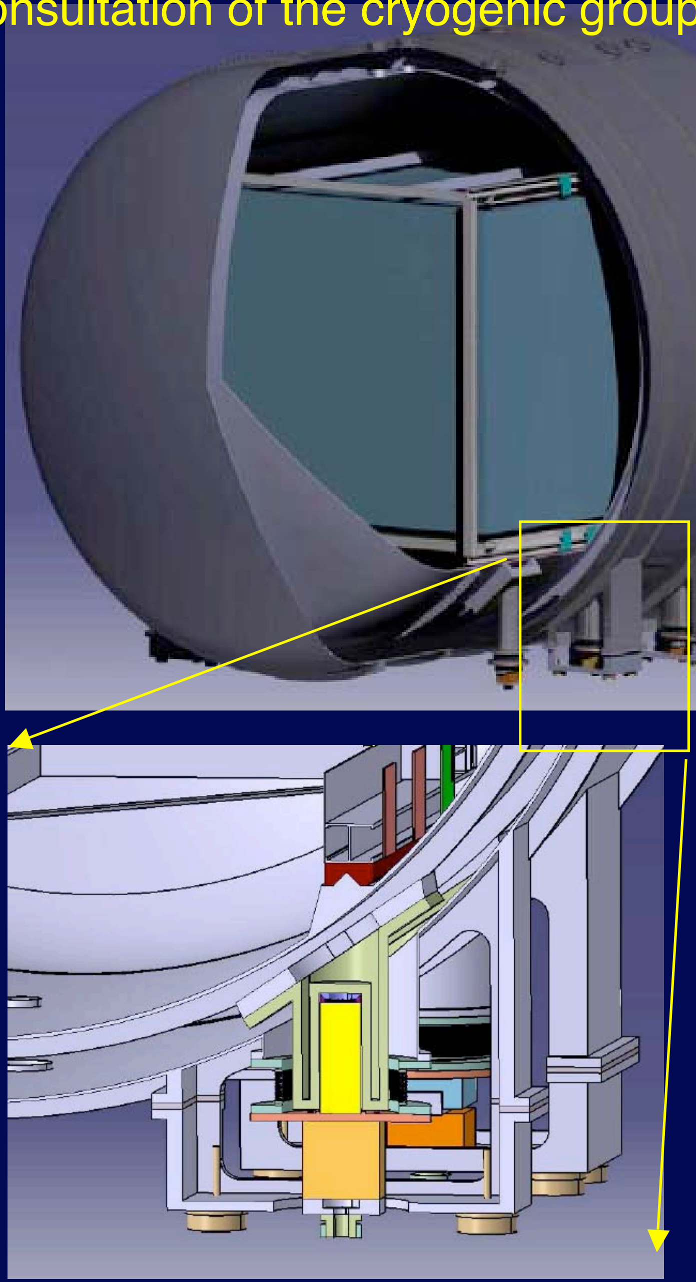
Liquid Argon imaging volume

Cathode and H_2O/CO_2 inner target

Wire chambers

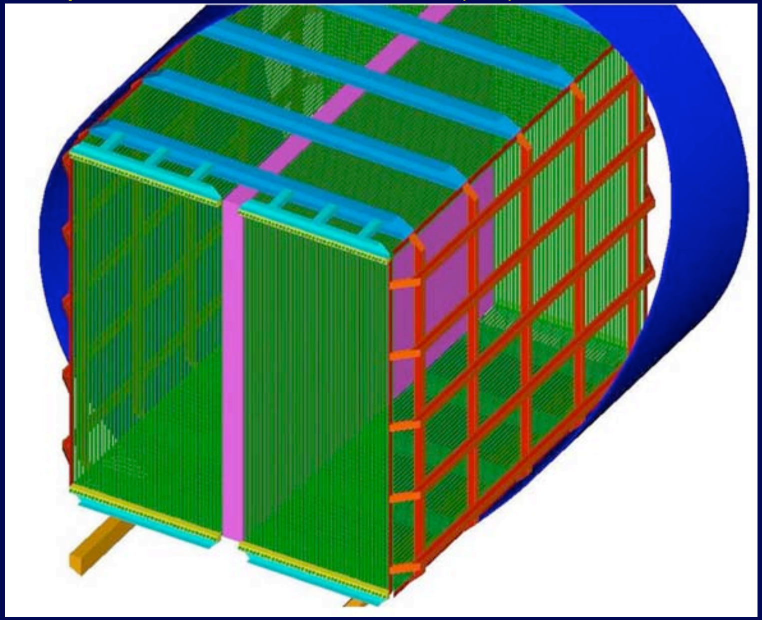
≈7,2 m

Cryostat designed at ETHZ with consultation of the cryogenic group at PSI



Inner detector designed at INFN Napoli

4.5 m x 4.5 m x 5 m stainless-steel supporting structure for wire planes, PMTs, auxiliary systems, cathode, inner target.
Two independent readout chambers (LR)



Total LAr mass ≈ 315 tons, total weight ≈ 100 tons, two independent stainless steel vessels, multilayer super-insulation in vacuum.

thermal Insulation	multi-layer super–insulation in vacuum
surface heat input	$1\ W/m^3$
total surface heat input	100 W
(accidental loss of vacuum)	(4 kW)
supporting feet	custom designed
heat input per supporting foot	< 50 W
number of supporting feet	6
total heat input through supporting feet	300 W
signal cables diameter	0.25 mm
length signal cables	0.75 m
number signal cables twisted pairs	10000
total heat input through cables	100 W
total heat input	500 W

Extrapolation of the technique to the 10÷100 kton scale

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

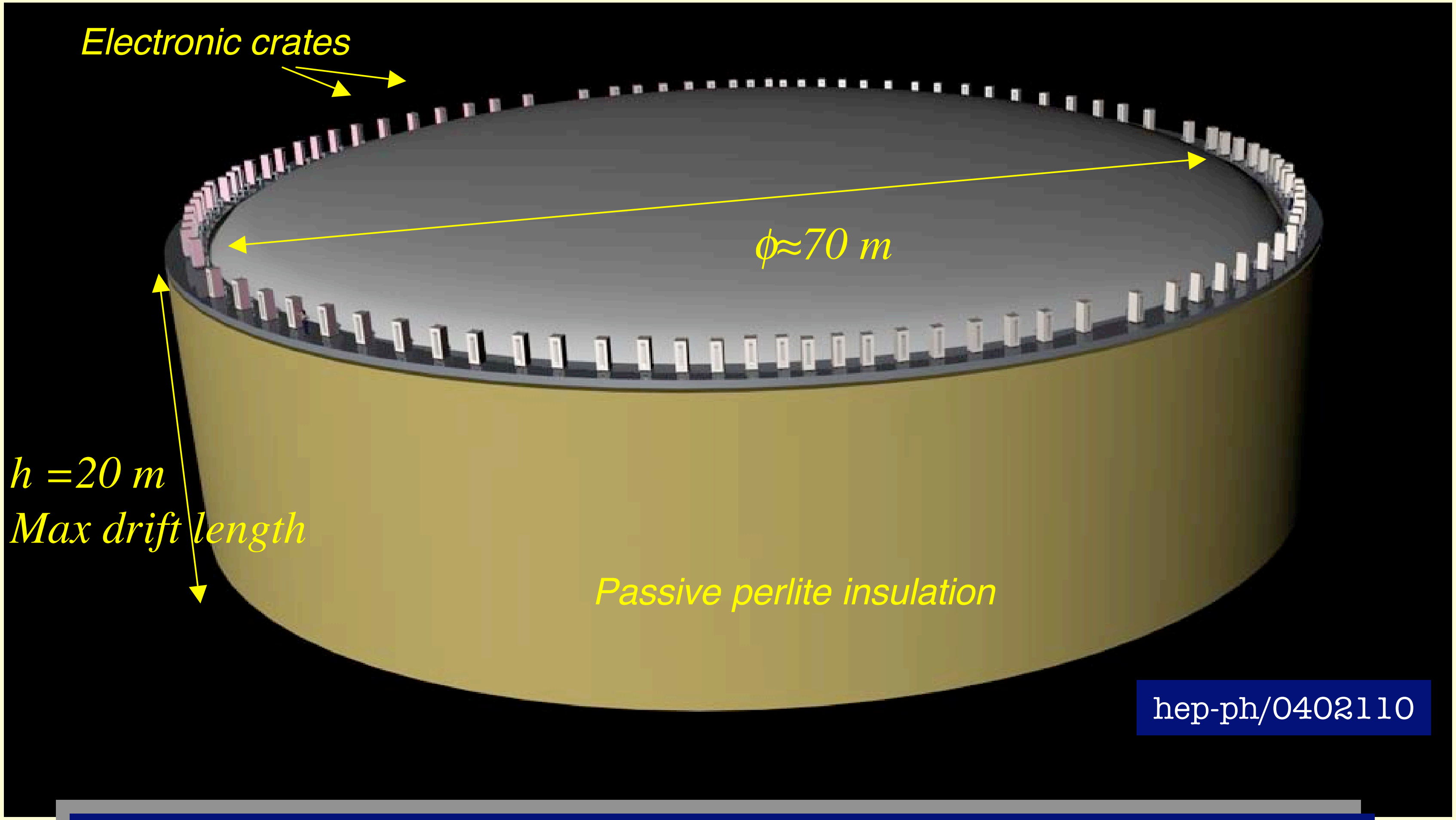
In order to reach the adequate fiducial mass for long-term future physics programs, a new concept is required to extrapolate further the technology.

We consider two 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 (only necessary for the neutrino factory).

And give a conceptual design in the following slides

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.

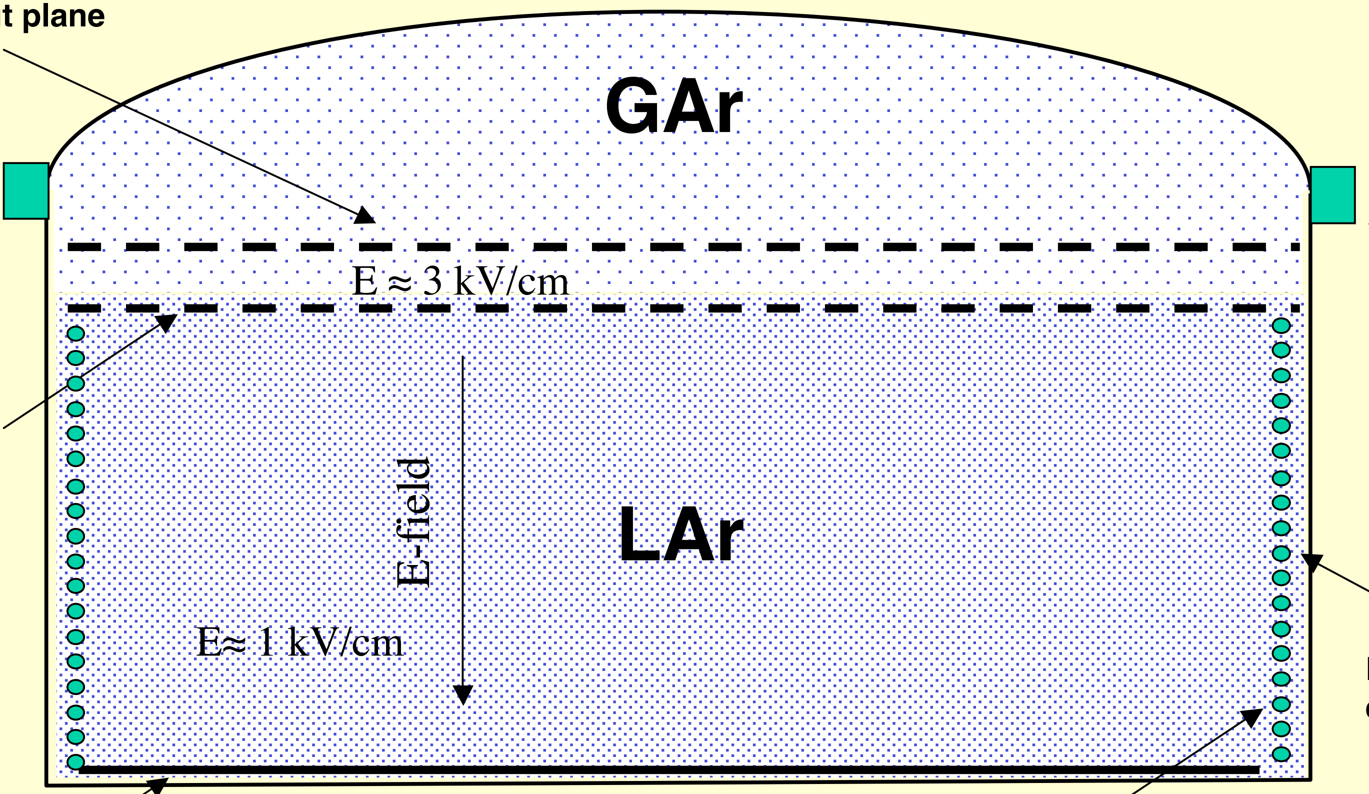
- **Charge amplification to allow for very long drift paths**. The detector is running in bi-phase mode. In order to allow for drift lengths as long as ≈20 m, which provides an economical way to increase the volume of the detector with a constant number of channels, charge attenuation will occur along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

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 ≈ 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 readout plane

Extraction grid

Cathode (- HV)

UV & Cerenkov light readout PMTs

Electronic racks

Field shaping electrodes

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

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

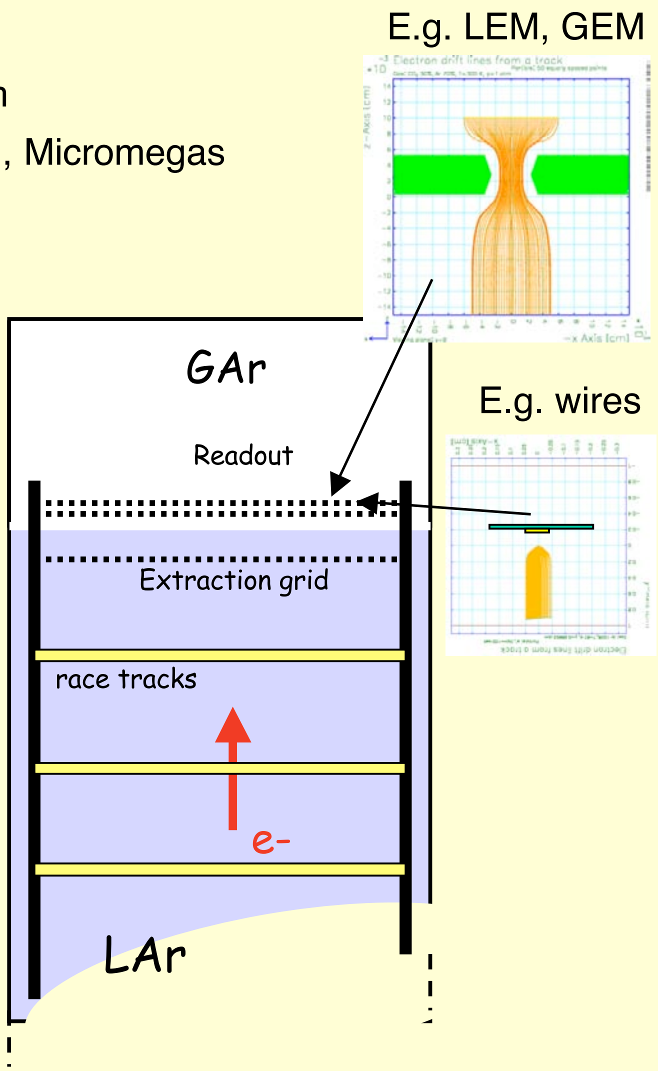
Cooling by "auto-refrigeration"

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, Micromegas

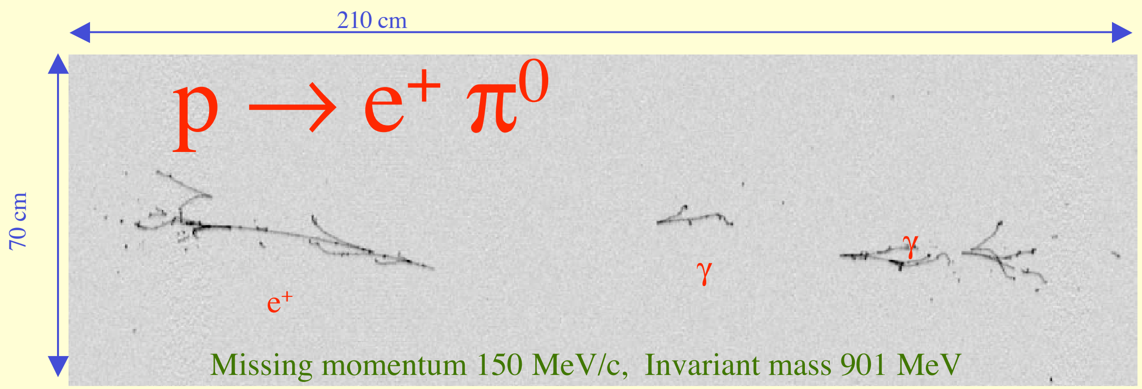
Electron drift in liquid	**20 m maximum drift, HV = 2 MV for E = 1 kV/cm, $v_d \approx 2$ mm/μs, max drift time ≈ 10 ms**
Charge readout view	**2 perpendicular views, 3 mm pitch, 100000 readout channels**
Maximum charge diffusion	**$\sigma \approx 2.8$ mm ($\sqrt{2Dt_{max}}$ for D = 4 cm²/s)**
Maximum 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 (ϕ ≈ 30 μm) + pad readout, GEM, LEM, Micromegas… Total area ≈ 3850 m²**

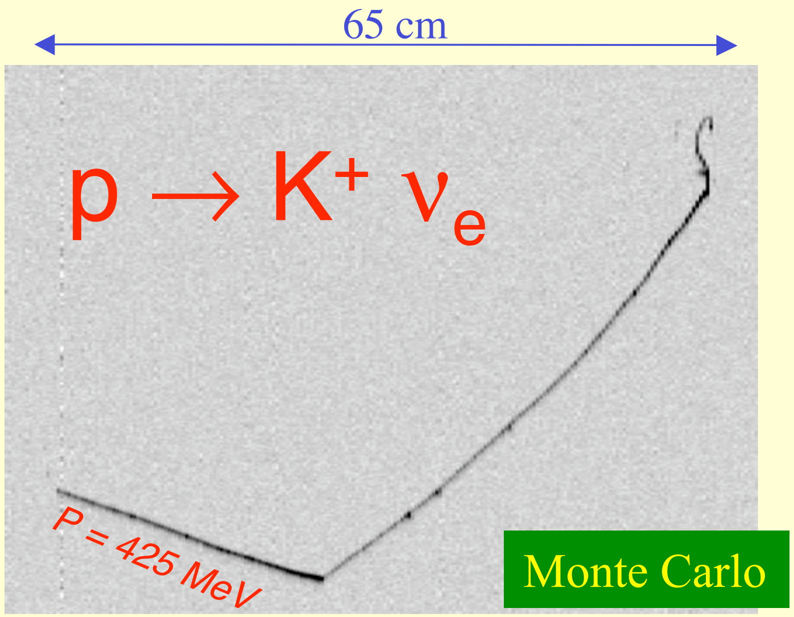


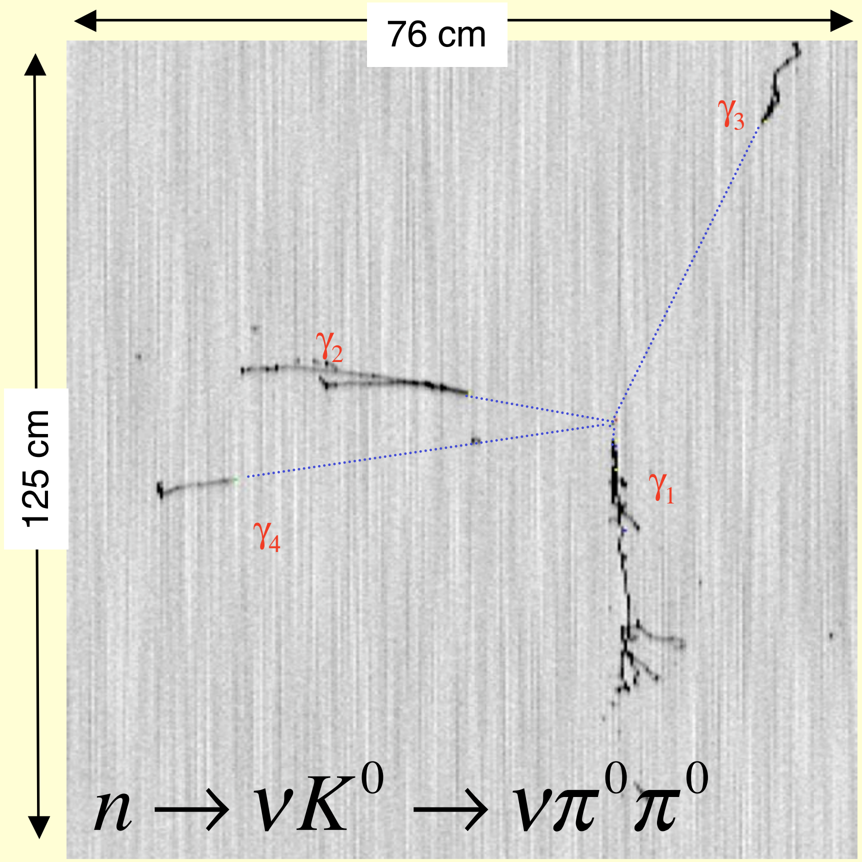
Outstanding non-accelerator physics goals

	Water Cerenkov	Liquid Argon TPC
Total mass	650 kton	100 kton
$p \rightarrow e\,\pi^0$ in 10 years	$1.6\text{x}10^{35}$ years $\varepsilon = 17\%$, ≈ 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 $\varepsilon = 8.6\%$, ≈ 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	≈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

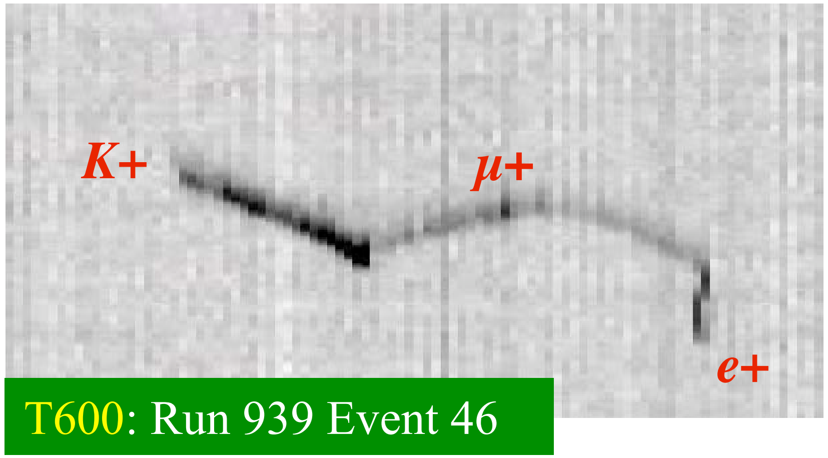
Nucleon decay



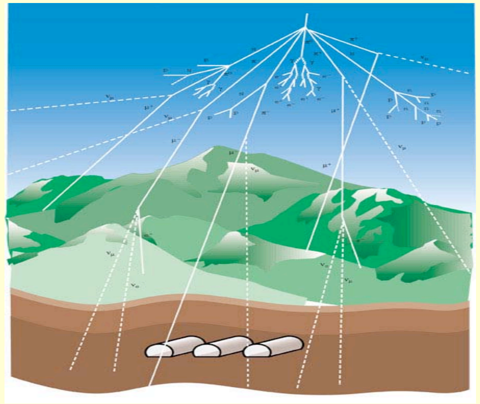


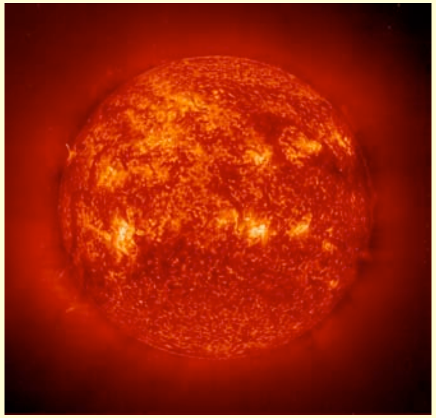


"Single" event detection capability



Astrophysical neutrinos





Atmospheric neutrinos:

High statistics, precision measurements

L/E dependence

Tau appearance, electron appearance

Earth matter effects

…

Solar neutrinos:

High statistics, precision measurement of flux

Time variation of flux

Solar flares

…

Supernova type-II neutrinos:

Access supernova and neutrino physics simultaneously

Decouple supernova & neutrino properties via different detection channels

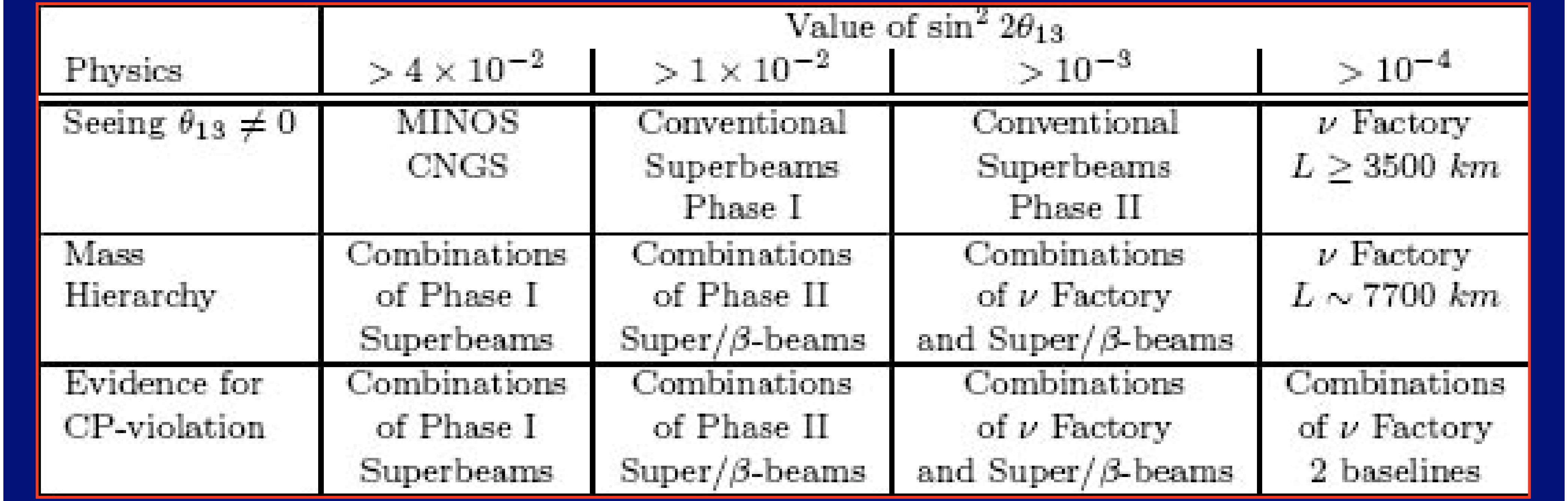
Relic supernova

Supernova in our galaxy or in Andromeda (1/15 years)

Initial burst

…

Goals at future neutrino beams



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 has the capability to act as a general purpose technique which will be modulated to the various physics programs depending on their relevance

Some recent physics references for liquid Argon TPCs

Proton driver optimization for new generation neutrino superbeams to search for subleading oscillations, A.Ferrari et al., New J. Phys 4 (2002) 88, hep-ph/0208047

On the energy and baseline optimization to study effects related to the delta phase (CP/T-violation) in neutrino oscillations at a neutrino factory, A. Bueno et al., Nucl. Phys. B631 (2002) 239, hep-ph/0112297 and references therein

Decoupling supernova and neutrino oscillations physics with LAr TPC detectors, I. Gil-Botella and A.Rubbia, JCAP 0408 (2004) 001

Oscillation effects on supernova neutrino rates and spectra and detection of the shock breakout in a liquid Argon TPC, I. Gil-Botella and A.Rubbia, JCAP 0310 (2003) 009

Supernova neutrino detection in a liquid Argon TPC, A. Bueno, I. Gil-Botella and A.Rubbia, hep-ph/0307222

Relic supernova neutrino detection with liquid Argon TPC detectors, A. Cocco et al., **JCAP 0412:002,2004**

Nucleon decay studies in a large liquid Argon detector, A.Bueno, M. Campanelli, A. Ferrari and A.Rubbia, Proceedings International Workshop on next generation nucleon decay and neutrino detector (NNN99), Stony Brook, NY, USA (1999)

Nucleon decay searches: study of nuclear effects and background, A. Ferrari, S. Navas, A.Rubbia and P. Sala, ICARUS technical memo TM/01-04 (2001)

Simulation of Cosmic Muon Induced Background to Nucleon Decay Searches in a Giant 100 kton LAr TPC, Z. Dai, A.Rubbia and P. Sala, ICARUS technical memo

GLACIER R&D working group

- Physics departments:

ETHZ:	A. Badertscher, W. Gruber, L. Knecht, M. Laffranchi, A. Meregaglia, M. Messina, A. Müller, G. Natterer, P.Otiougova, A. Rubbia,J. Ulbricht
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Niewodniczanski Institute (Krakow):	A. Zalewska

- Cryogenic departments:

Southampton University:	C. Beduz, Y. Yang

- Industry:

Technodyne Ltd, Eastleigh, UK

CUPRUM (KGHM group), Wroclaw, Poland

CAEN, Viareggio, Italy

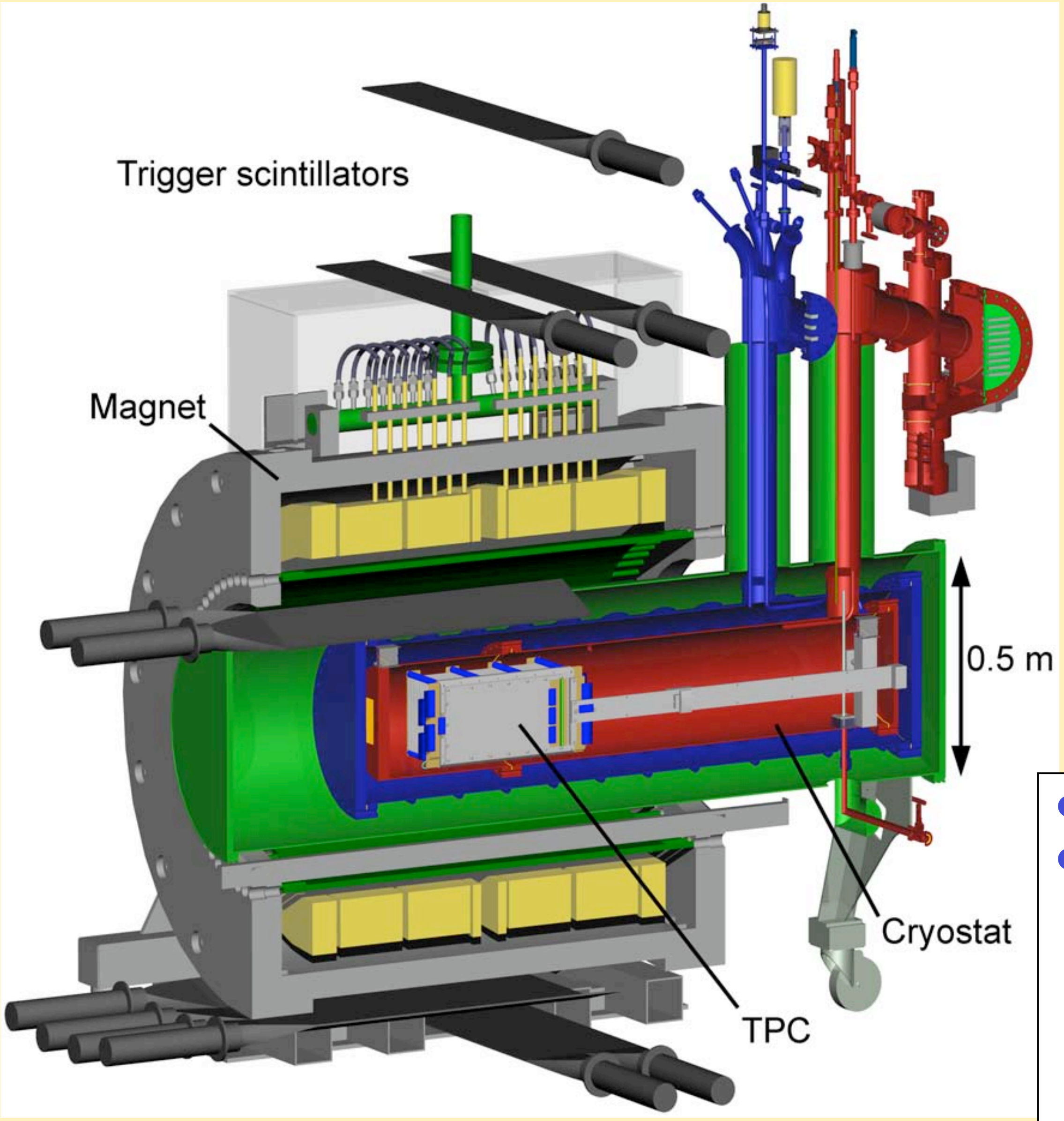
R&D strategy

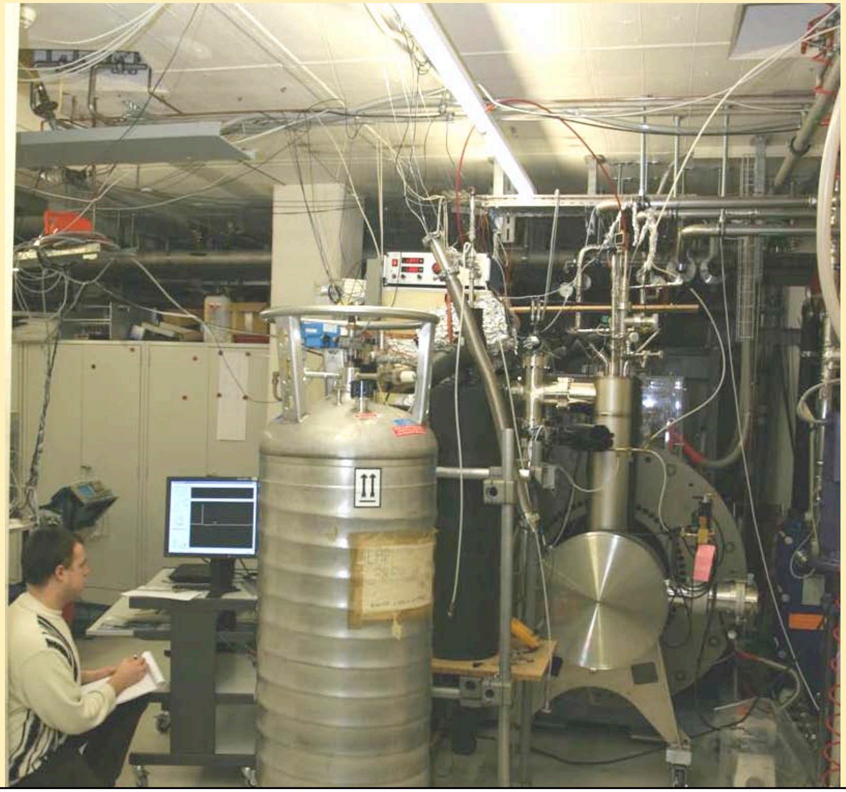
In order to assess our conceptual design, we are performing dedicated tests in the laboratory and studying specific items in more details:

- Study of suitable charge extraction, amplification and imaging devices
- Understanding of charge drift properties under high hydrostatic 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
- Study of large scale argon purification

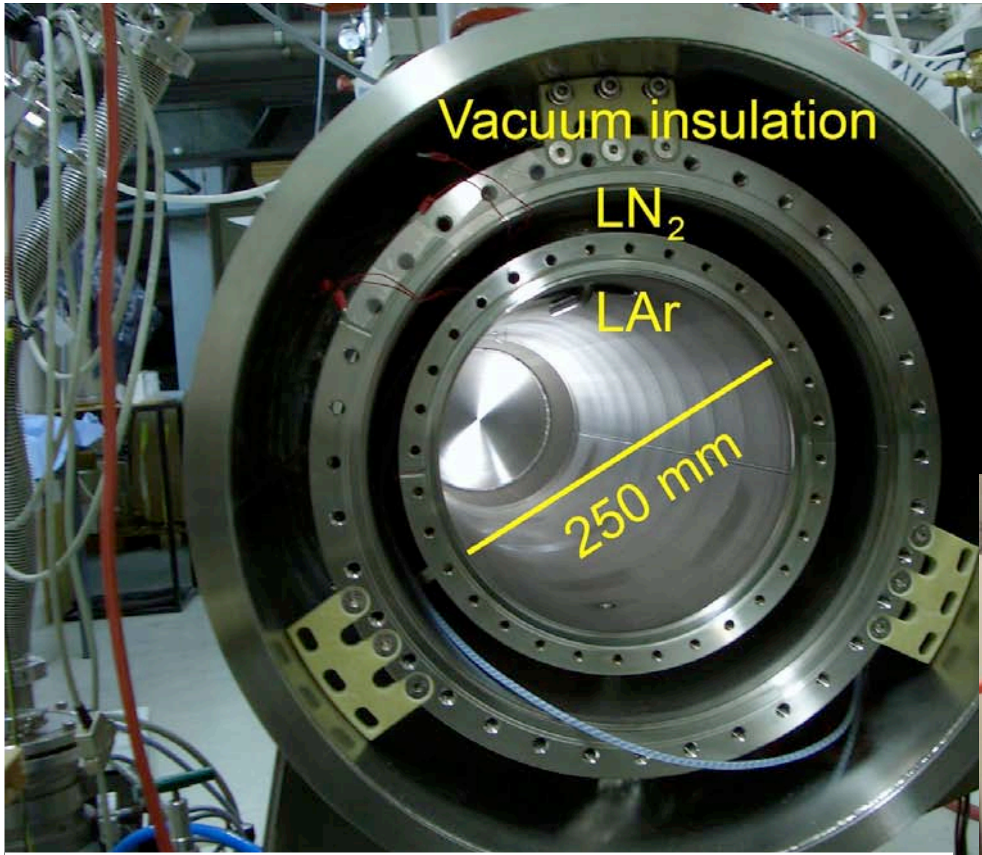
(1) First operation of a LAr TPC embedded in a B-field

New J.Phys.7:63 (2005)



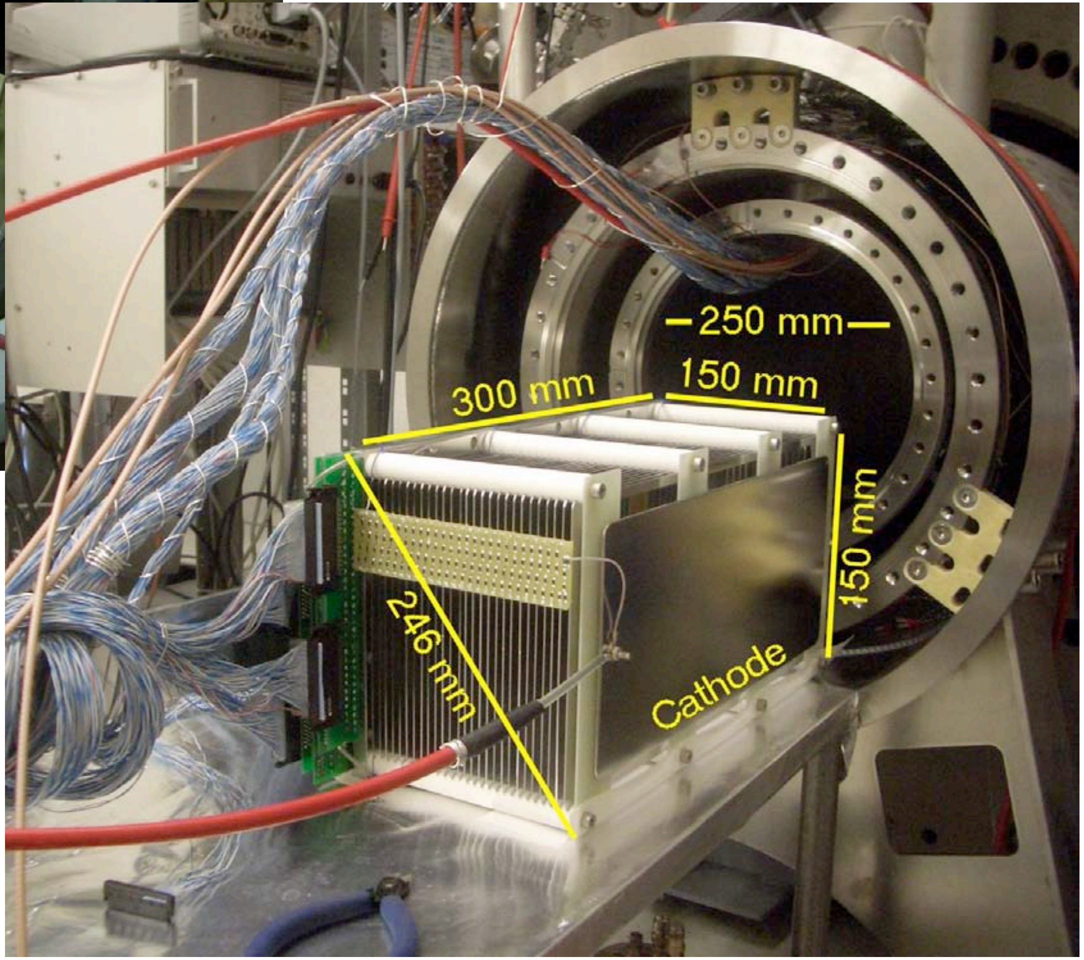


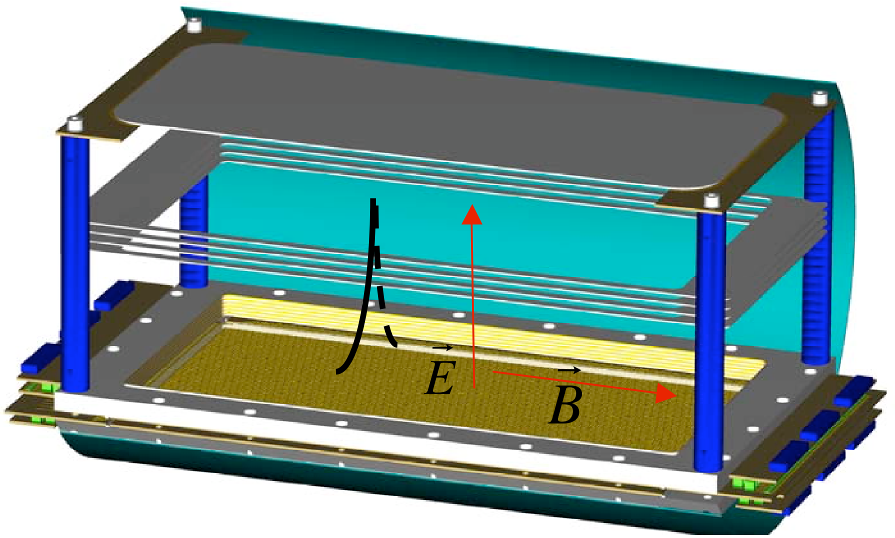
- **Small chamber magnetic field**
- **Test program:**
  - ➥ Check basic imaging in B-field
  - ➥ Measure traversing and stopping muons bending
  - ➥ Charge discrimination
  - ➥ Check Lorentz angle ($\alpha \approx 30$mrad @ E=500 V/cm, B=0.5T)

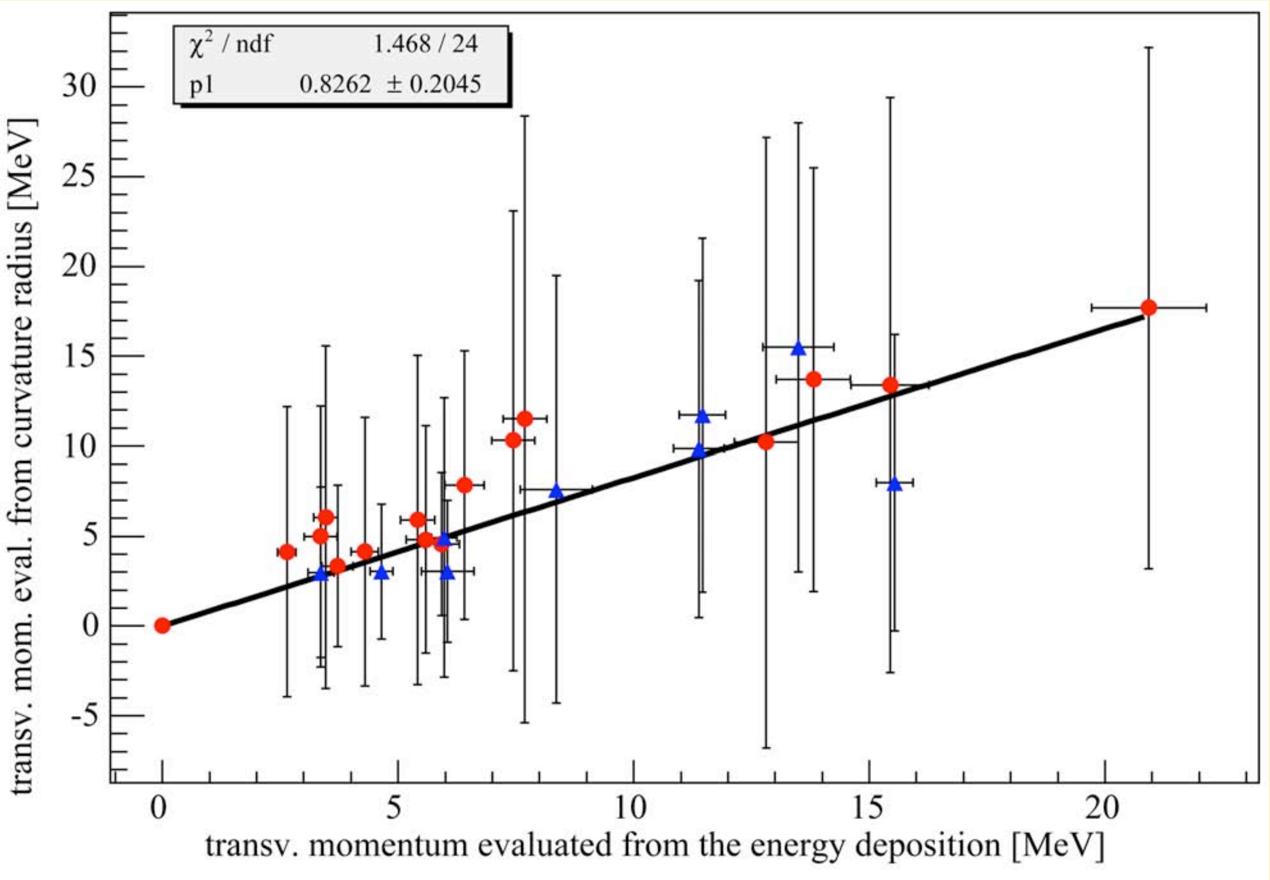


PhD thesis M. Laffranchi, March 2005

Available at http://neutrino.ethz.ch/



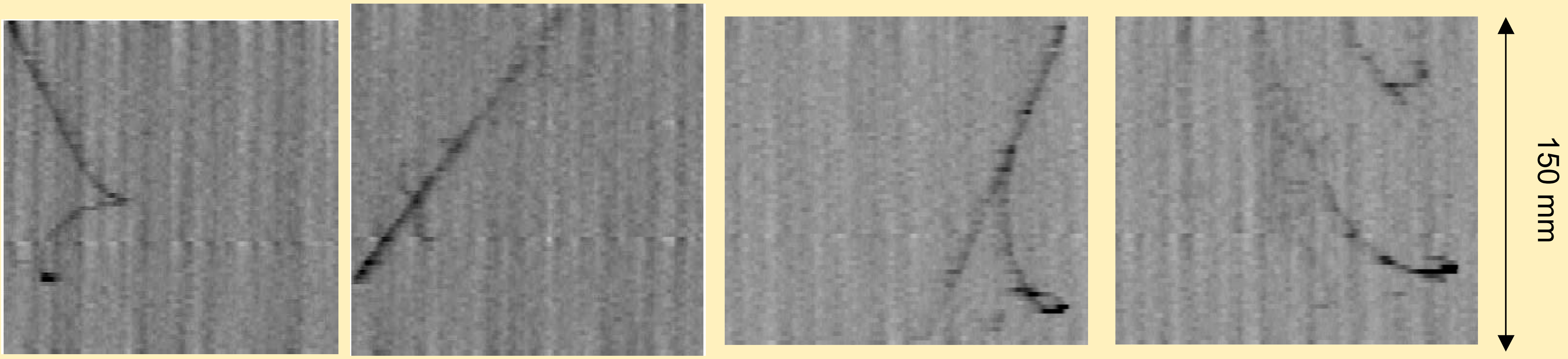




Diploma thesis A. Müller, March 2005

Available at http://neutrino.ethz.ch/

First events in magnetic field B=0.55T



Discrimination of the electron charge

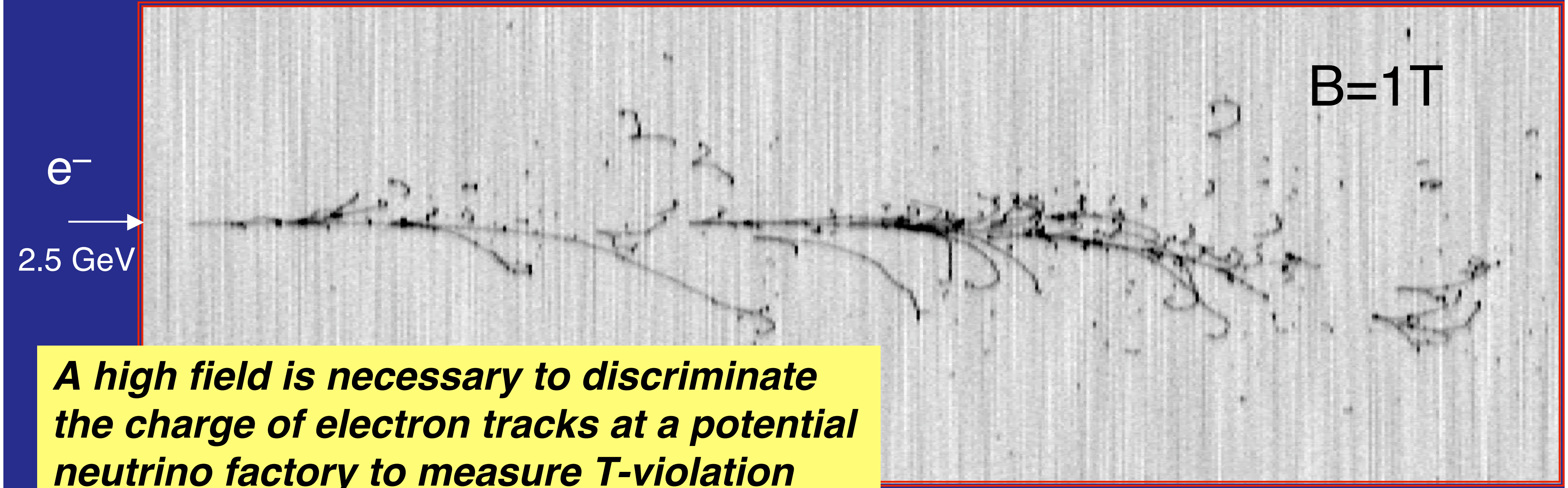
E-print: hep-ph/0106088

$$B \geq \frac{0.2[T]}{\sqrt{x[m]}}$$

$x=1X_0 \Rightarrow B>0,5T$

$x=2X_0 \Rightarrow B>0,4T$

$x=3X_0 \Rightarrow B>0,3T$



A high field is necessary to discriminate the charge of electron tracks at a potential neutrino factory to measure T-violation

MC STUDY: CHARGE CONFUSION$<10^{-3}$ @ B=1 T, E<5 GEV

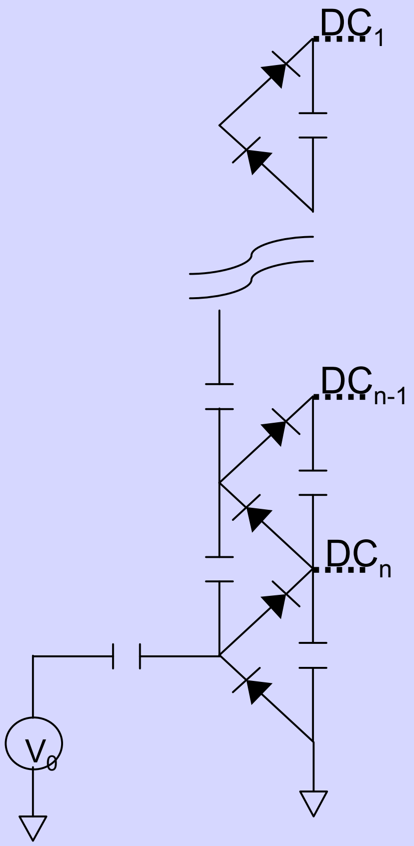
a) Primary electron momentum … curvature radius obtained by the calorimetric energy measurement

b) Soft bremsstrahlung γ's … the primary electron remembers its original direction → long effective x for bending

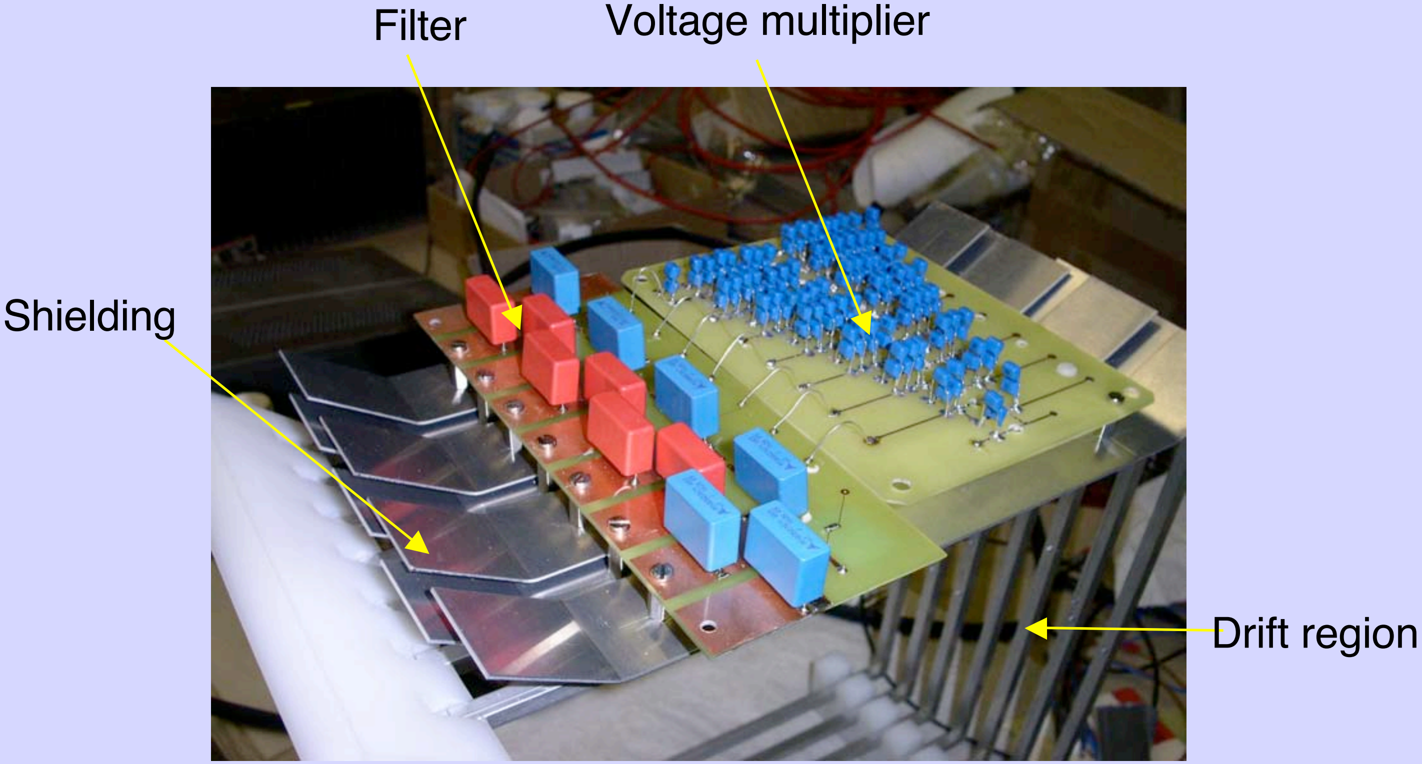
c) Hard initial bremsstrahlung γ's … the energy is reduced → low P → small curvature radius

(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

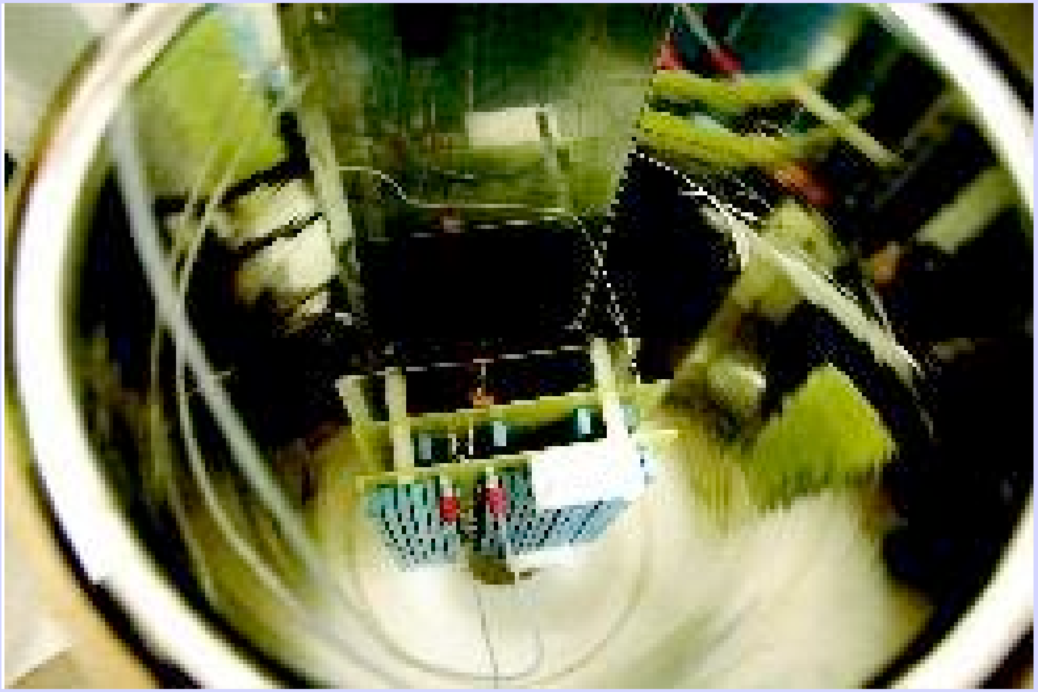


Greinacher or Cockroft/Walton voltage multiplier



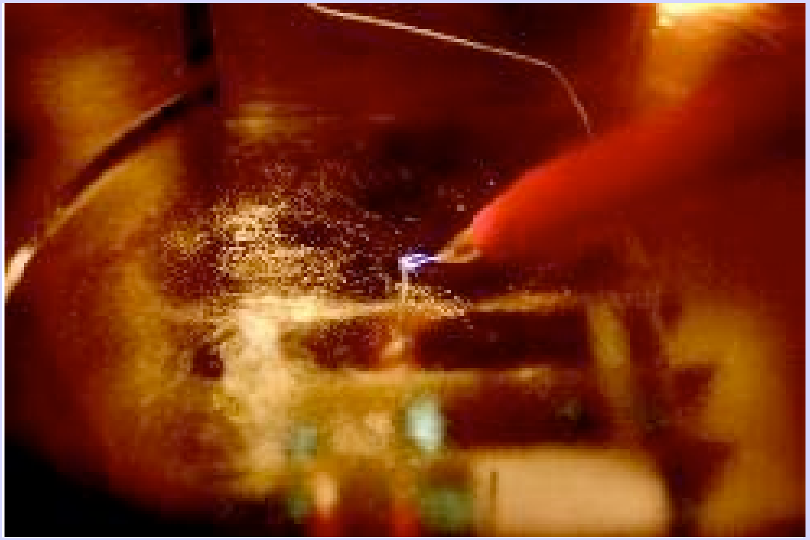
Prototype connected to actual electrodes of 50 liter TPC (ripple noise test)
Successfully tested up to ≈20kV

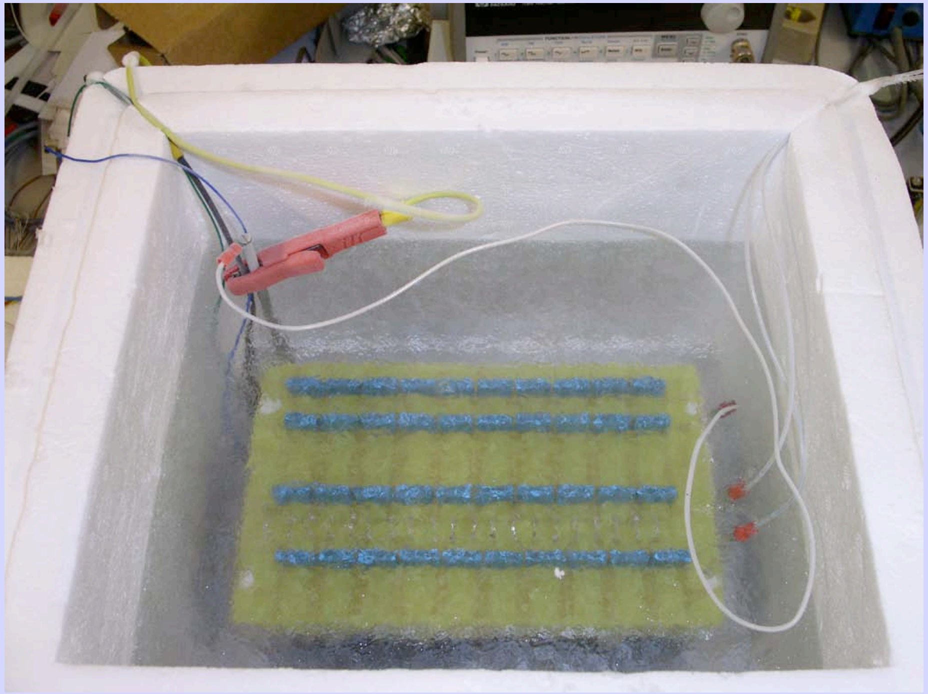
Drift very high voltage: 40 kV multiplier in LAr



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

- HV diodes from Vishay/Phillips





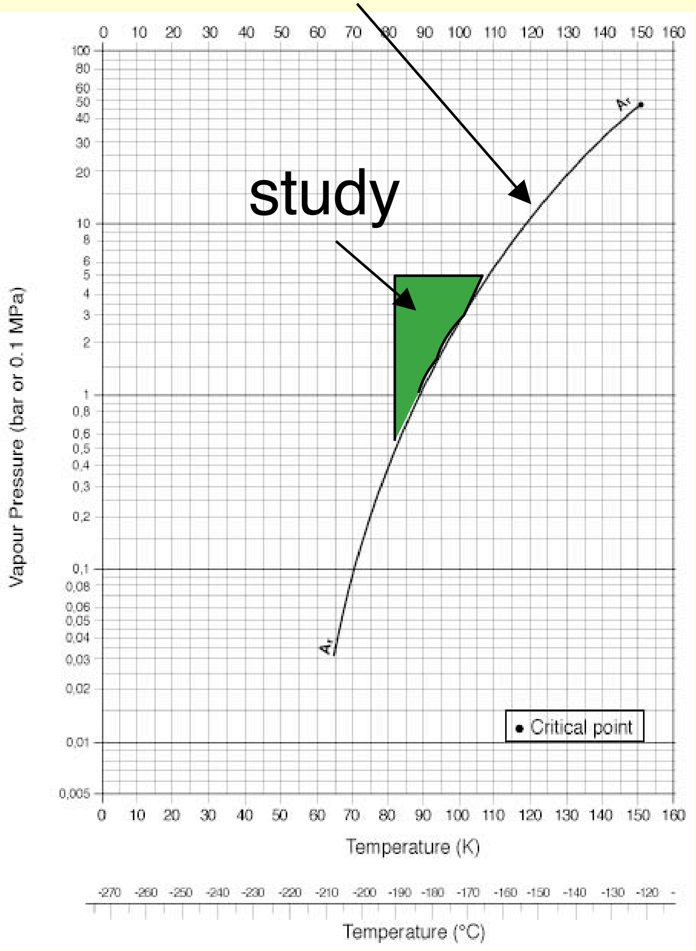
(3) High-pressure drift properties in liquid Argon

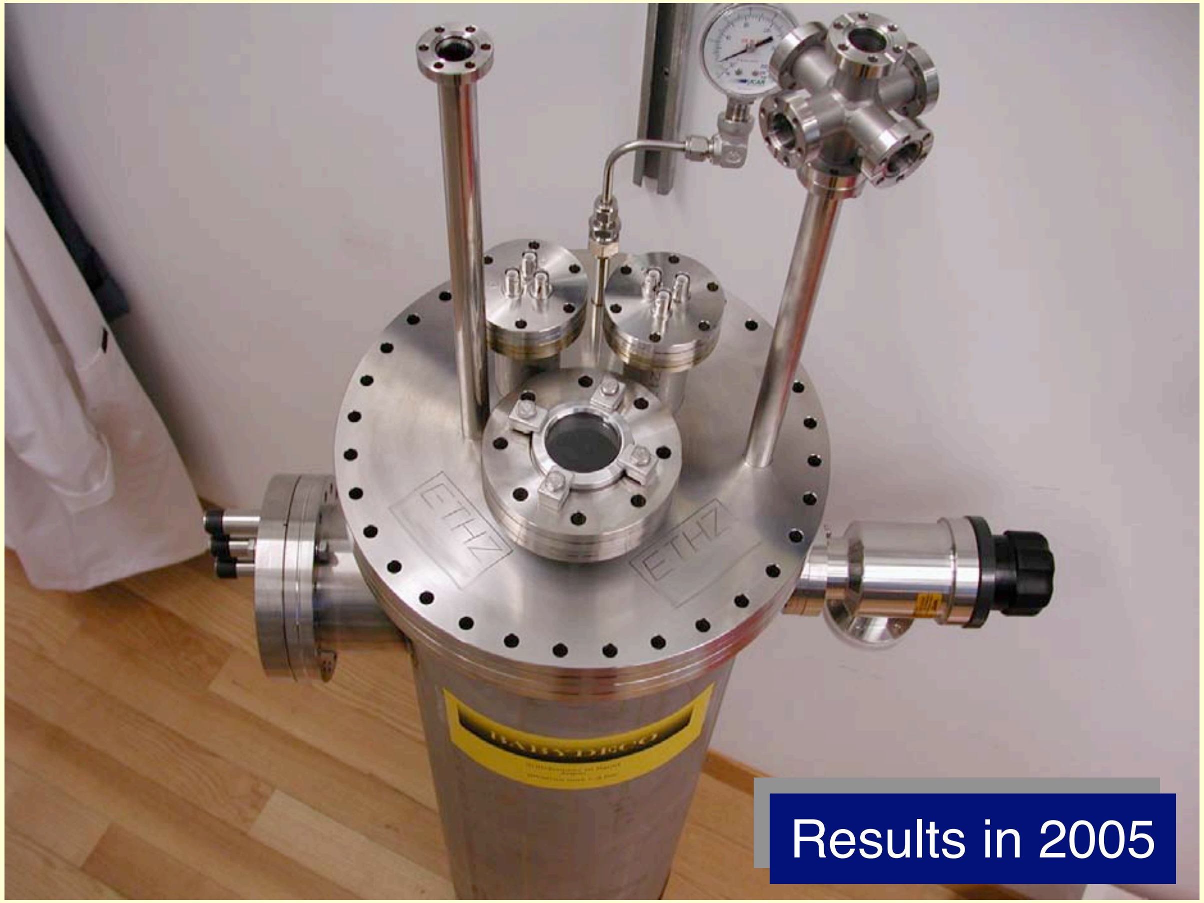
- **At the bottom of the large tankers:**

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

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

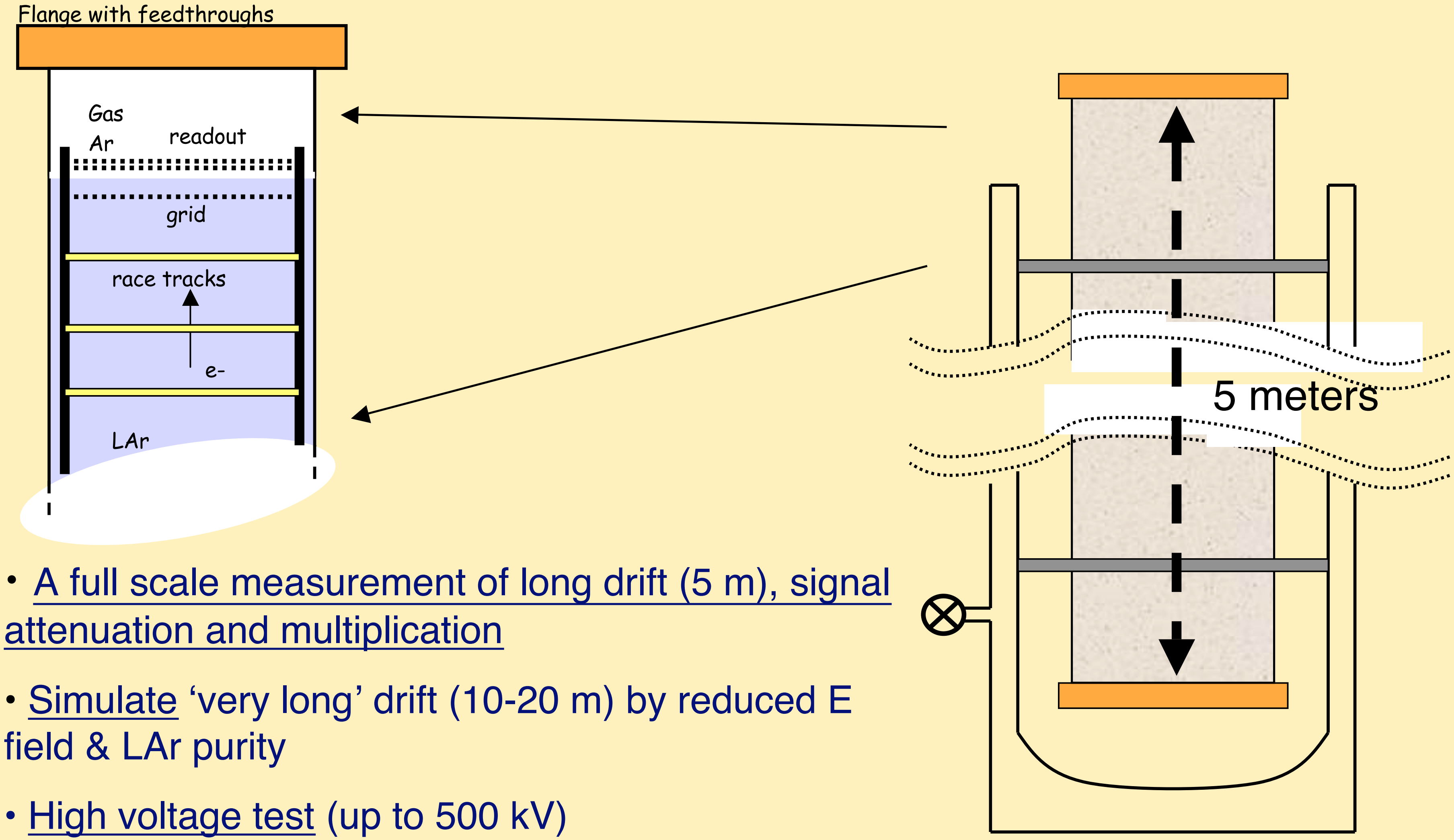
  Important to understand the electron drift properties and imaging under pressure above equilibrium vapor pressure





Results in 2005

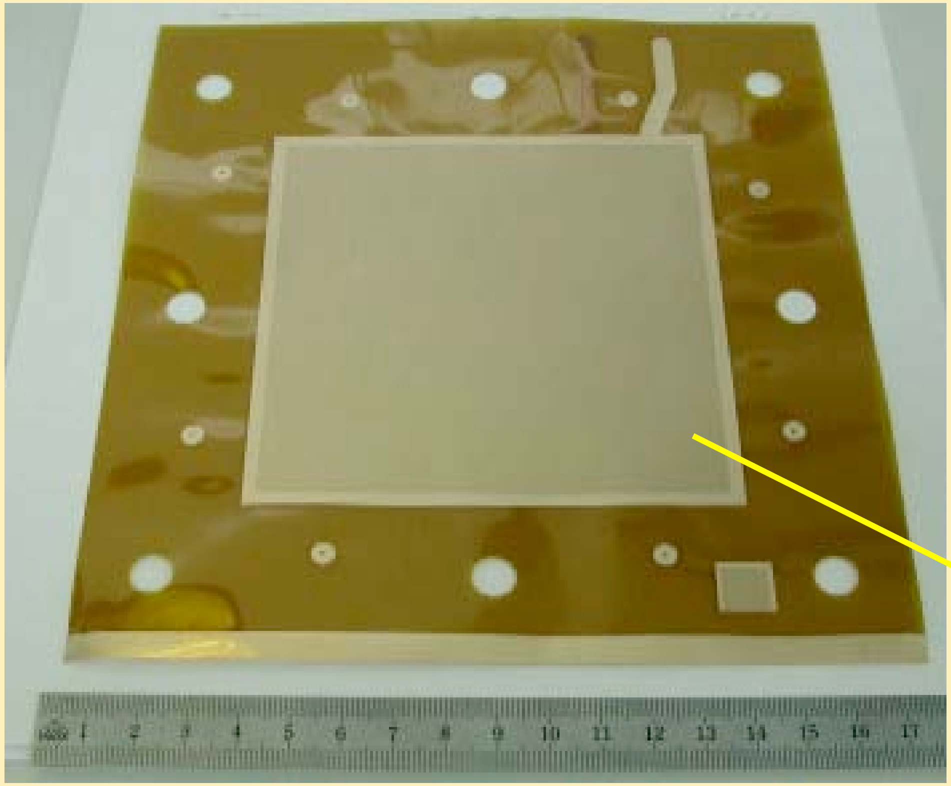
(4) Long drift, extraction, amplification: “ARGONTUBE”



- A 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 in progress: external dewar, detector container, inner detector, readout system, …

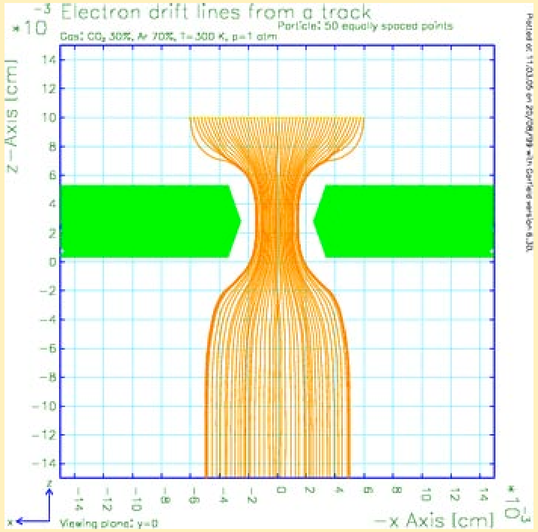
Results in ≈2006

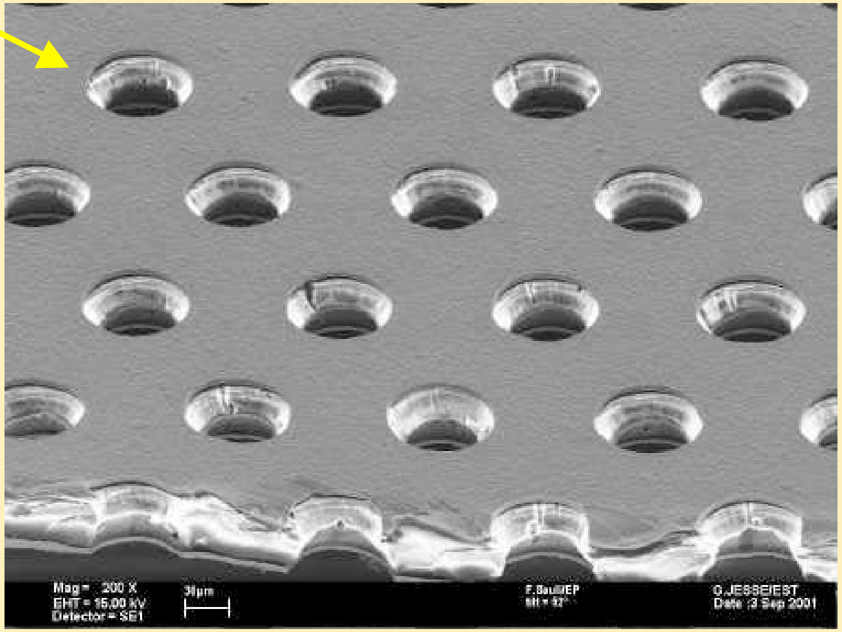
Gas Electron Multiplier GEM (F. Sauli et al., CERN)



100x100 mm^2

A gas electron multiplier (GEM) consists of a thin, metal-clad polymer foil, chemically pierced by a high density of holes. On application of a difference of potential between the two electrodes, electrons released by radiation in the gas on one side of the structure drift into the holes, multiply and transfer to a collection region.



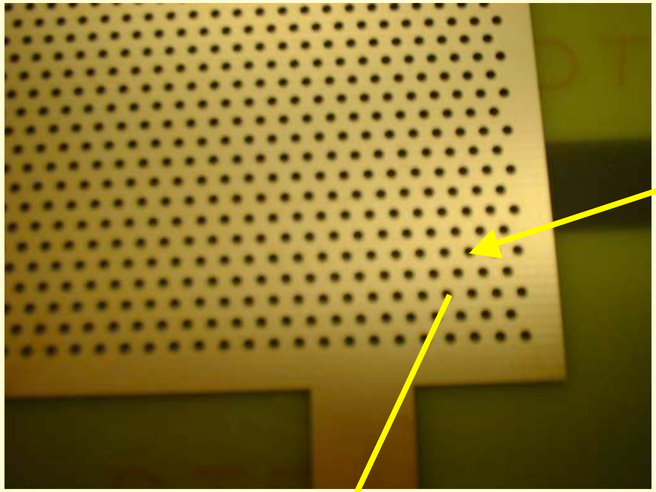


Thick Large Electron Multiplier (LEM)

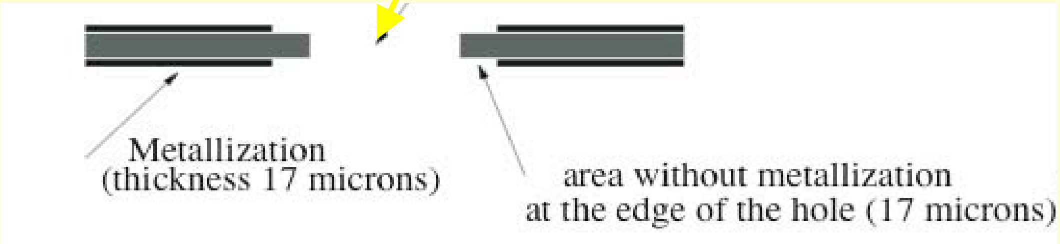
Thick-LEM (vetronite Cu coated + holes)

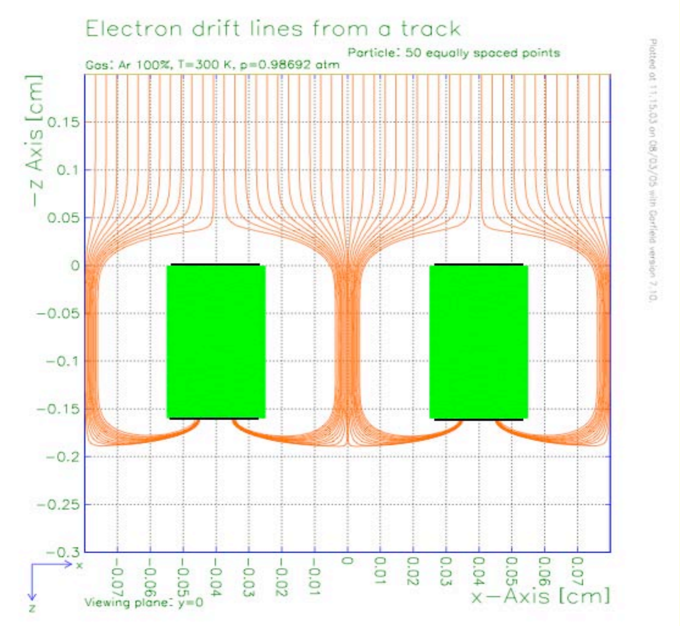
Sort of macroscopic GEM

A priori more easy to operate at cryogenic temperature

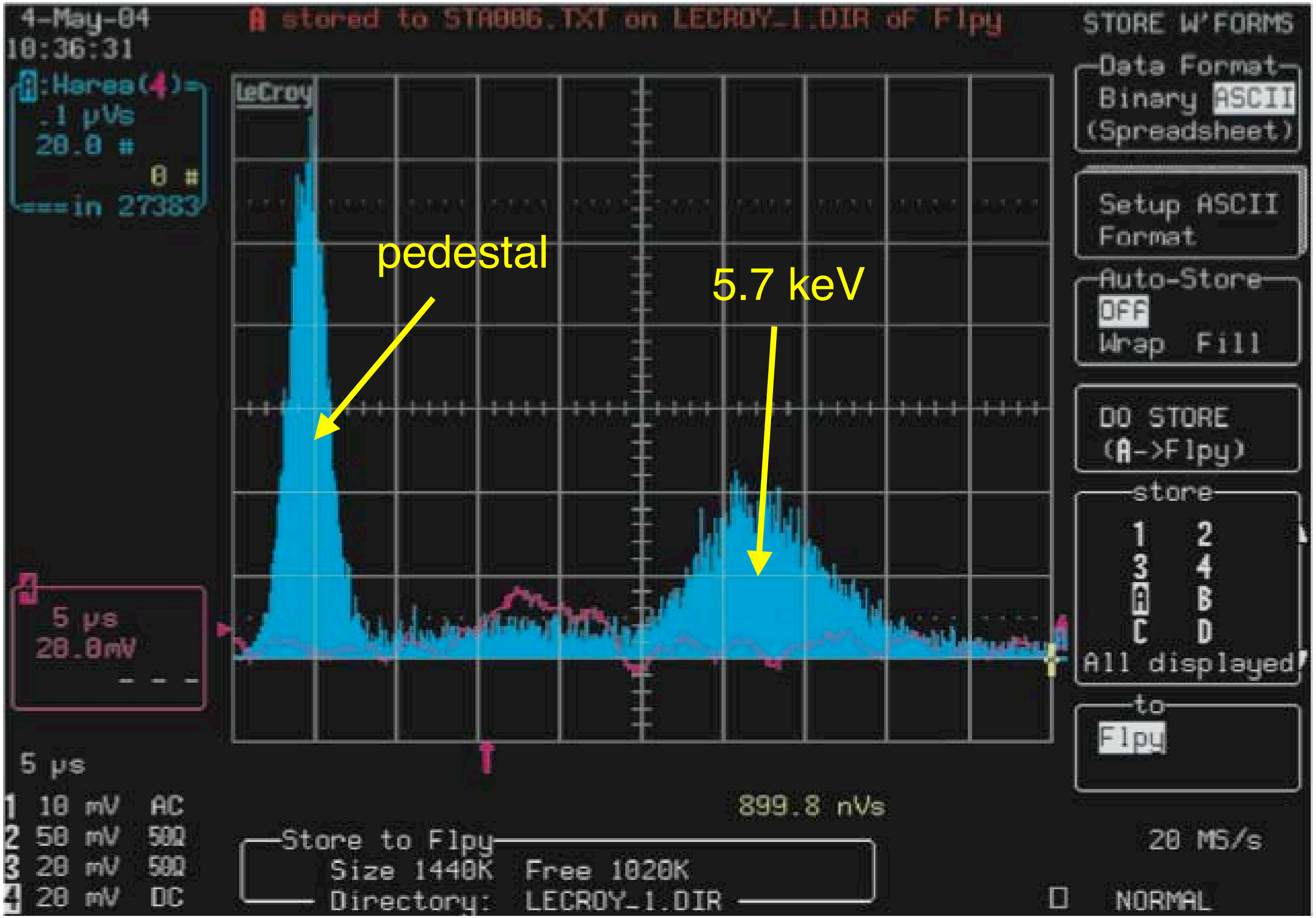


- Three thicknesses: 1, 1.6 and 2.4 mm
- Amplification hole diameter = 500 μm





The typical spectrum (Fe55, 5.7 keV or O(100 e⁻))



4-May-04
10:36:31

A stored to STA006.TXT on LECROY_1.DIR of Flpy

A:Harea(4)=
.1 µVs
20.0 #
0 #
===in 27383

4
5 µs
20.0mV

5 µs
1 10 mV AC
2 50 mV 50Ω
3 20 mV 50Ω
4 20 mV DC

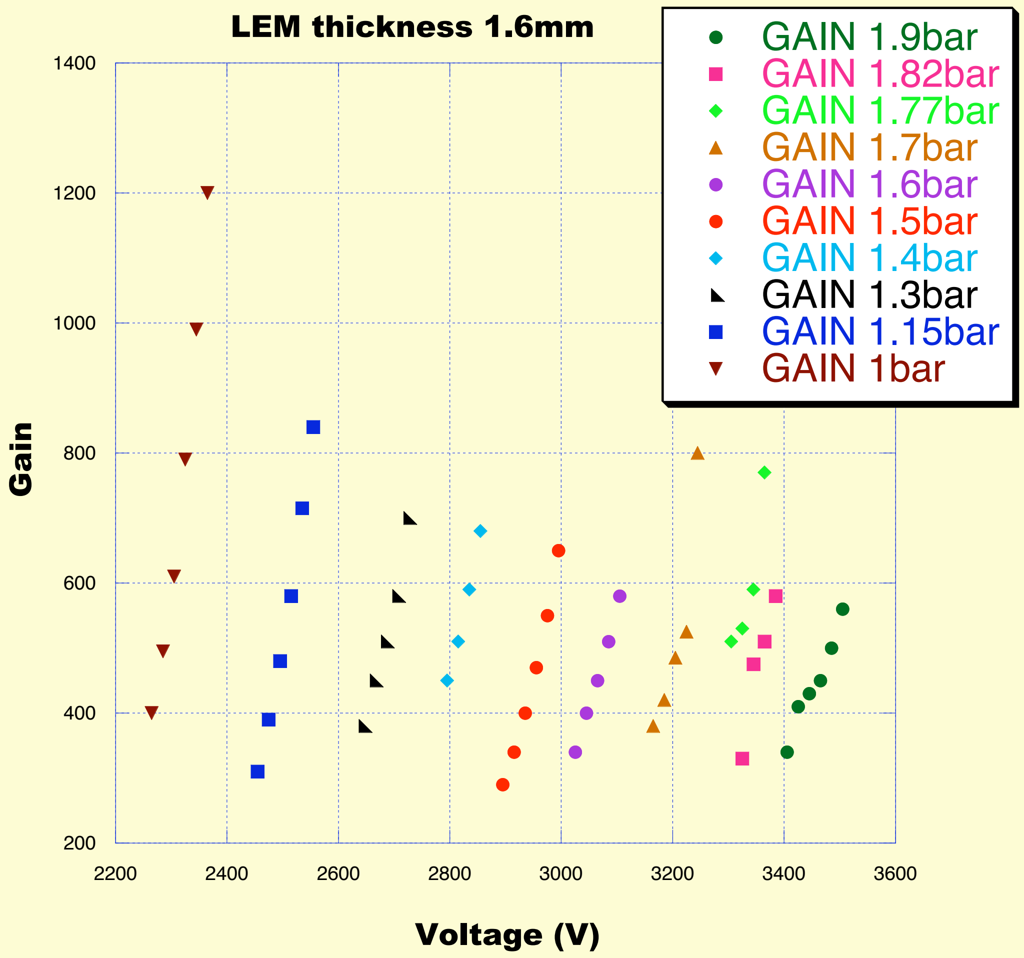
899.8 nVs

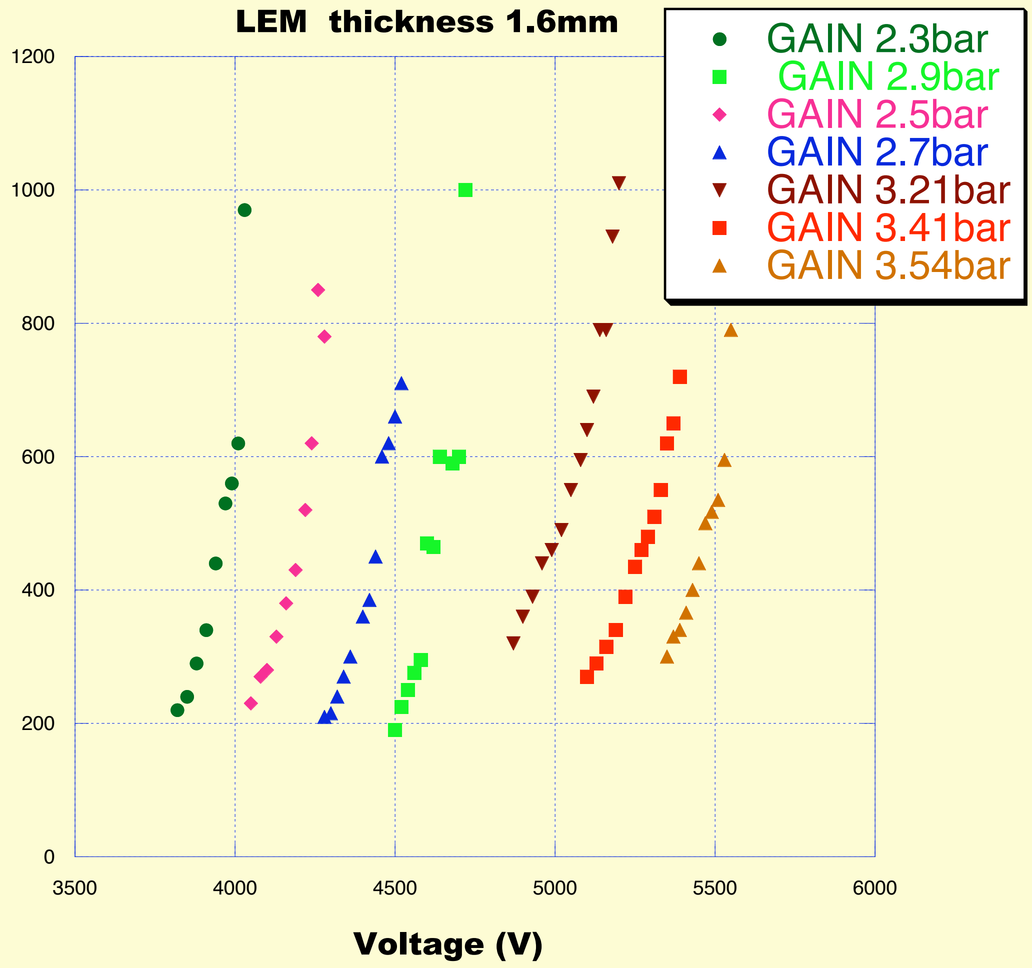
Store to Flpy
Size 1440K Free 1020K
Directory: LECROY_1.DIR

20 MS/s
NORMAL

High gain operation of LEM in pure Ar at high pressure

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



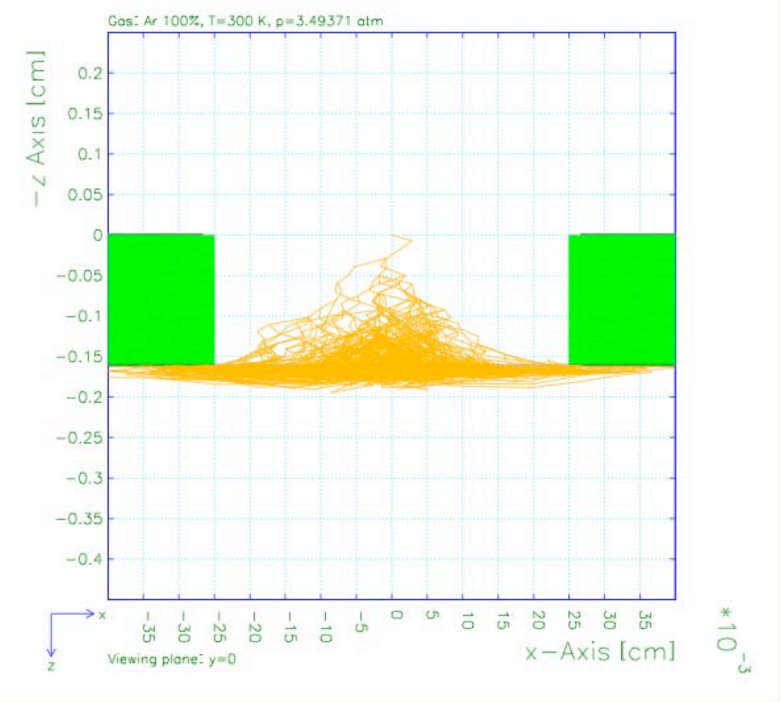


Gain up to ≈800 possible even at high pressure (good prospects for operation in cold)

Resolution ≈ 28% FWHM for Fe-55 source

e-print in preparation

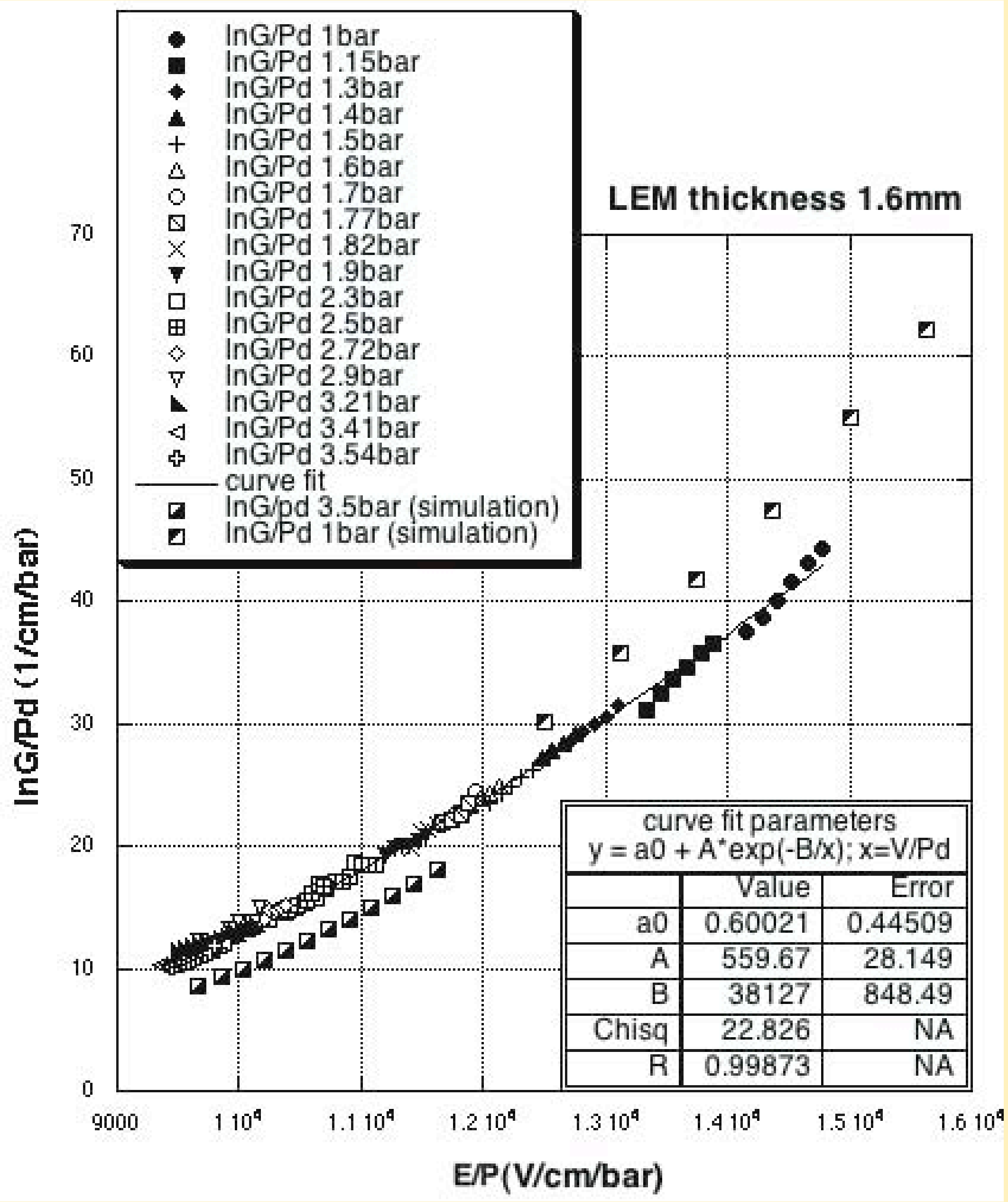
Comparison with GARFIELD simulations



At 3.5bar most electrons are created within the region of ~130 microns and electron diffusion inside the hole is ~100microns

Results are consisted with avalanche confinement :

$$G \leq \exp(\alpha d)$$



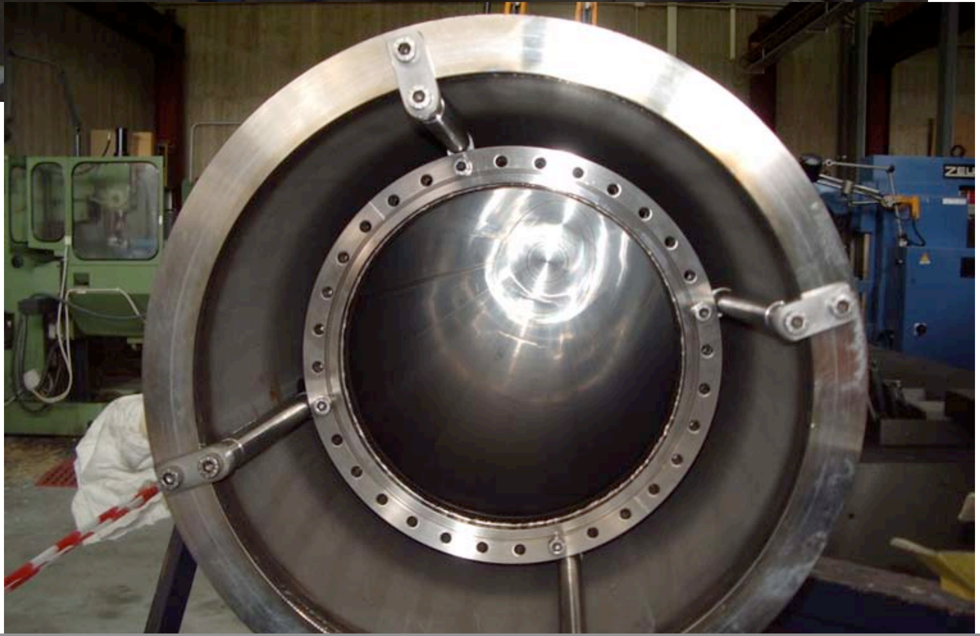
curve fit parameters
y = a0 + A*exp(-B/x); x=V/Pd

	Value	Error
a0	0.60021	0.44509
A	559.67	28.149
B	38127	848.49
Chisq	22.826	NA
R	0.99873	NA

Long drift, extraction, amplification: “ARGONTUBE”

Inner diameter 250 mm, drift length 5000 mm
Drift H.V. up to 500 kV

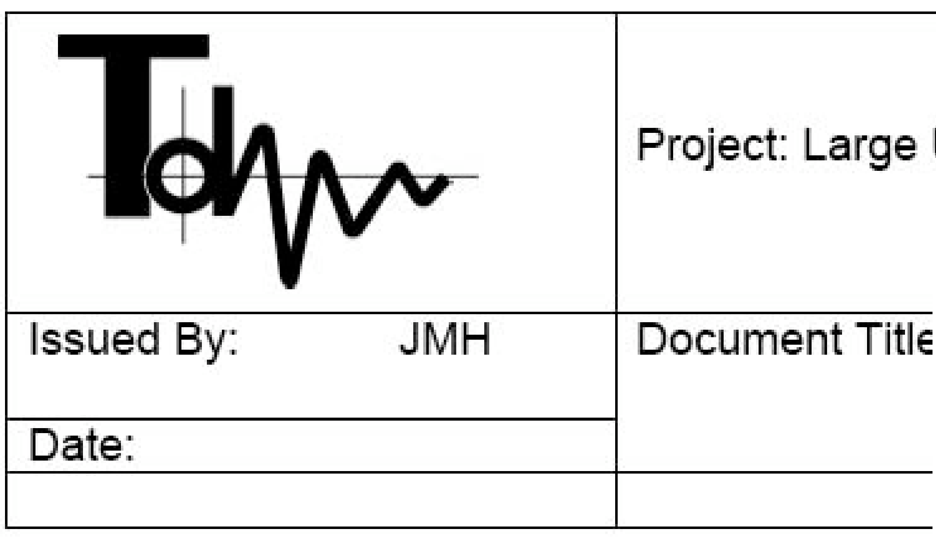
Vacuum leak tests



Superinsulation

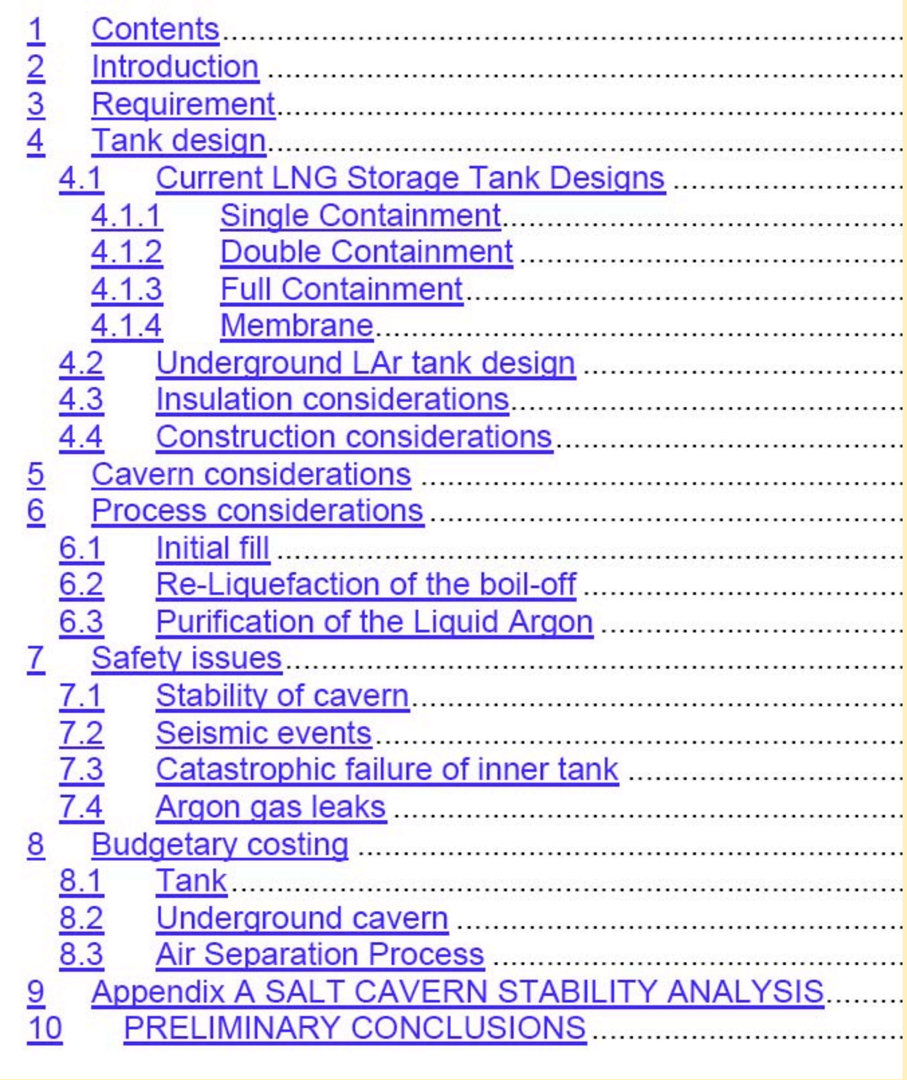
“ARGONTUBE” cryostat assembly finished on March 23, 2005

(5) 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:

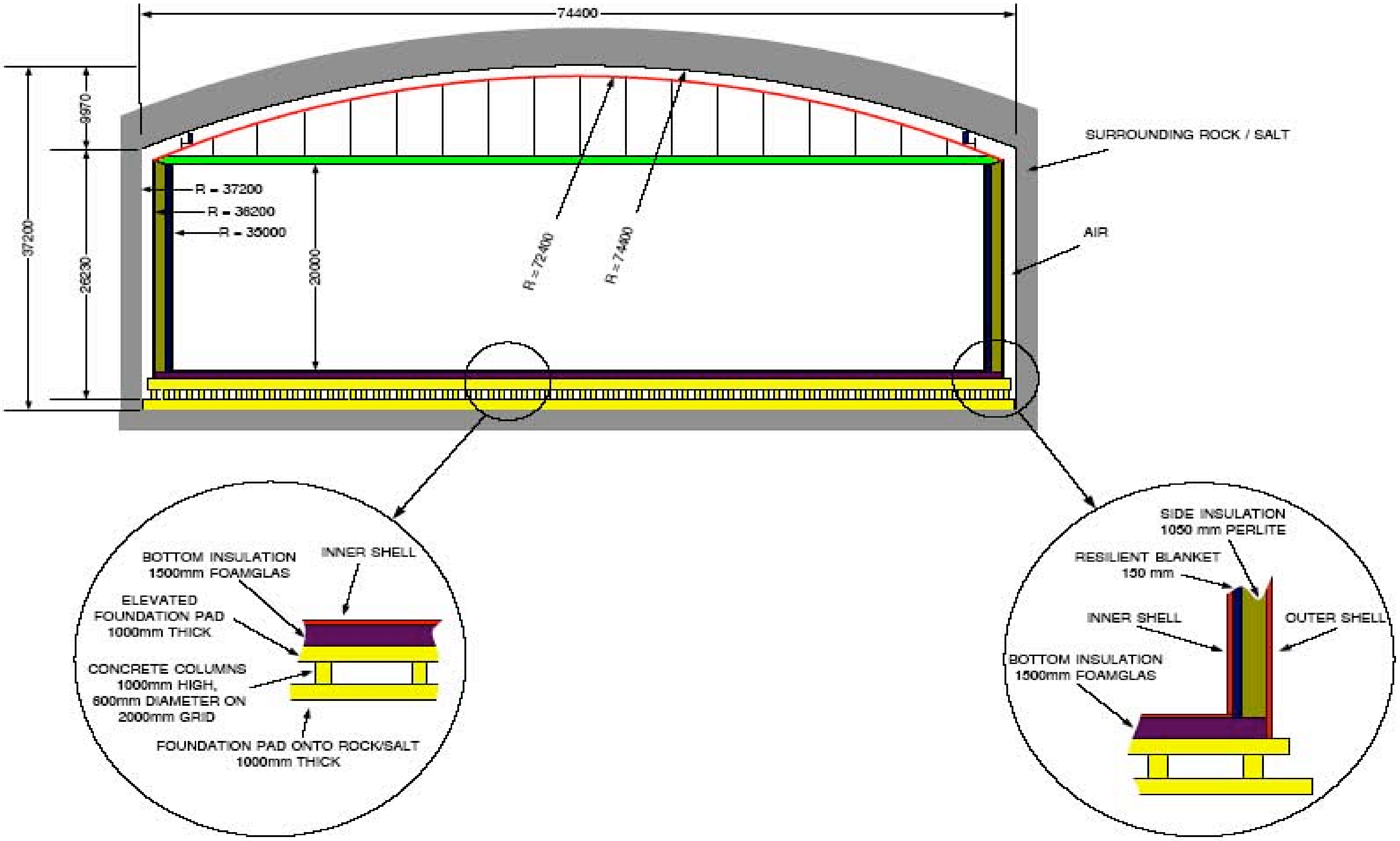
February - December 2004

Funded by ETHZ

Technodyne baseline design

TECHNODYNE INTERNATIONAL LIMITED

LARGE UNDERGROUND LIQUID ARGON STORAGE TANK



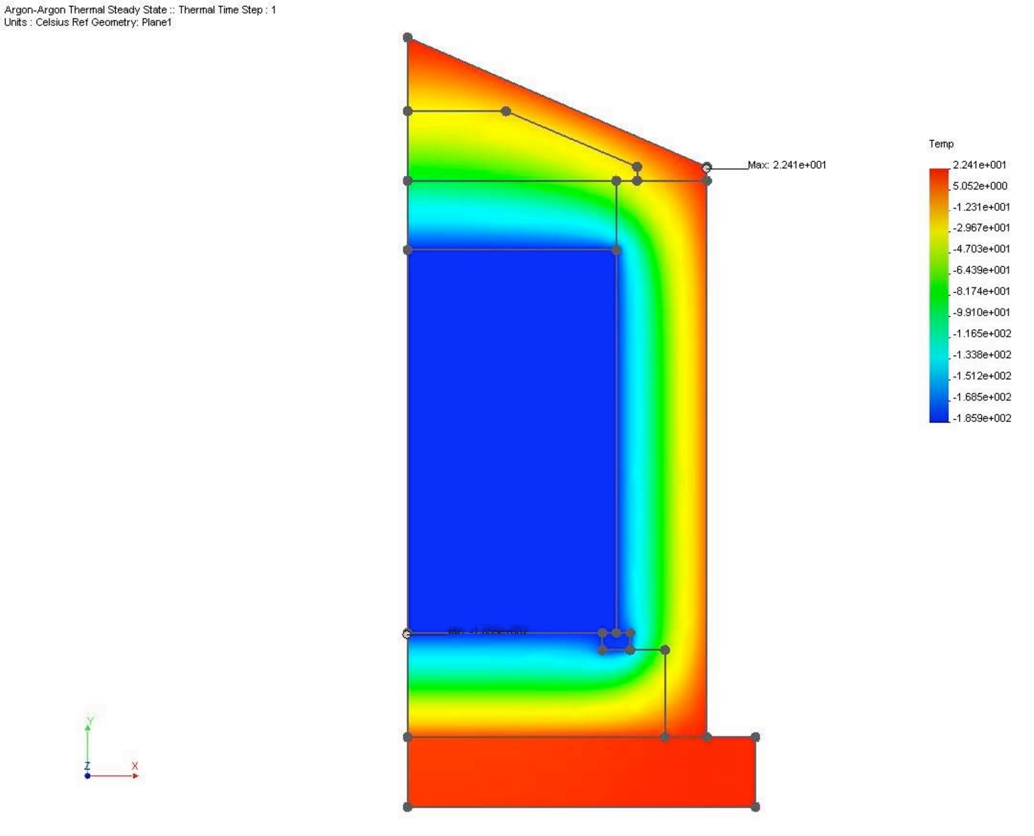
NOT TO SCALE

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.

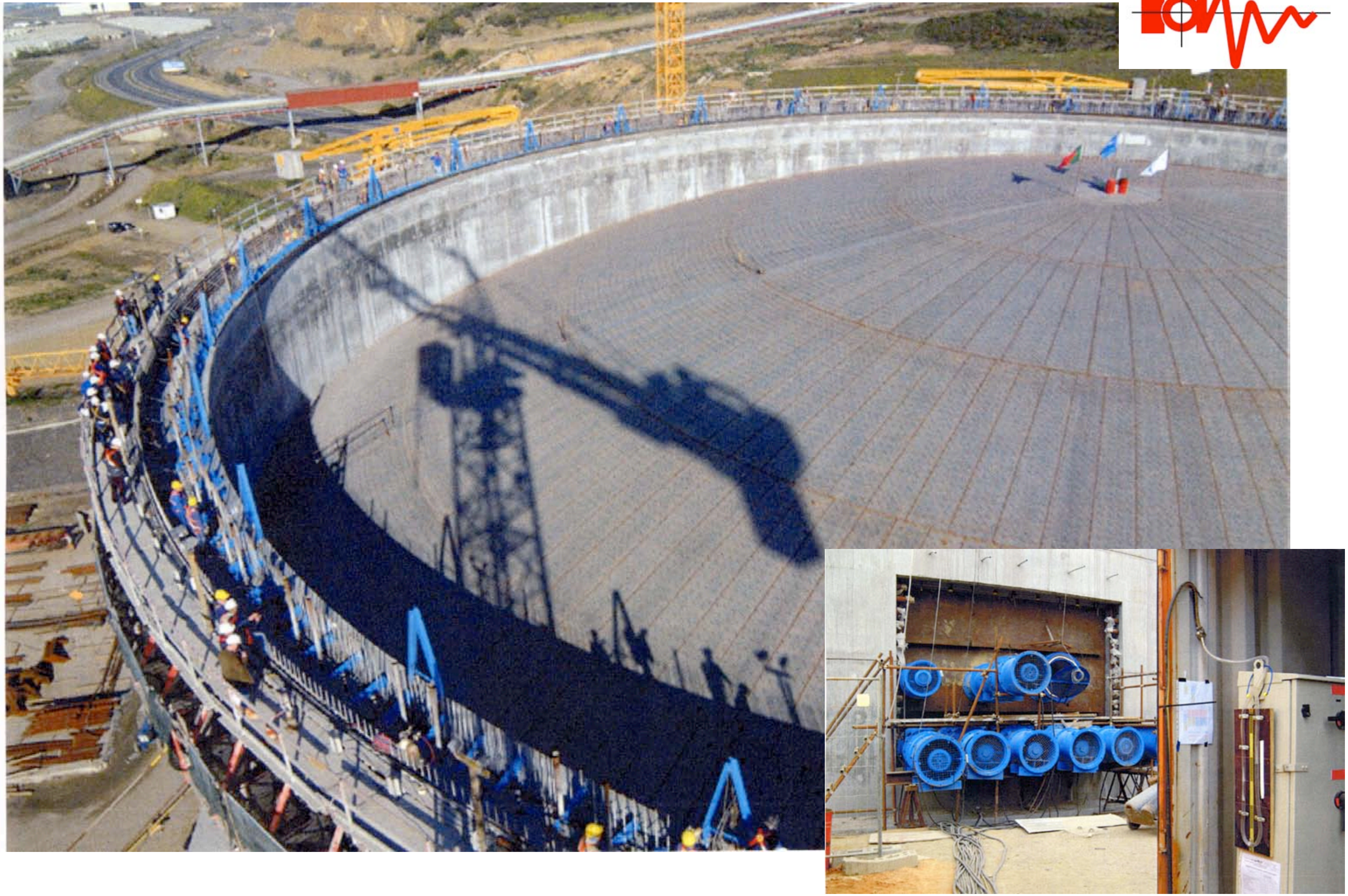
A dream come true? (A) Concrete base

(B) Construction of the concrete outer-shell

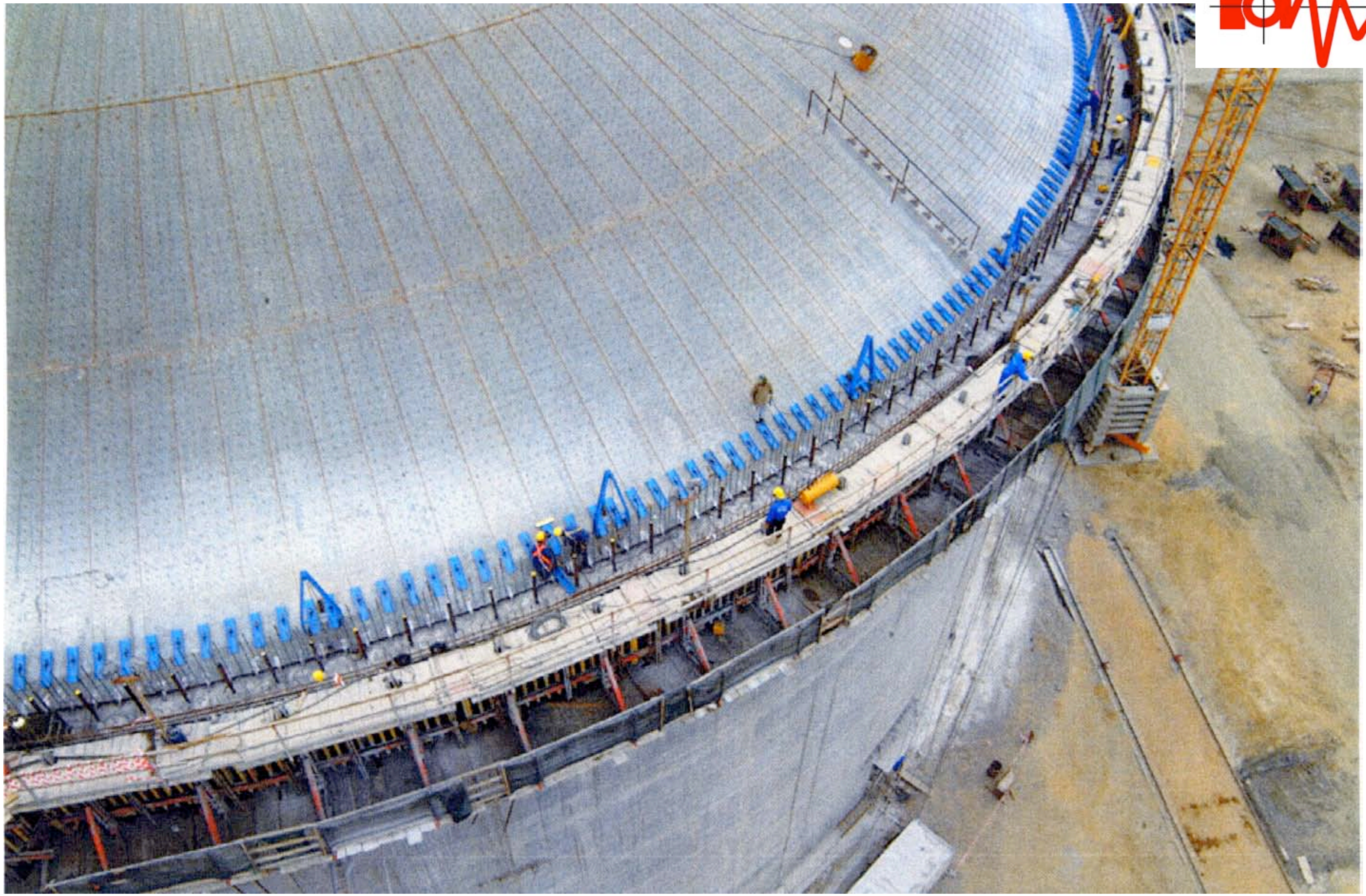
(C) Roof construction (inside tank)


10. 2. 2000

(D) Air-raising of the roof



(E) Roof welding



Tank budgetary costing

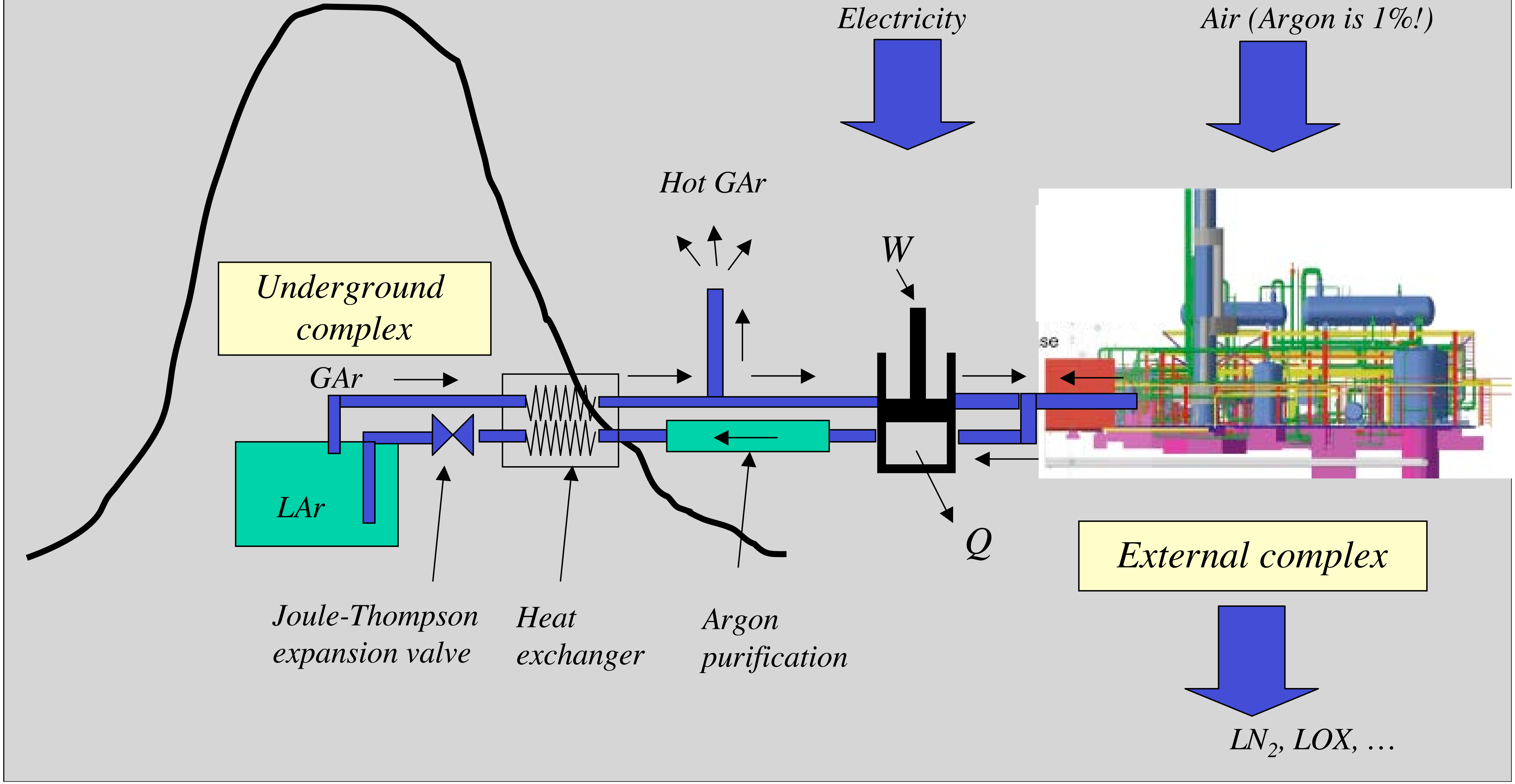
- The estimated costs tabulated below are for an inner tank of radius 35m and height 20m, an outer tank of radius 36.2m and height 22.5m. The product height is assumed to be 19m giving a product mass of 101.8 k tonnes.

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

(*) 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

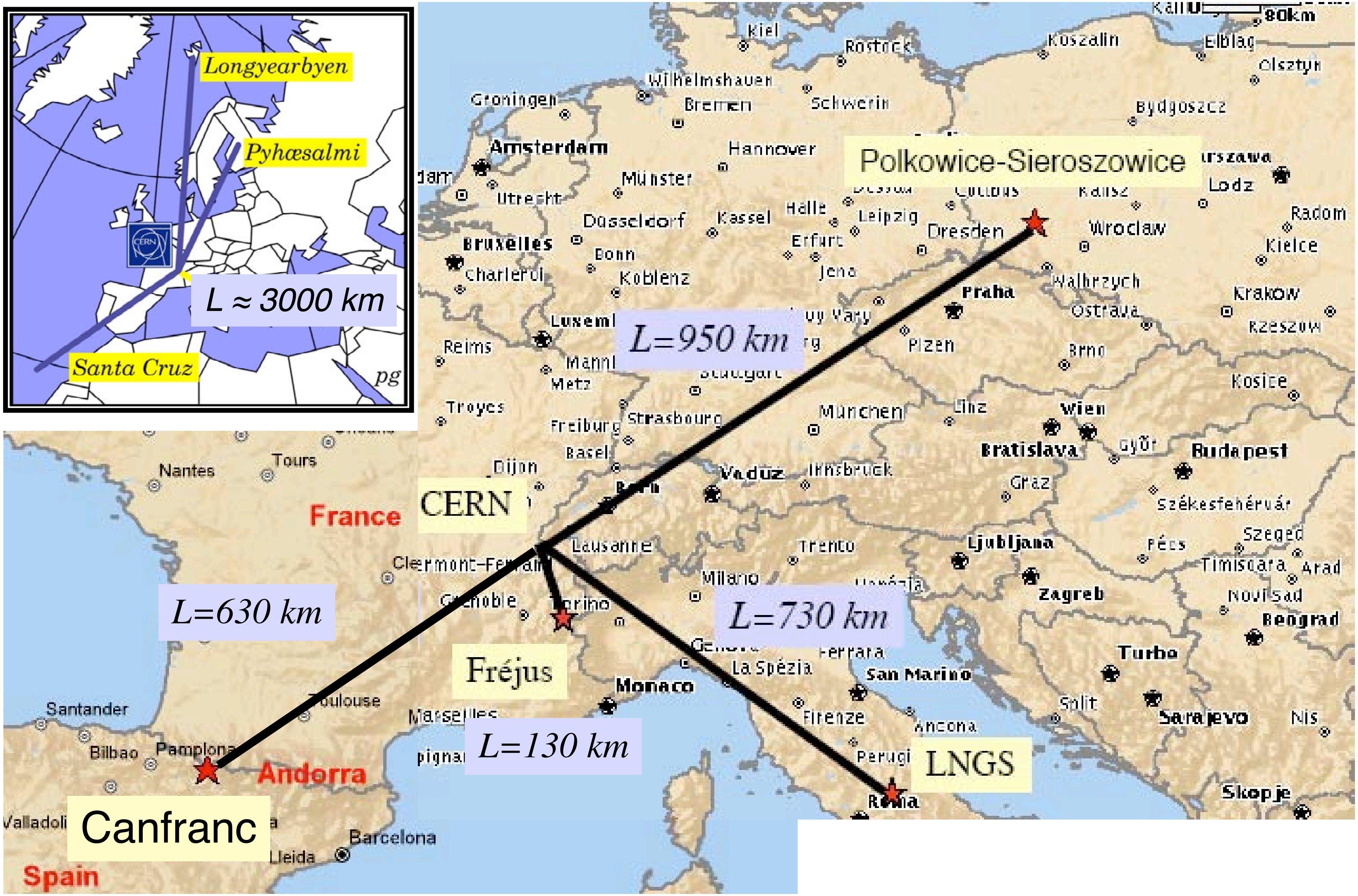
- There are three major items required for generating and maintaining the Liquid Argon needed in the tank. These are:
  - ➥ Filling the tank with the initial Liquid Argon bulk
  - ➥ Re- liquefaction of the gaseous Argon boil-off.
  - ➥ Continuous purification of the Liquid Argon.

- *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.

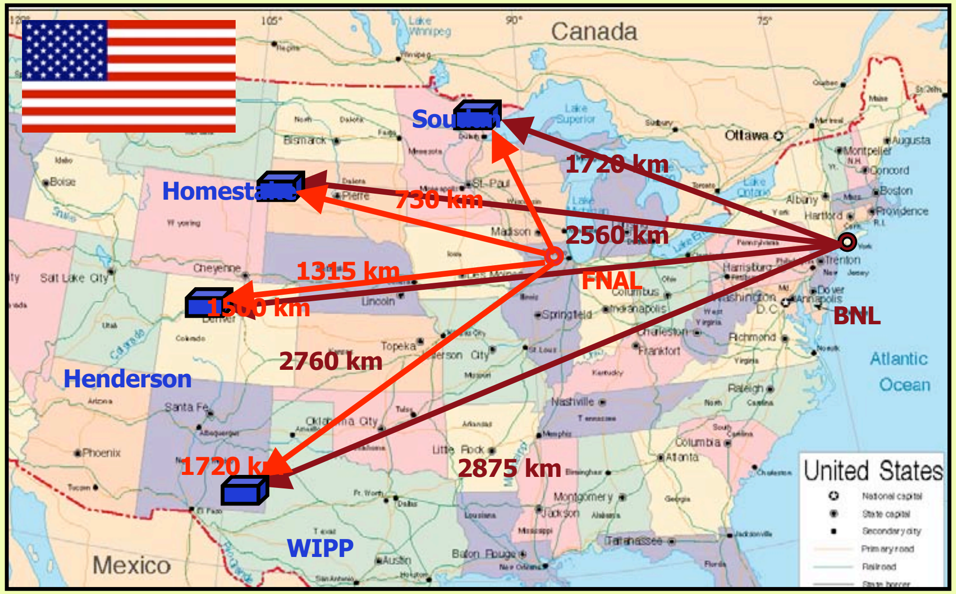
Process considerations

- *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.

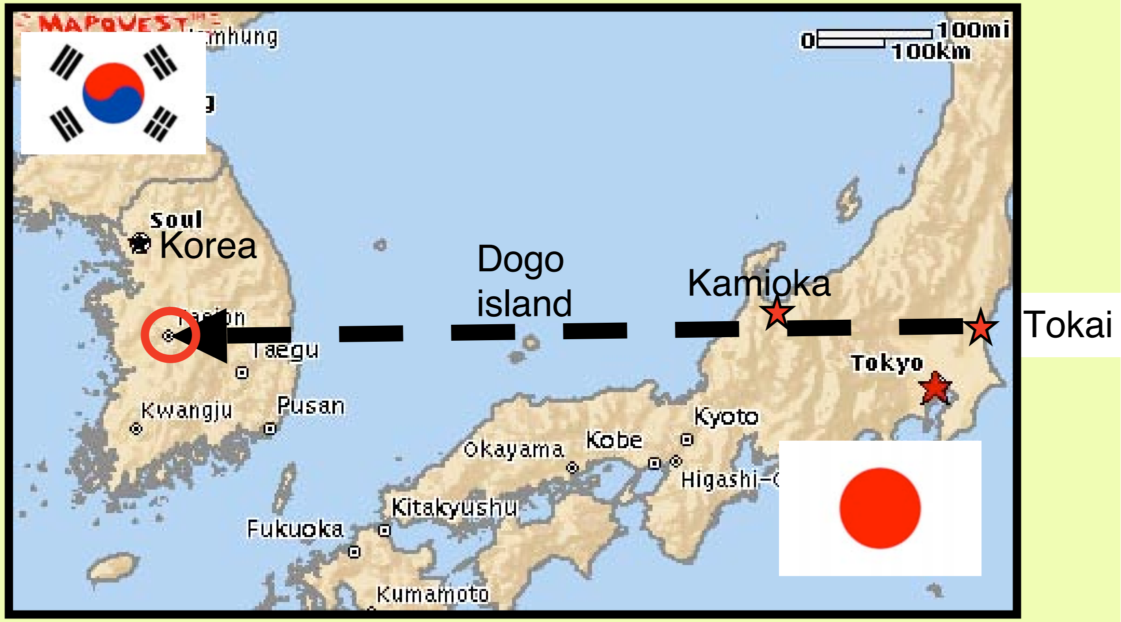
Possible underground sites in Europe ?



Non-European sites for very large liquid argon TPC



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

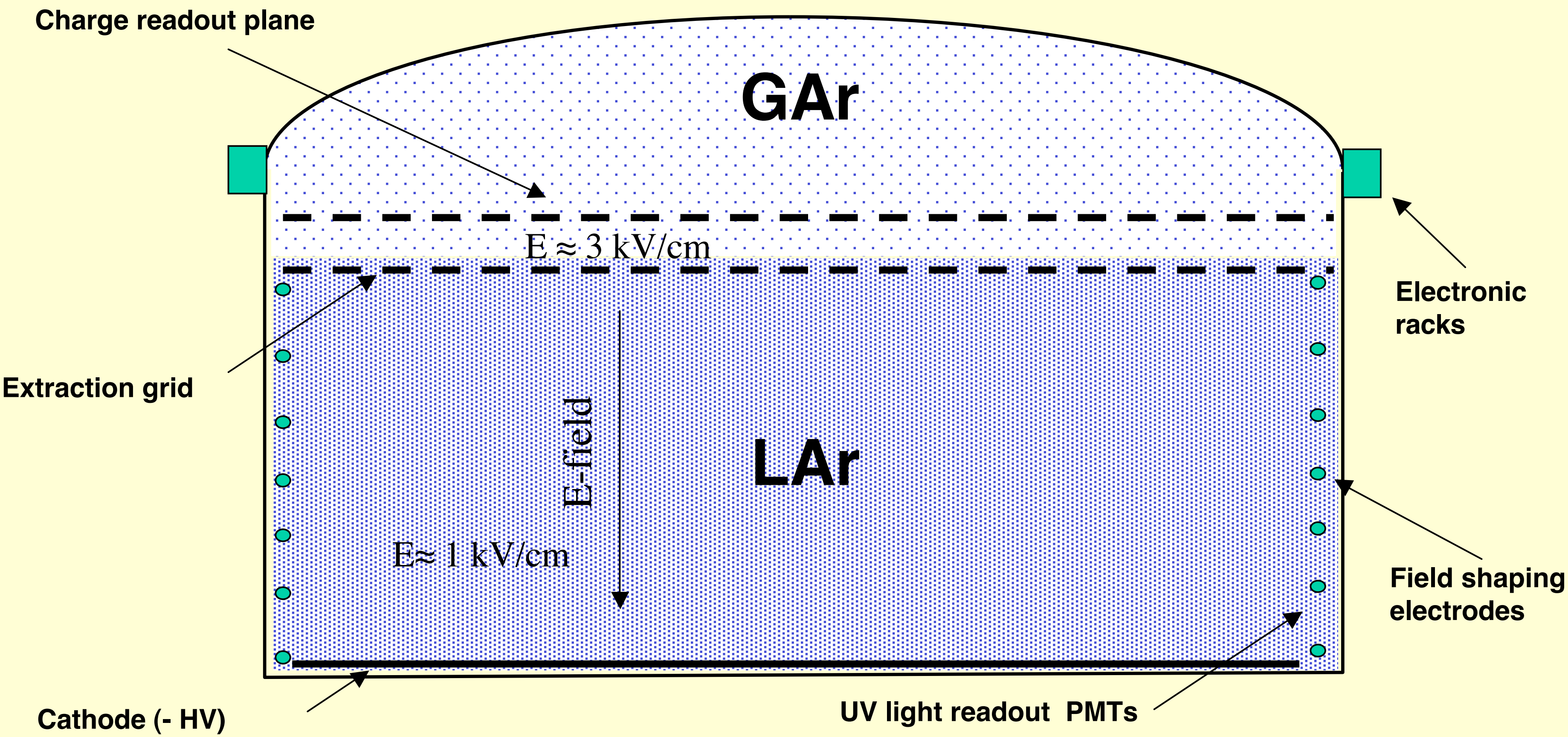


10 kton prototype

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

(e.g. sensitivity for $p\rightarrow\nu K$: $\tau>10^{34}$ yrs for 10 years running)

Dewar	$\phi \approx 30$ 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 $\approx$ 33%
Argon total mass	9900 tons
Hydrostatic pressure at bottom	1.5 atmospheres
Inner detector dimensions	Disc $\phi \approx 30$ 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



Charge readout plane

GAr

$E \approx 3$ kV/cm

Electronic racks

Extraction grid

E-field

LAr

$E \approx 1$ kV/cm

Field shaping electrodes

Cathode (- HV)

UV light readout PMTs

≈7000 m^3 cryogenic tanker (without outer shell)

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)

Outlook

- **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, …)

- **A 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 LAr storage
    - ➥ (b) improved detector performance for very long drift paths w 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)

- **Accordingly we think that:**
    - ➥ The long-term strategy of the neutrino mixing matrix studies should envisage a 100 kton liquid Argon TPC. The tentative design outlined above seems technically sound and would deliver extraordinary physics output. It would be an ideal match for a Superbeam, Betabeam or a Neutrino Factory. This phase has to wait for the results of T2K & NoVa.

    - ➥ In the meantime, we think that there is a window of opportunity to consider a 10% full-scale, cost effective prototype of the design, on the scale of 10 kton, as an engineering design test with a physics program of its own, directly comparable to that of Superkamiokande.