A very large liquid Argon TPC for astroparticle physics, matter stability and neutrino physics

http://neutrino.ethz.ch/GLACIER/

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Southampton-RAL meeting, 4th February 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.**

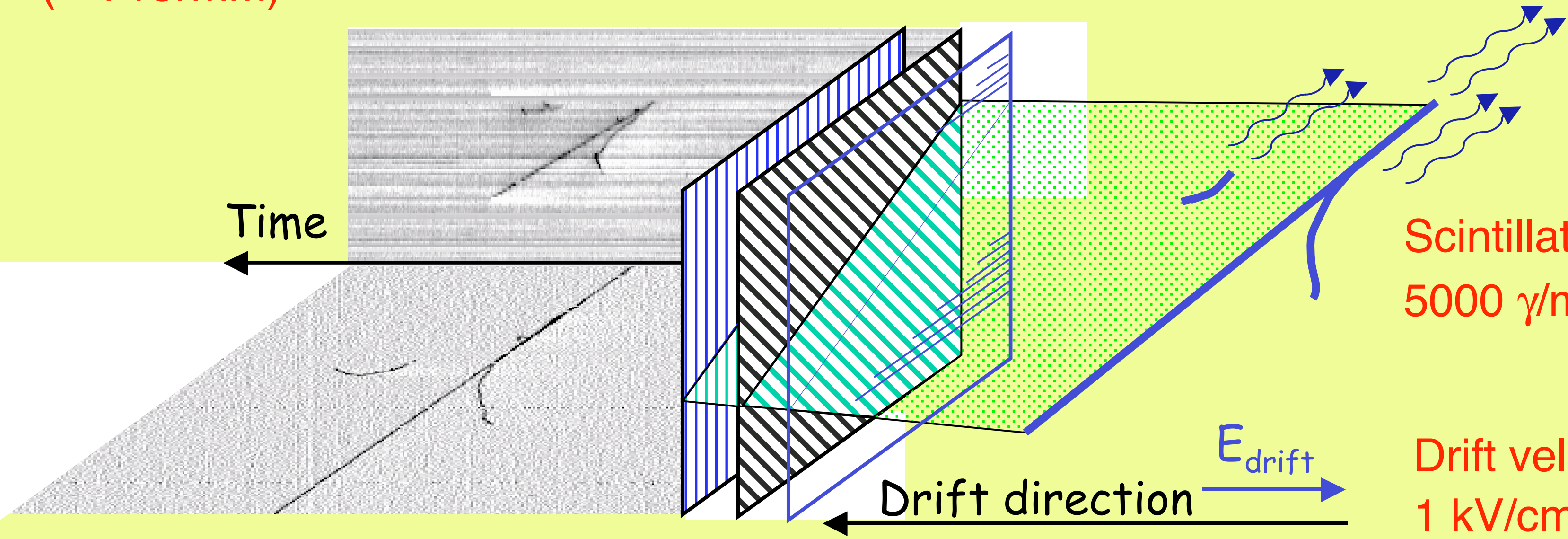
- **The ICARUS experiment, which acts as an observatory for the study of neutrinos and the instability of matter, is starting to come together. In the summer of 2001, the first module of the ICARUS T600 detector passed brilliantly a series of tests. It has now being transported to the Underground Gran Sasso Laboratory and installation there 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

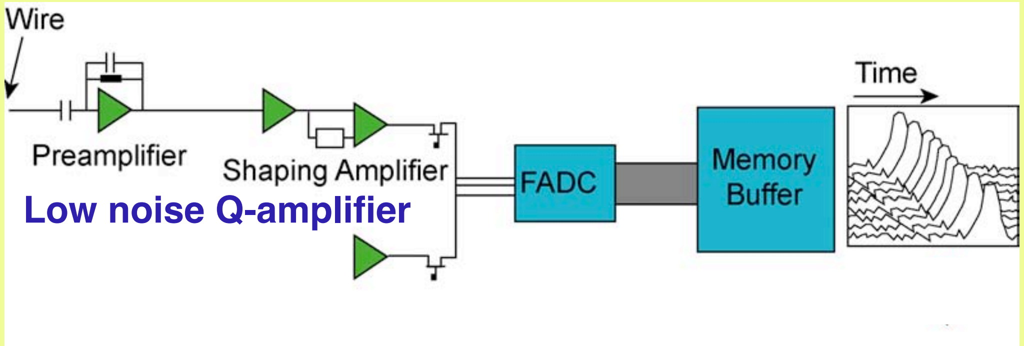
The Liquid Argon TPC principle

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



Scintillation light yield ~ 5000 γ/mm @ 128 nm

Drift velocity ~ 2 mm/μs @ 1 kV/cm



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).

Dependence of the electron lifetime to the drift field

- By direct injection of given amounts of impurities:

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

- Essentially independent of the electric field for O_2

- **Within the ICARUS program, routinely reach LAr purification level of < 0,1 ppb of impurities via liquid recirculation.**

A. Bettini et al., NIM A305 (1991) 177

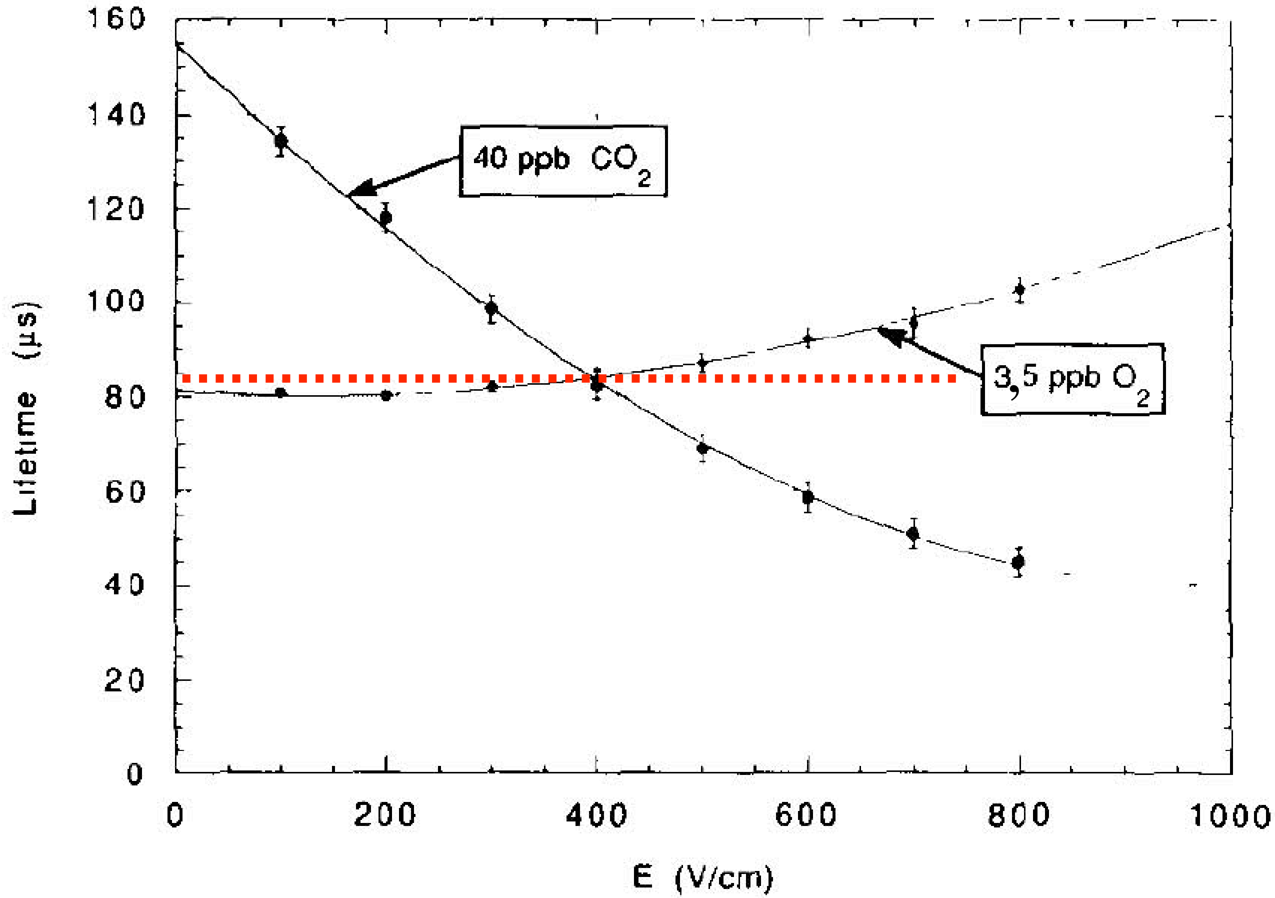


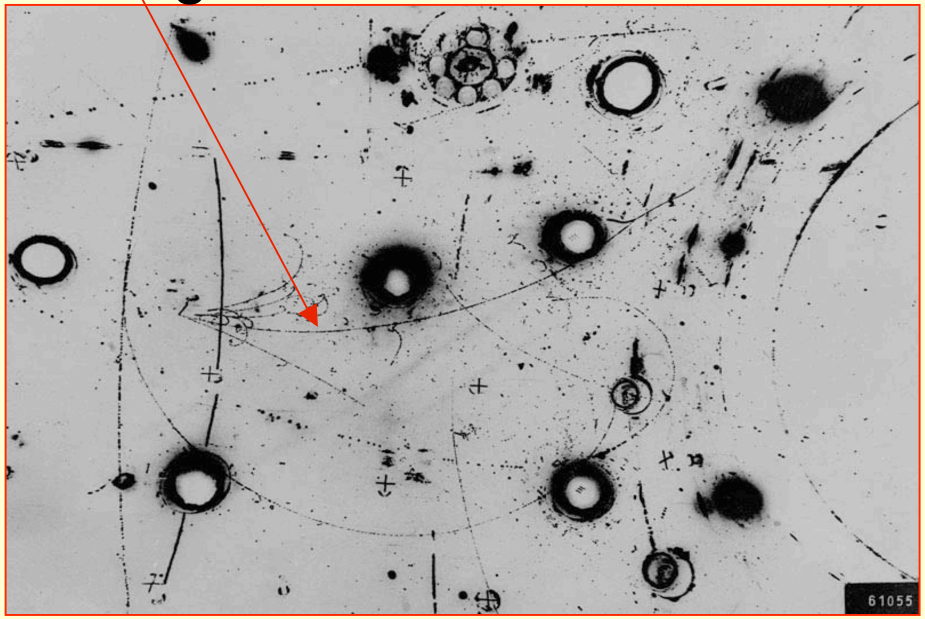
Fig. 12. Electric field dependence of the electron lifetime τ in purified LAr doped with 40 ppb CO_2 and 3.5 ppb O_2. Lines are drawn to guide the eye.

Liquid Argon TPC: an electronic bubble chamber

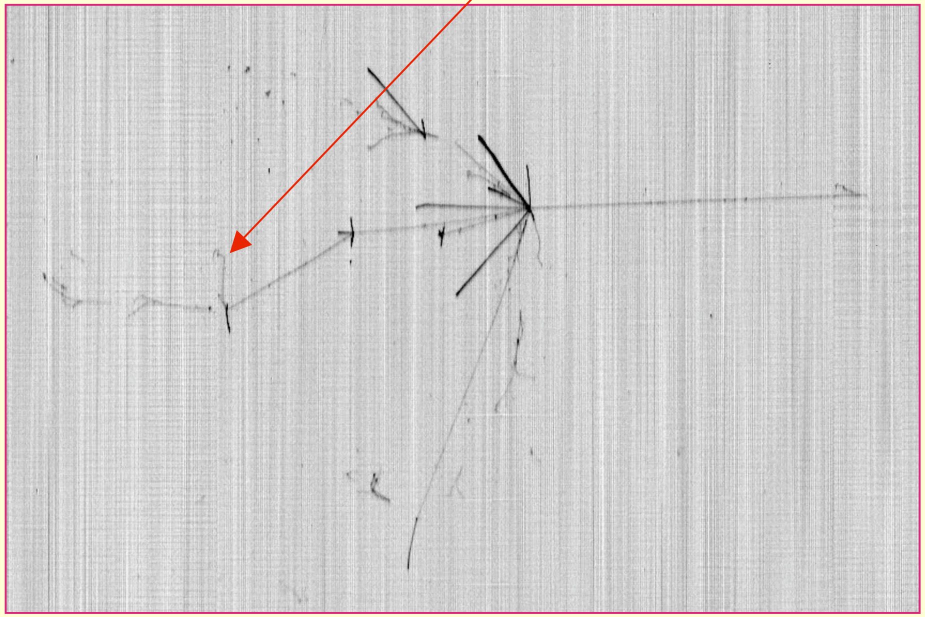
Bubble diameter ≈ 3 mm (diffraction limited)

Bubble size ≈ 3x3x0.4 mm^3

Gargamelle bubble chamber



ICARUS electronic chamber



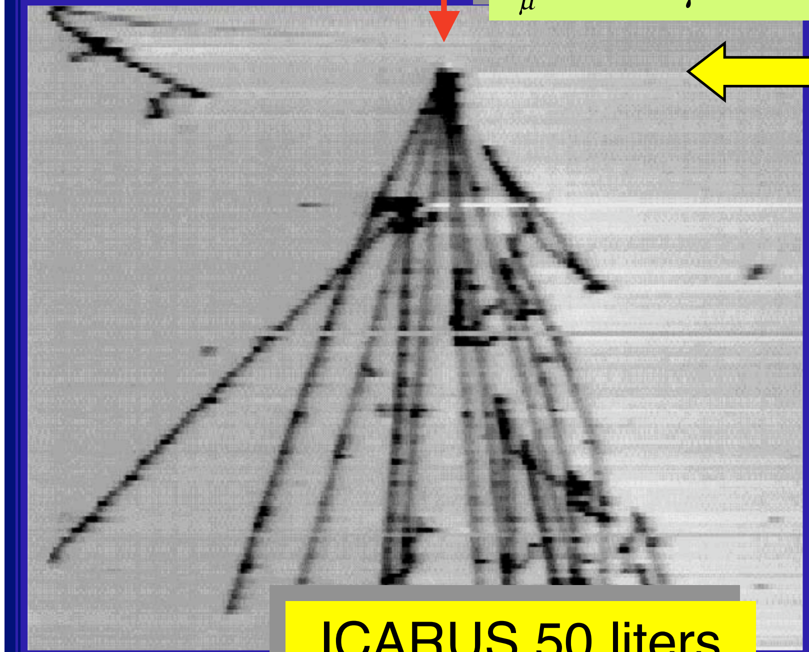
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm^3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

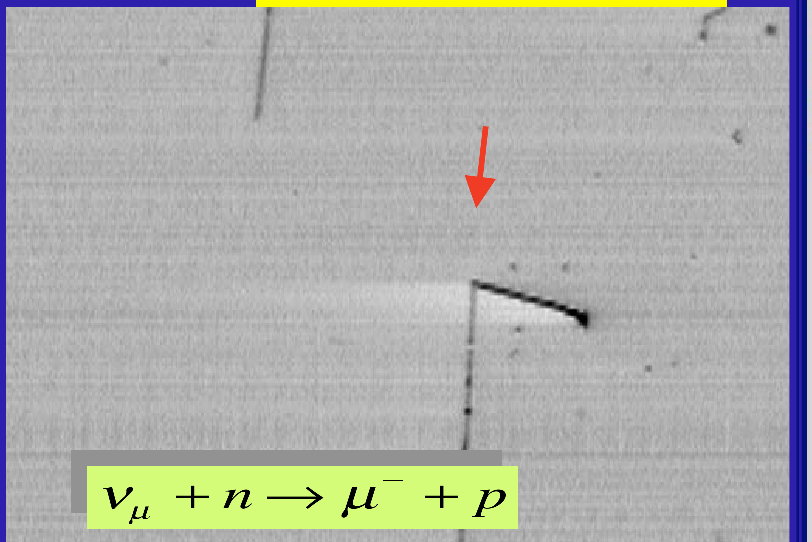
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm^3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

Neutrino detection: LAr TPC vs water Cerenkov

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

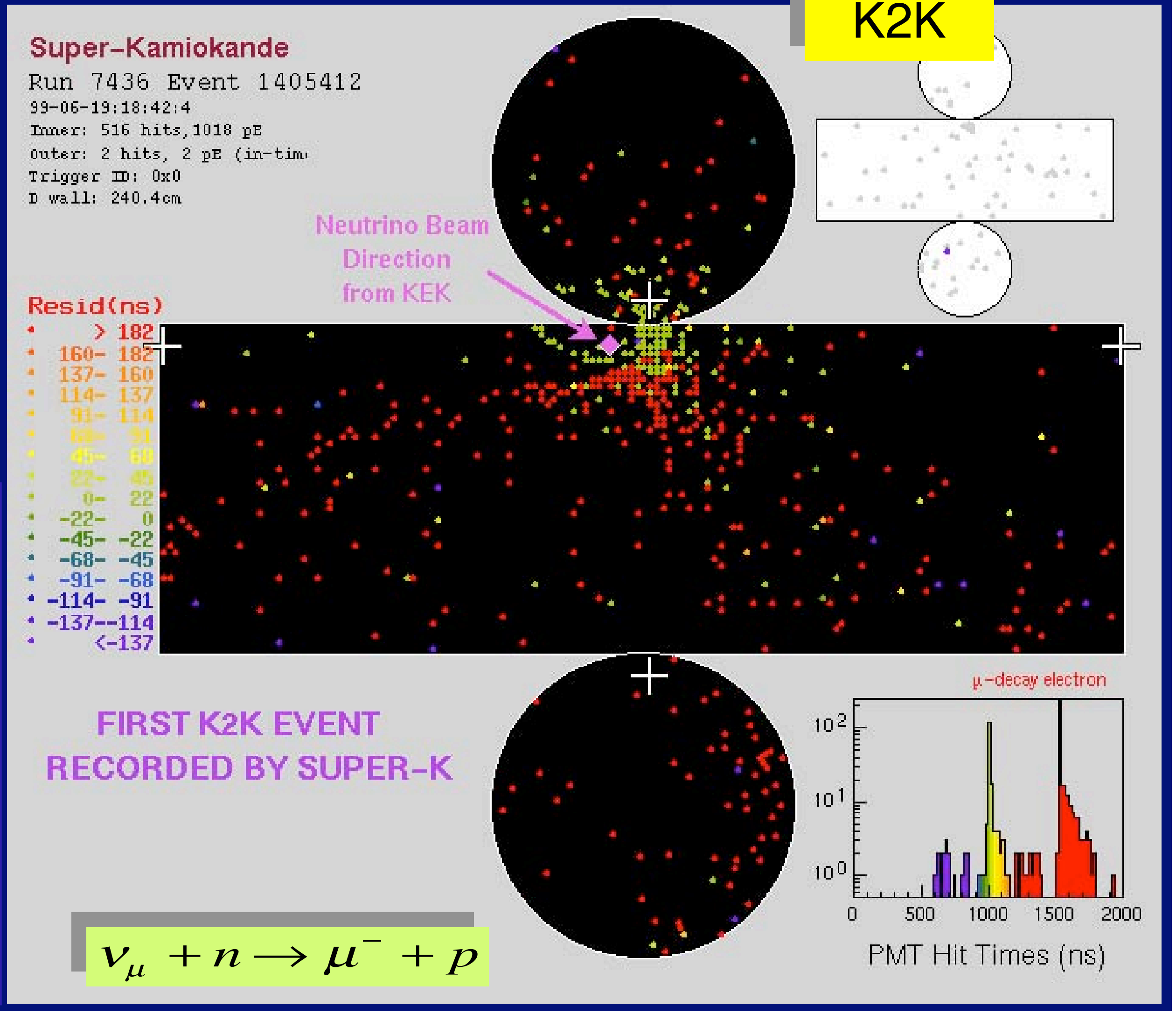
Multi prong event detection not possible with water Cerenkov





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

K2K



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

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 $d^2N/dEdx$ (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)
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 ± 0.3 eV

2) Scintillation (luminescence)

W_γ = 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)

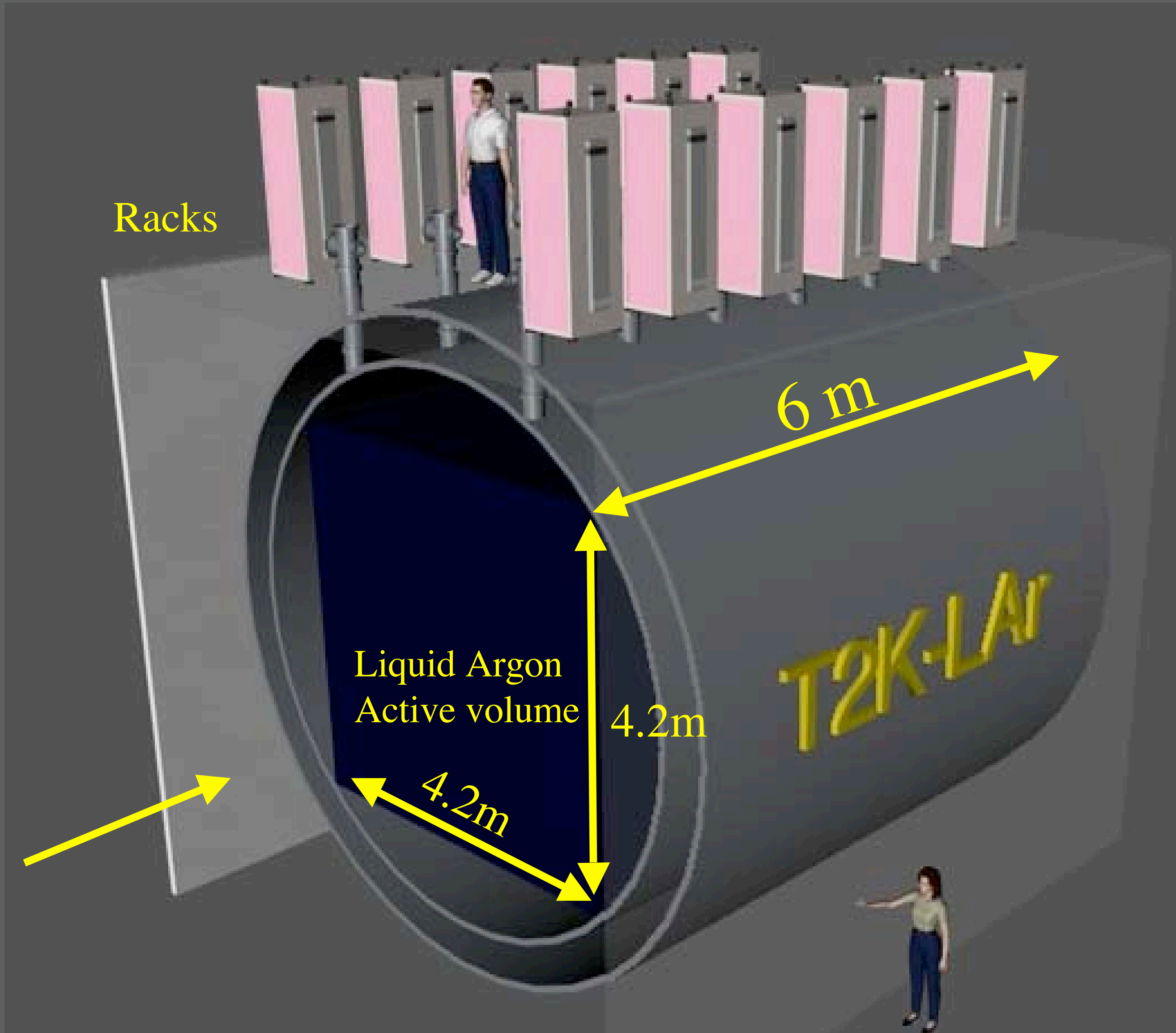
☞ **Charge**

☞ **Scintillation light (VUV)**

☞ **Cerenkov light (if β>1/n)**

Scintillation & Cerenkov light can be detected independently !

New compact conceptual design of the ~100 ton LAr TPC:



Outer vessel	$\phi \approx$ 7m, L≈8m, 15mm thick, weight ≈ 20 t
Inner vessel	$\phi \approx$ 6 m, L ≈ 6 m, 8 mm thick, ≈ 10 t
LAr	Total ≈ 240 t Fiducial ≈ 100 t
Max e- drift	4.2 m @ HV=420 kV E = 1000 V/cm
Charge R/O	2 views (90°) or 3 views (60°) 2 (3) mm pitch
Wires	≈O(10'000), ϕ = 150 μm
R/O electronics	on top of the dewar
Scintillation light	Also for triggering
B-field	Possible
Insulation	Multi-layer vacuum
Refrigeration	Closed Liquid Argon circuit

The approved T2K experiment in Japan will provide the ideal conditions and high statistical accuracy. Plan to submit EOI for March 2005.

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

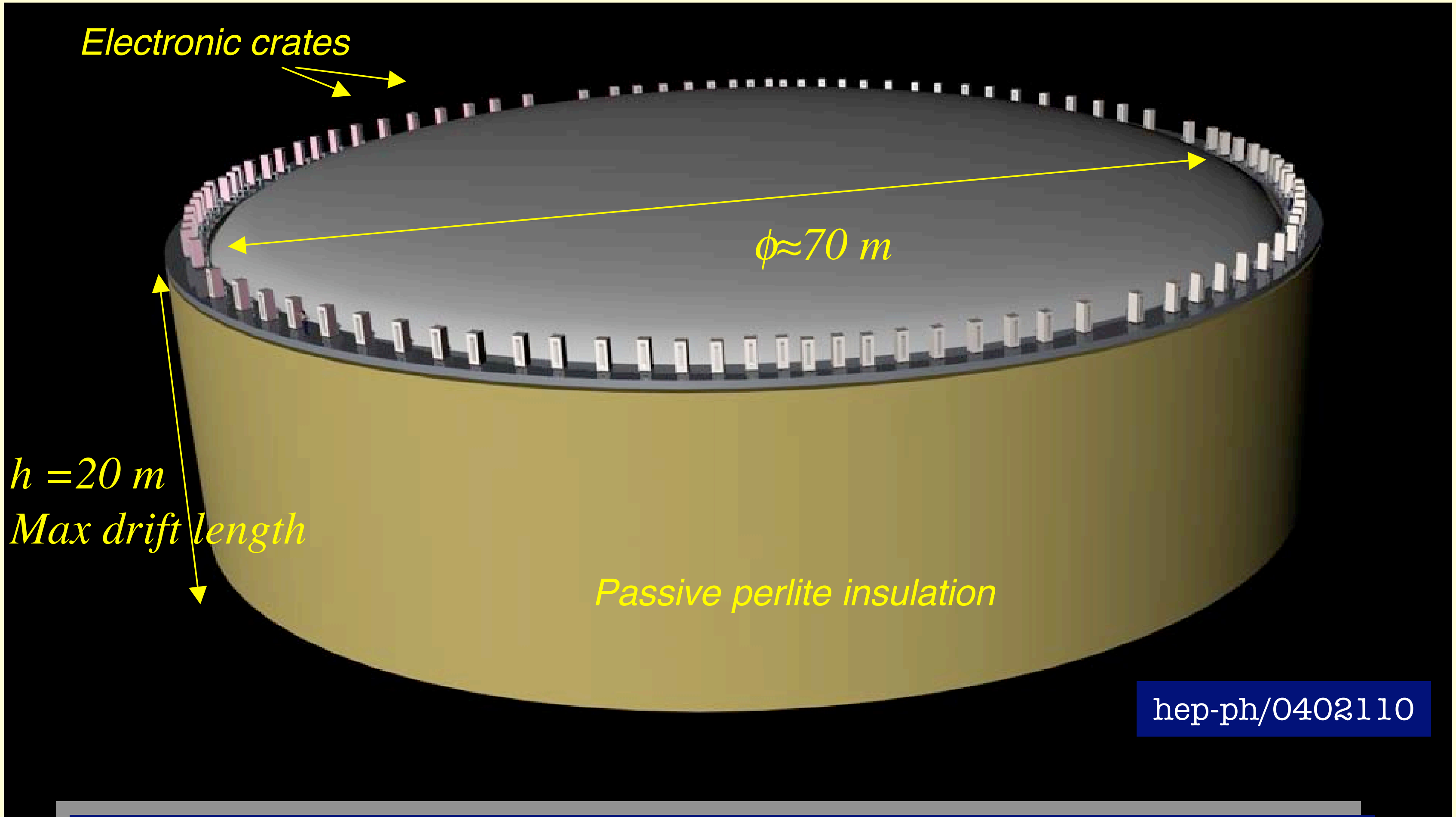
In order to reach the adequate fiducial mass for future physics programs, a new concept is required to extrapolate further the technology.

We consider two mass scales:

- **A 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. 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.**
- **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



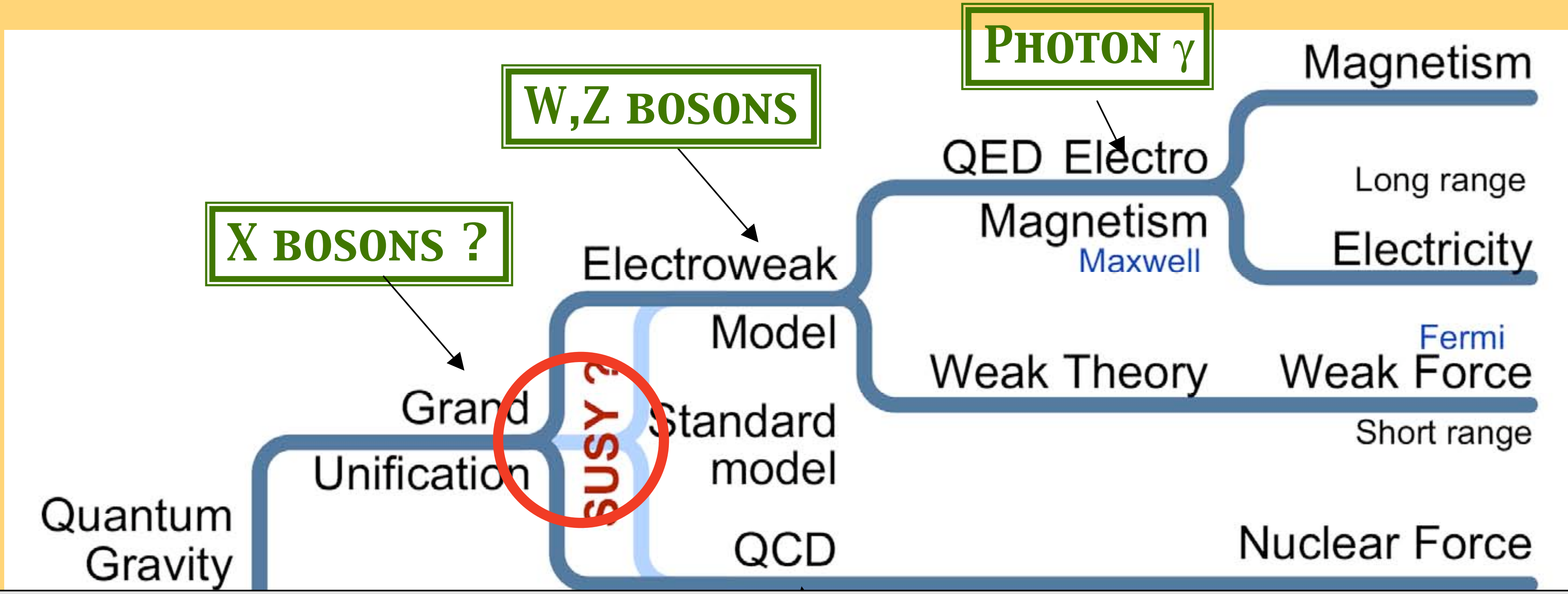
Single module cryo-tanker based on industrial LNG technology

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

Outstanding non-accelerator physics goals

	Water Cerenkov (UNO)	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 (central module)	324000 events/year E_e > 5 MeV

Force unifications: GUT physics

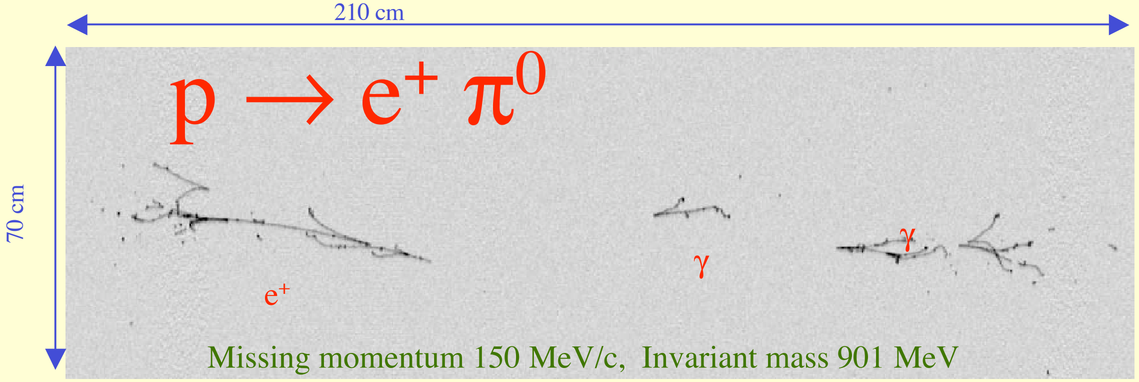


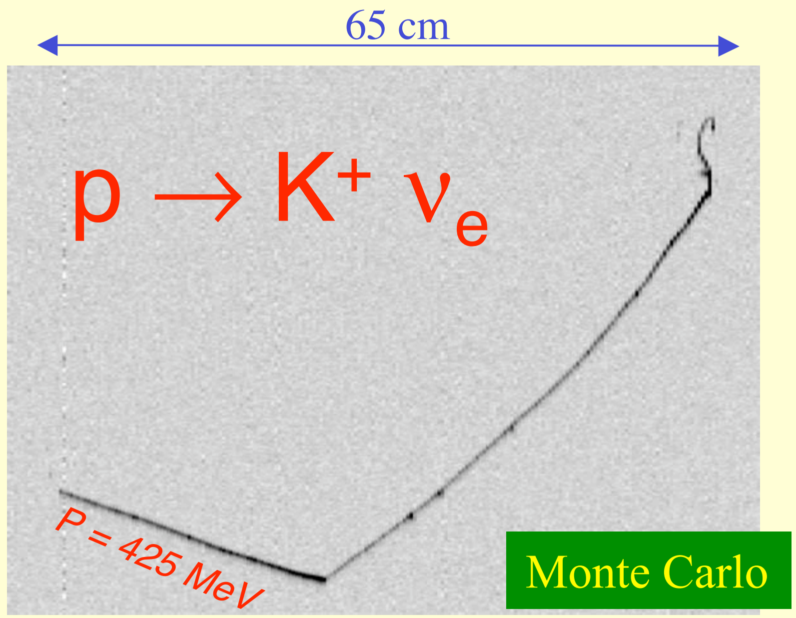
Unification of electroweak and strong force

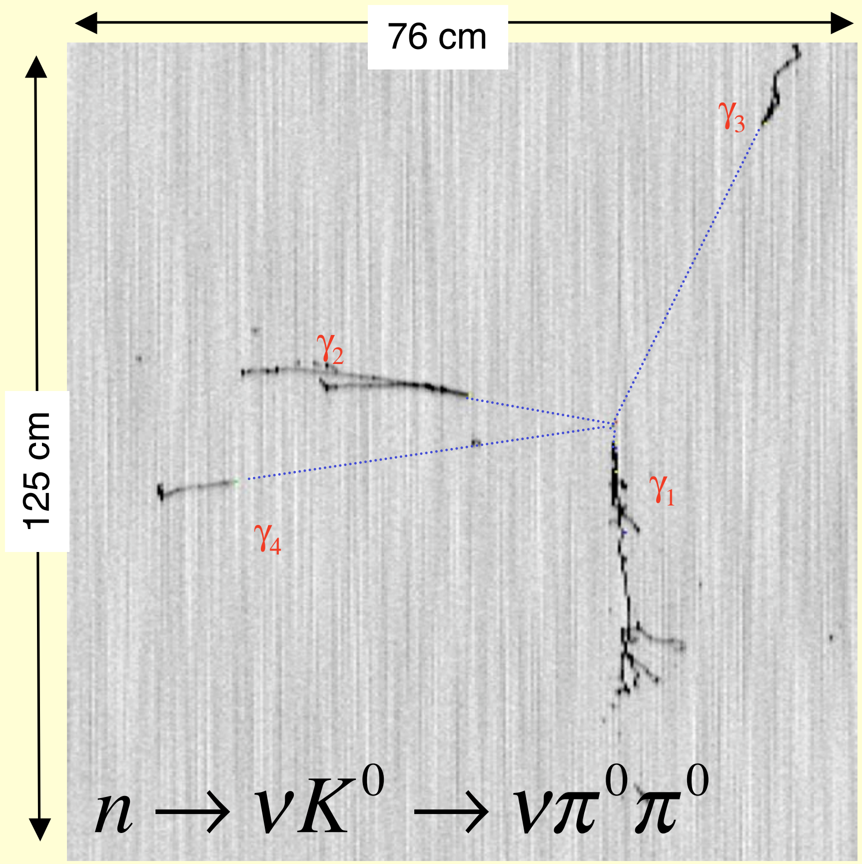
Symmetry between quarks and leptons

Transmutation between quarks and leptons → Proton unstable

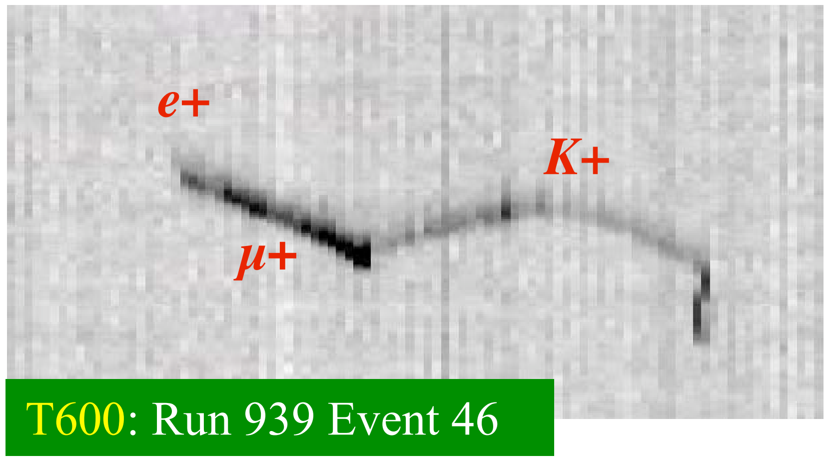
Nucleon decay







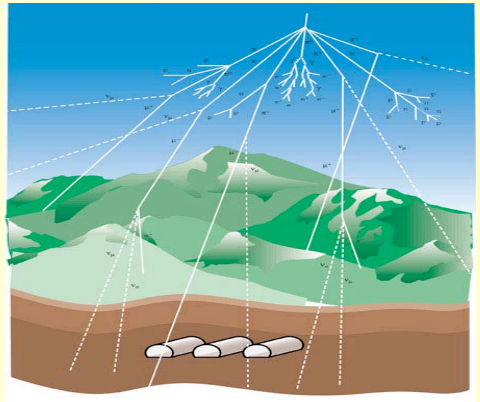
"Single" event detection capability



Astrophysical neutrinos

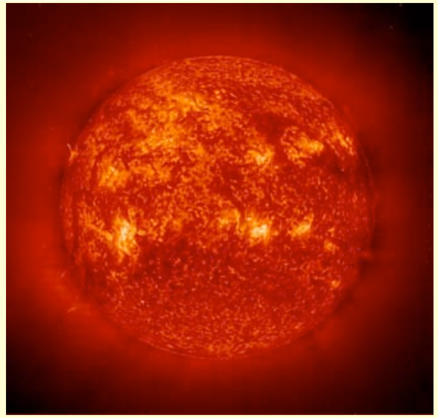
Atmospheric neutrinos:

- 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:

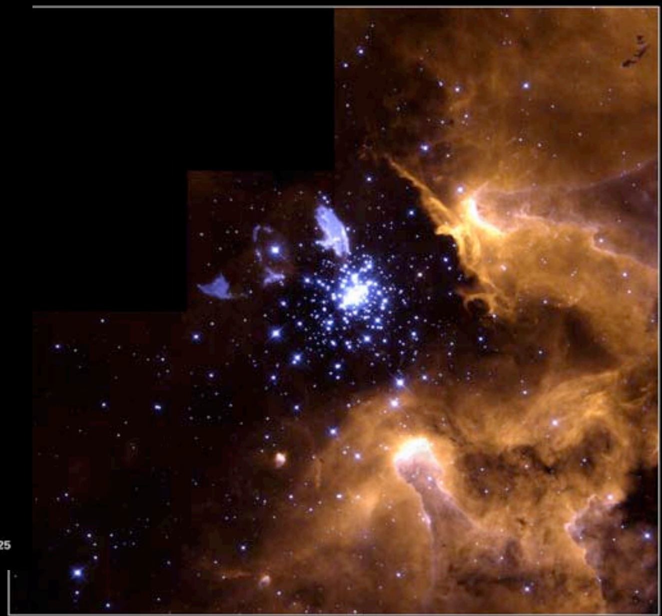
- Access supernova and neutrino physics simultaneously
- Decouple supernova & neutrino properties via different detection channels
- Relic supernova
- Supernova in our galaxy or in Andromeda (1/15 years)
- Initial burst
- …

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

The total contribution to Ω from neutrinos is similar to that of all the visible matter

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC00-25

Stars: $\Omega \sim 0.005$

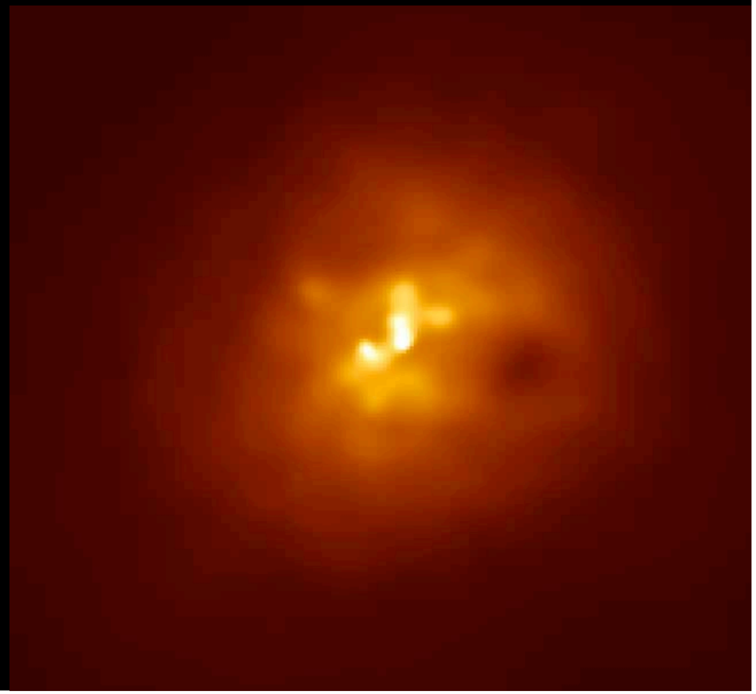


NGC 3603
Hubble Space Telescope • WFPC2

PRC99-20 • STScI OPO
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington), You-Hua Chu (University of Illinois, Urbana-Champaign) and NASA

Interstellar gas: $\Omega \sim 0.005$

Hot gas in clusters: $\Omega \sim 0.03$



Relic neutrinos constitute the hot dark matter (HDM) in our Universe

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

Discrimination of the electron charge

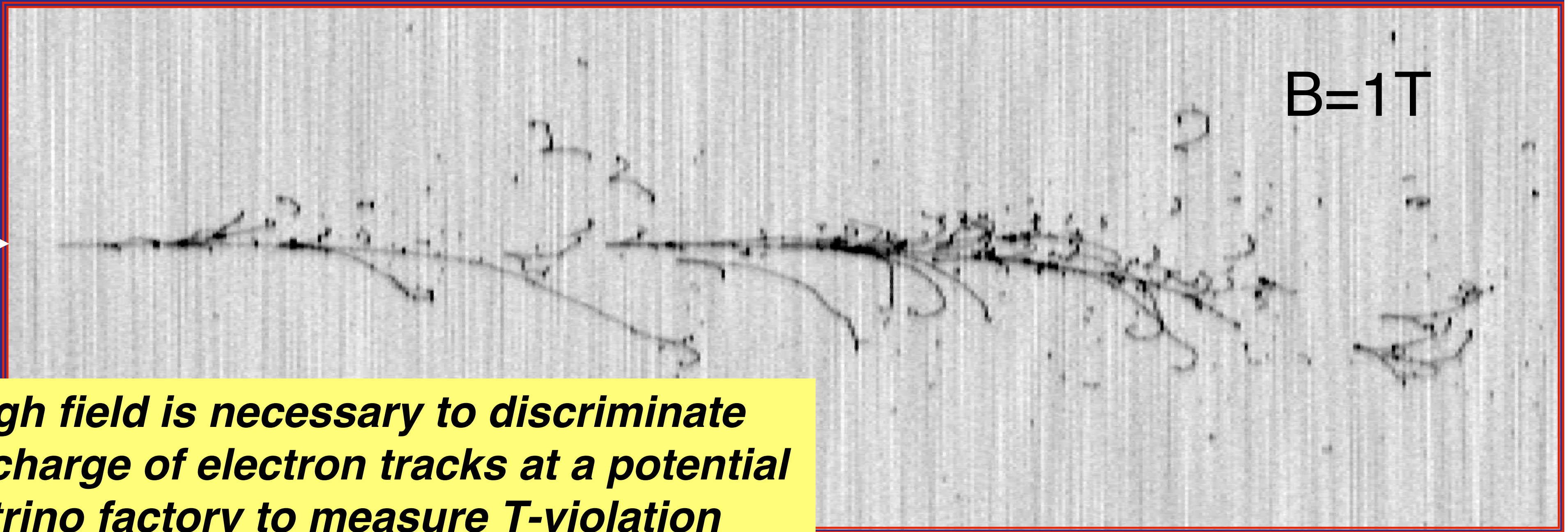
E-print: hep-ph/0106088

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

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

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

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



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

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., hep-ph/040831

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)

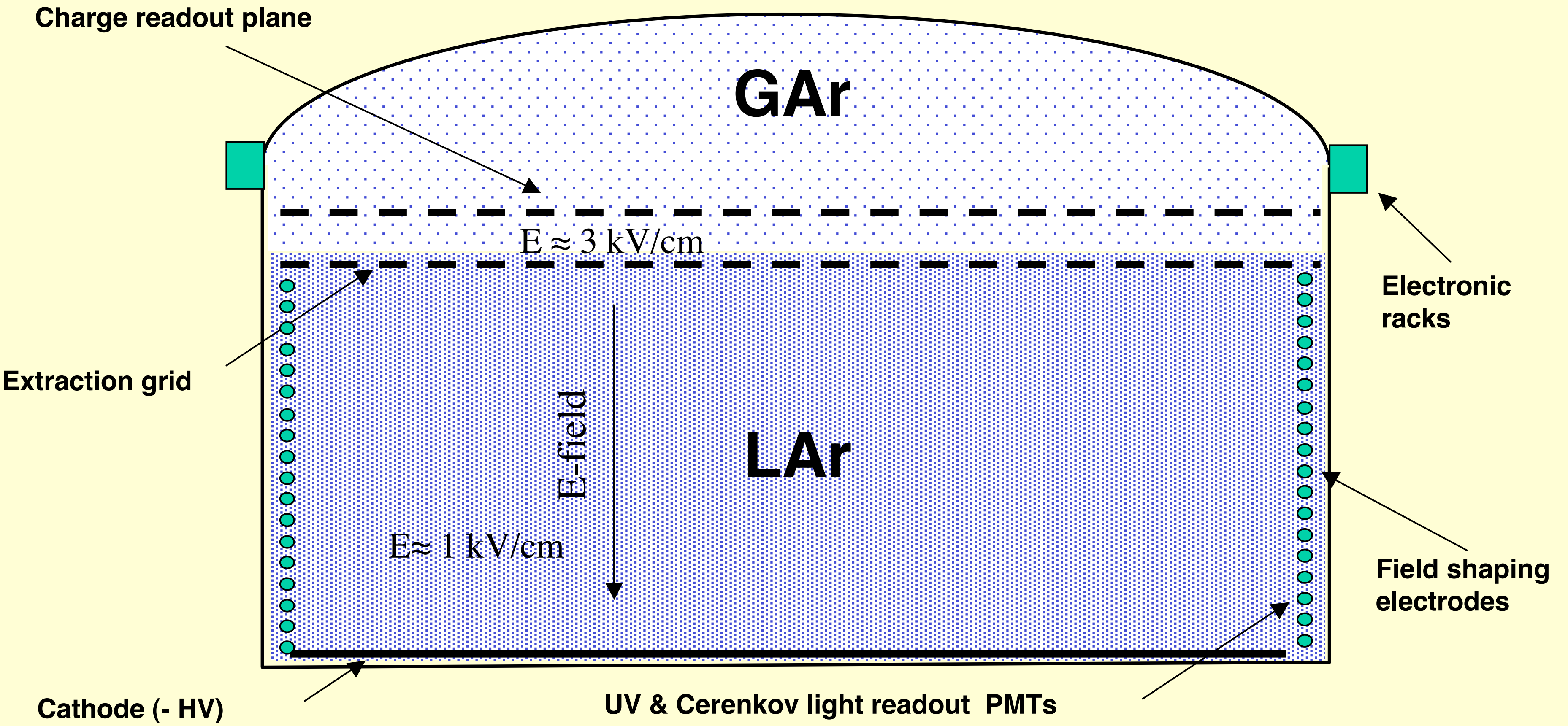
Nucleon decay searches: study of nuclear effects and background, A. Ferrari, S. Navas, A.Rubbia and P. Sala, ICARUS technical memo TM/01-04 (2001)

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

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



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.

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

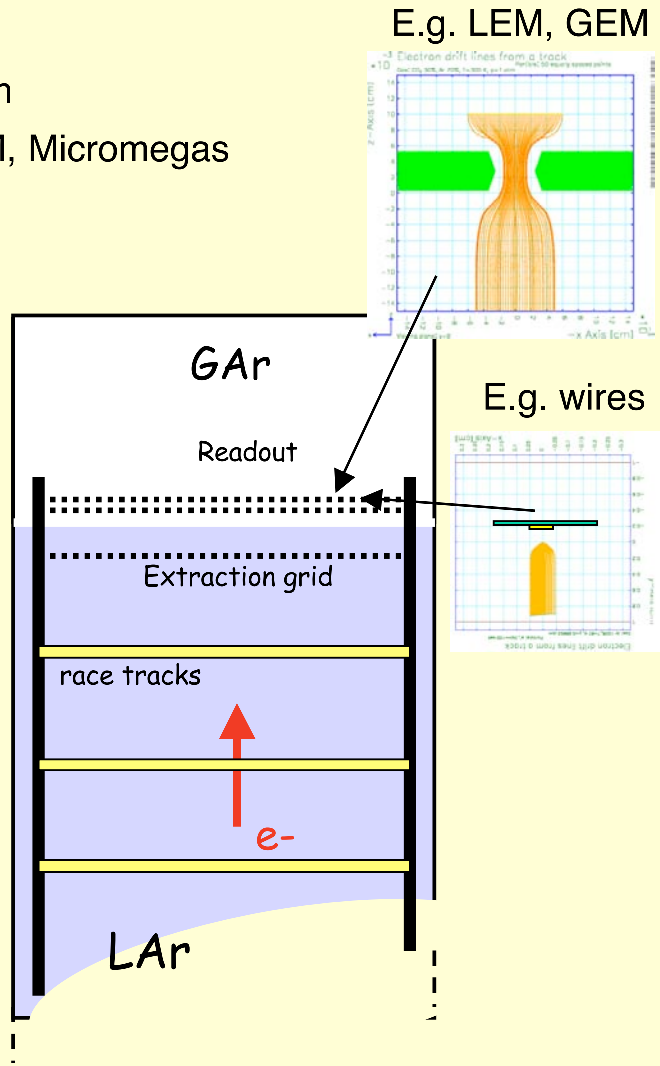
Cooling by "auto-refrigeration"

Charge extraction, amplification, readout

Detector is running in **BI-PHASE MODE** to allow for a very long drift path

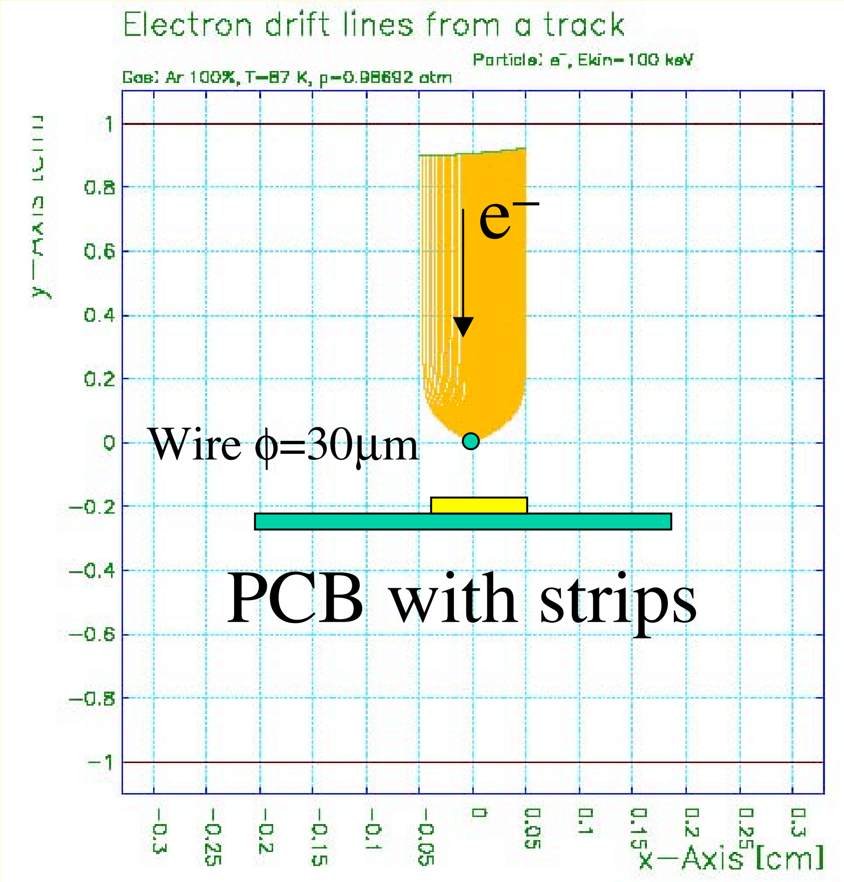
- Long drift (≈ 20 m) ⇒ charge attenuation to be compensated by charge amplification near anodes located in gas phase (18000 e^- / 3 mm for a MIP in LAr)
- Amplification operates in proportional mode
- After maximum drift of 20 m @ 1 kV/cm ⇒ diffusion ≈ readout pitch ≈ 3 mm
- Amplification can be implemented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

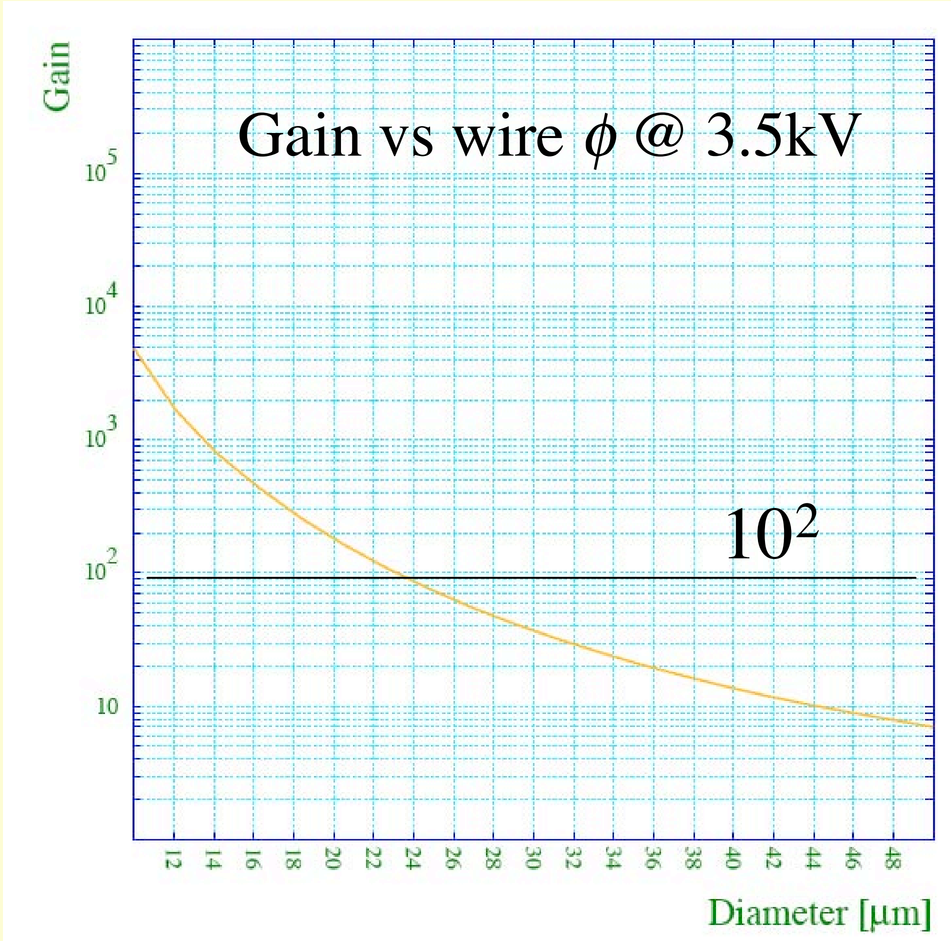
Electron drift in liquid	**20 m maximum drift, HV = 2 MV for E = 1 kV/cm, $v_d \approx$ 2 mm/μs, max drift time ≈ 10 ms**
Charge readout view	**2 perpendicular views, 3 mm pitch, 100000 readout channels**
Maximum charge diffusion	**$\sigma \approx$ 2.8 mm ($\sqrt{2Dt_{max}}$ for D = 4 cm²/s)**
Maximum charge attenuation	**$e^{-(t_{max}/\tau)} \approx$ 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**



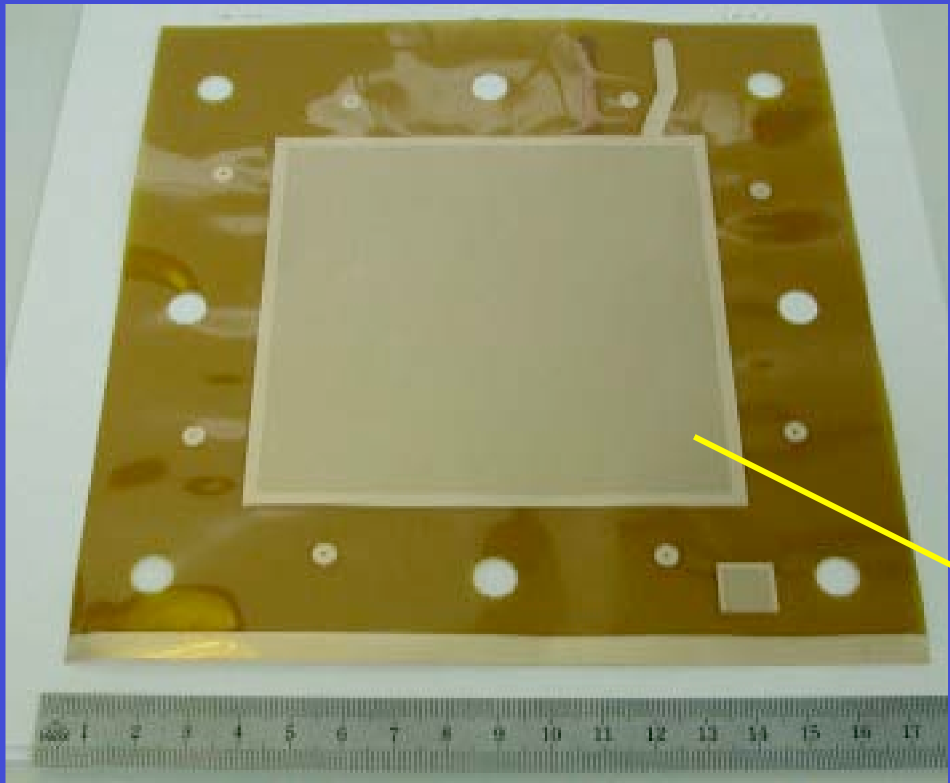
Amplification near wires à la MWPC

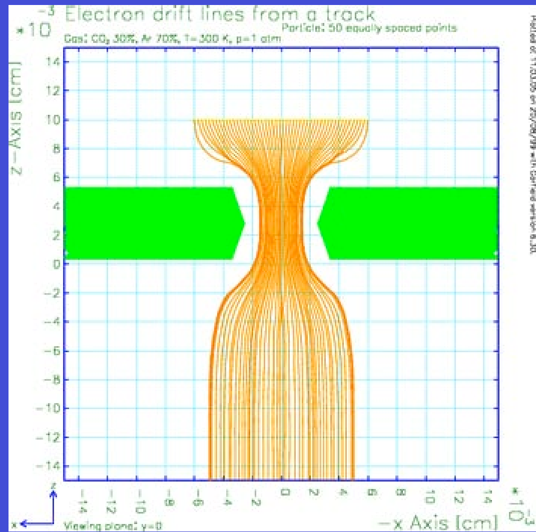
- Amplification in Ar 100% gas up to factor G≈100 is possible
- GARFIELD calculations in pure Ar 100%, T=87 K, p=1 atm
- Amplification near wires, signal dominated by ions
- Readout views: induced signal on (1) wires and (2) strips provide two perpendicular views

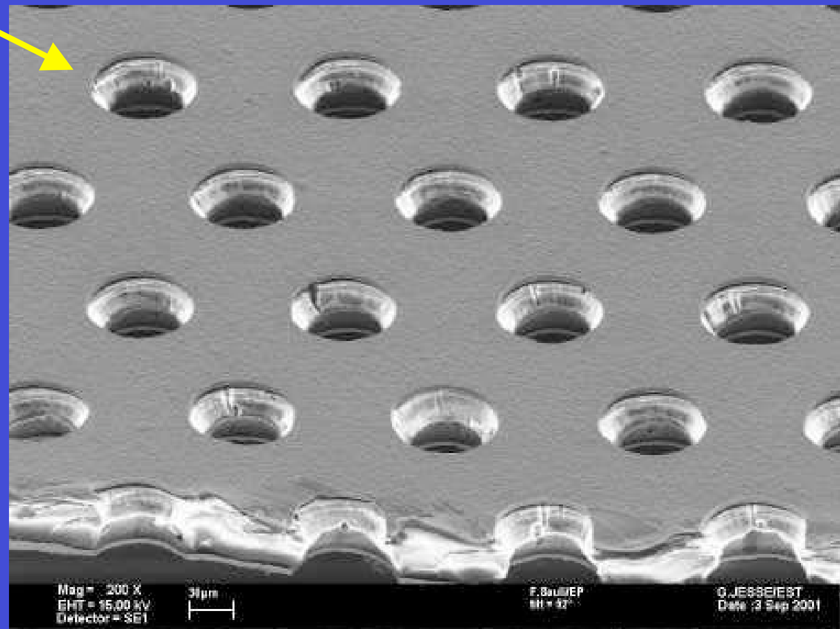




Gas Electron Multiplier GEM (F. Sauli et al., CERN)



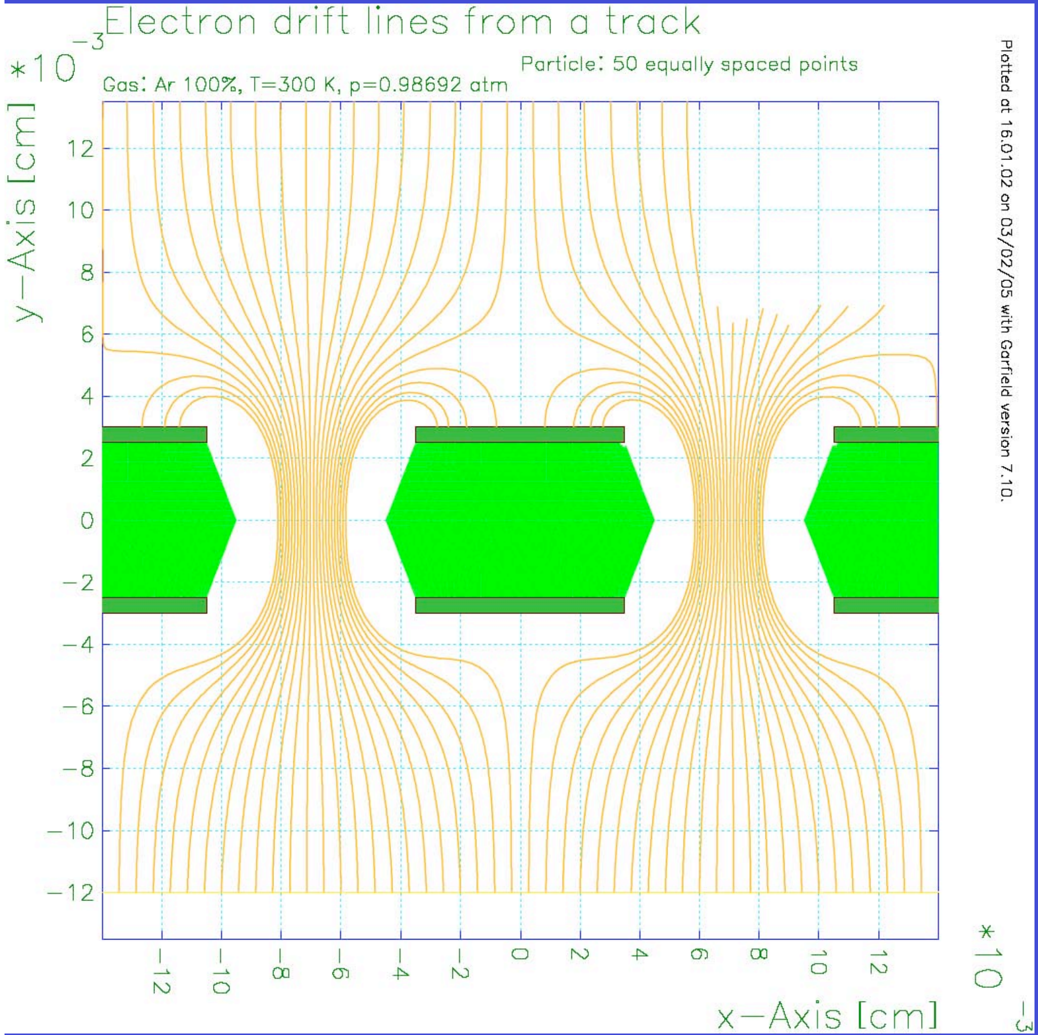


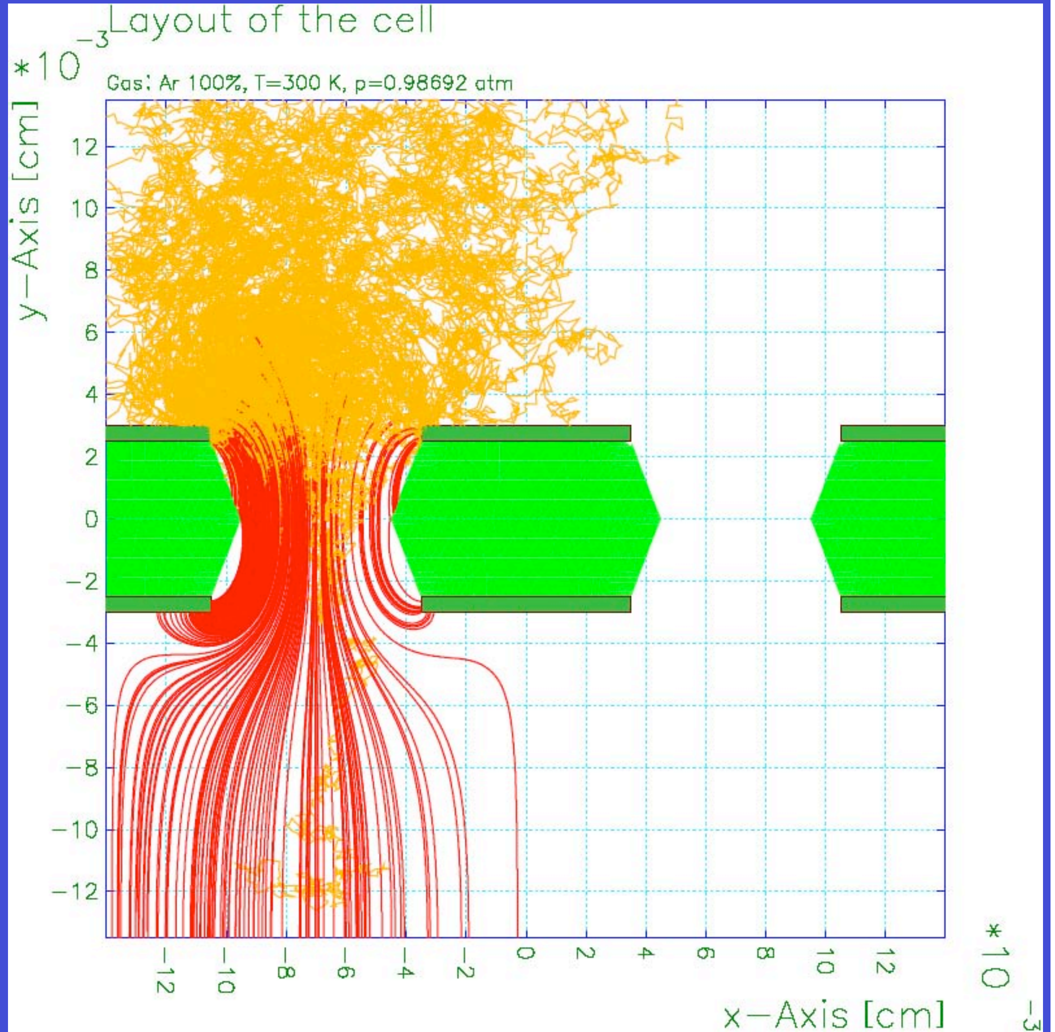


100x100 mm²

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.

GEM: field lines and electron multiplication





R&D strategy

In order to assess our conceptual design, we are performing tests in the laboratory:

- 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

In addition, we have mandated an office of engineering experts in the field of LNG tanker (Technodyne Ltd, Eastleigh, UK) to perform a feasibility study of a 100kton LAr storage tank:

- Study of large liquid underground storage tank, costing
- Study of logistics, infrastructure and safety issues for underground sites
- Study of large scale argon purification

Thick Large Electron Multiplier in pure Ar at high pressure

Mannocchi, Messina, Otiougova, Picchi, Pietropoalo, Rubbia

•Bi-phase mode: plan to operate in 100% Argon

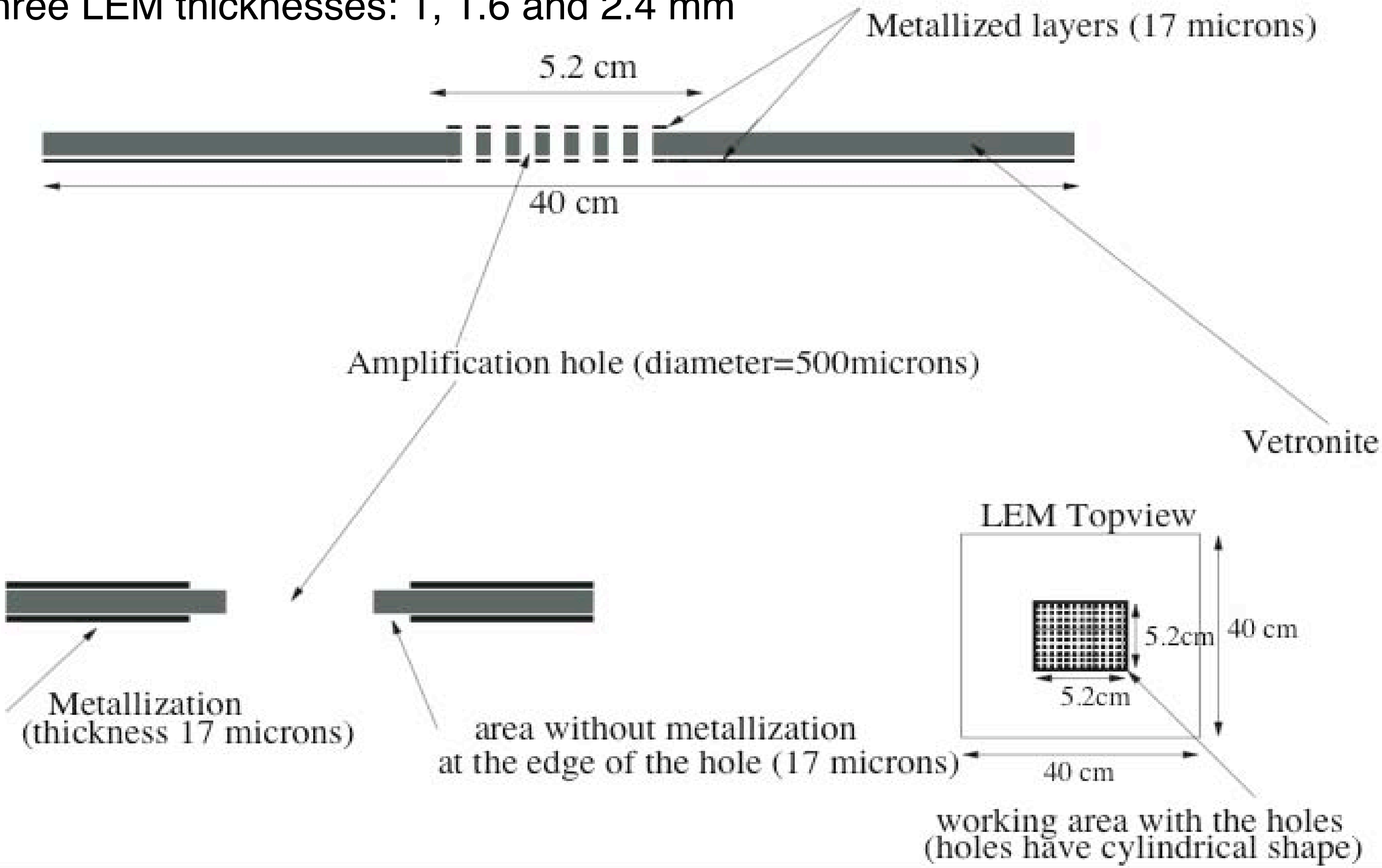
•Gas phase on top of liquid phase (T=87K) has high density, equivalent to p≈3.5 bar @ T=273K

•Seeking a "solid" solution, able to function at cryogenic temperature, withstand large temperature variations (during cooldown), need a very large area (≈3800 m^2)

We report here on attempts with thick-LEM (vetronite Cu coated + holes)

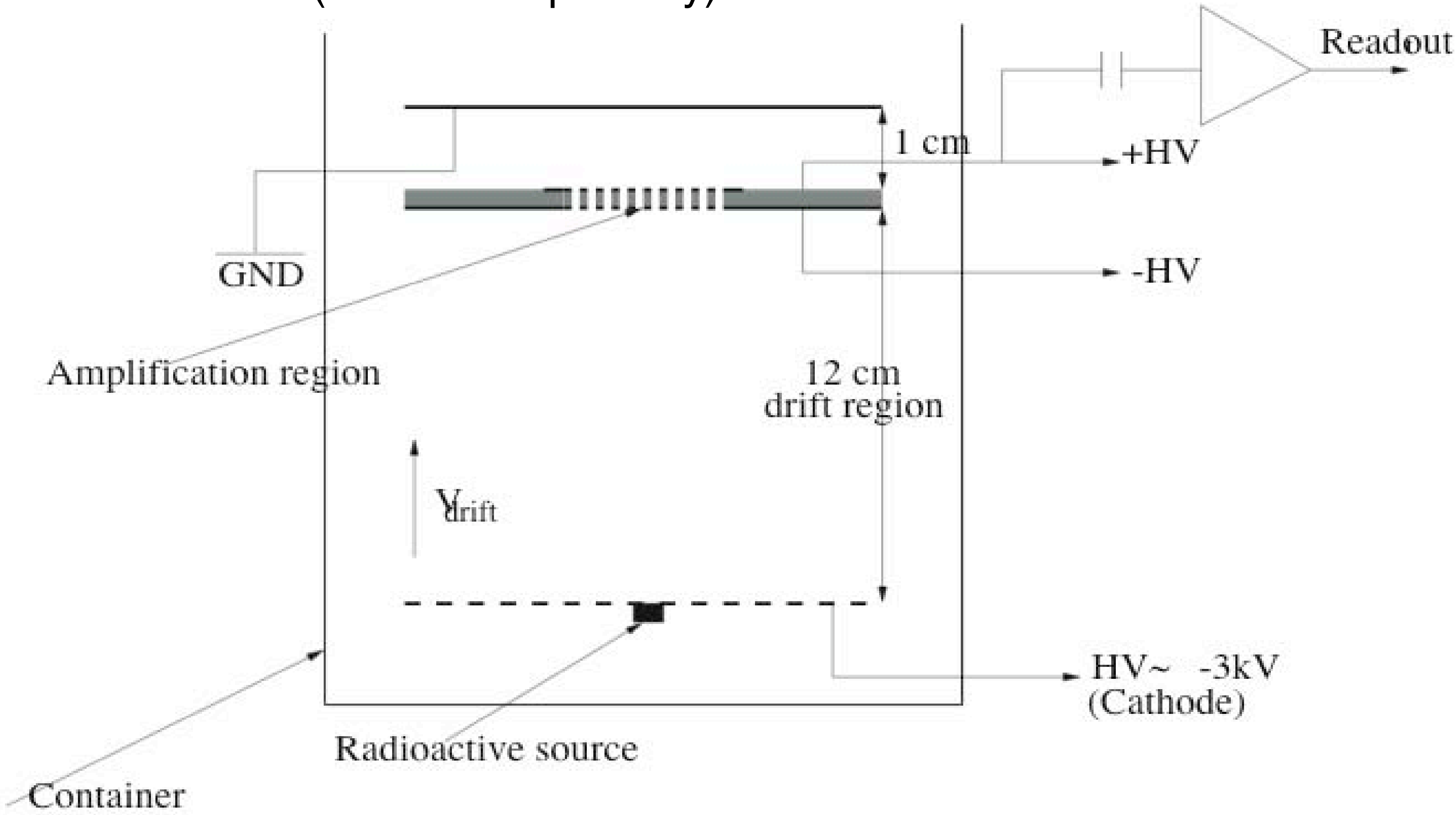
High gain operation of LEM in pure Ar at high pressure

- Three LEM thicknesses: 1, 1.6 and 2.4 mm

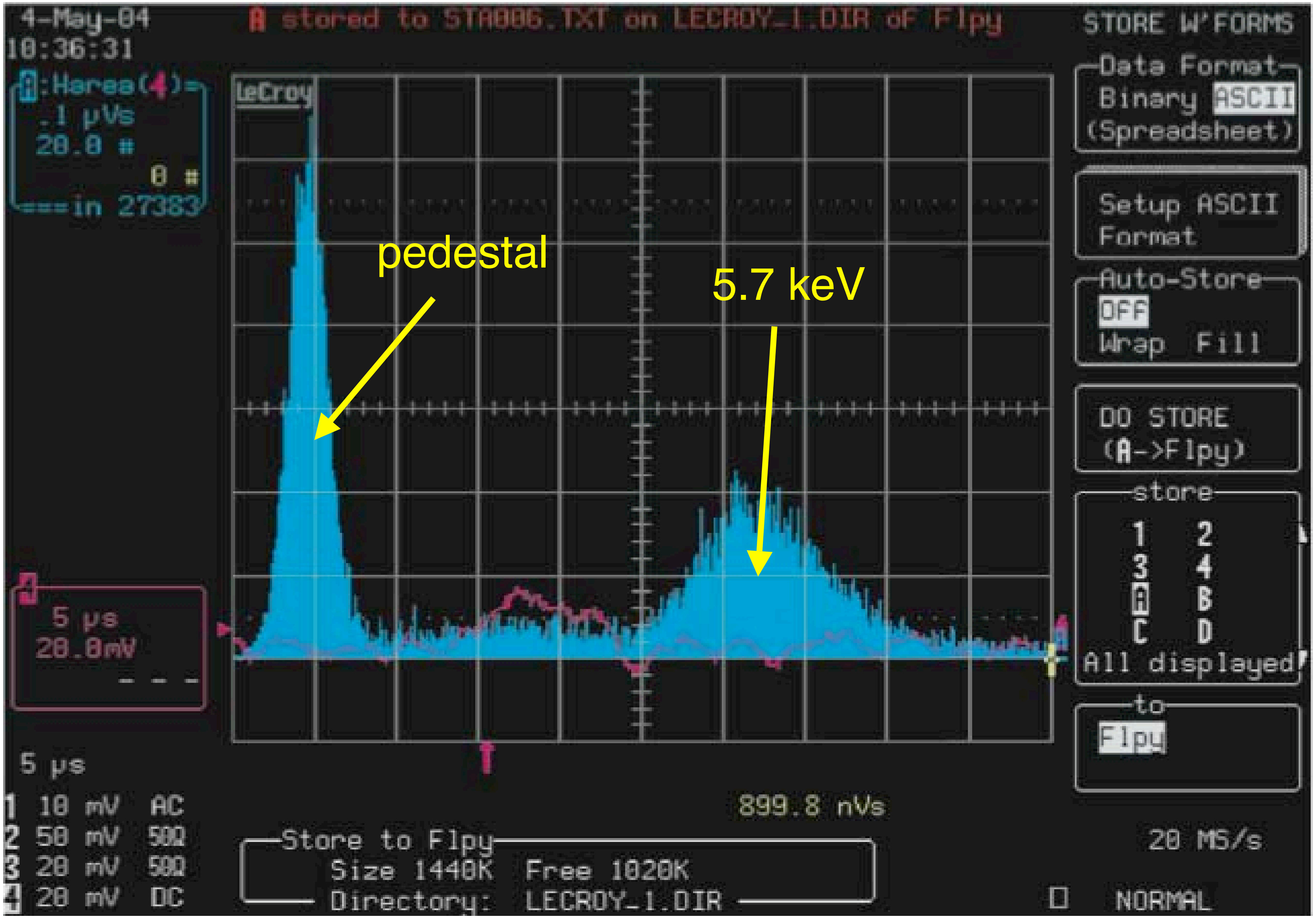


High gain operation of LEM in pure Ar at high pressure

- 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)

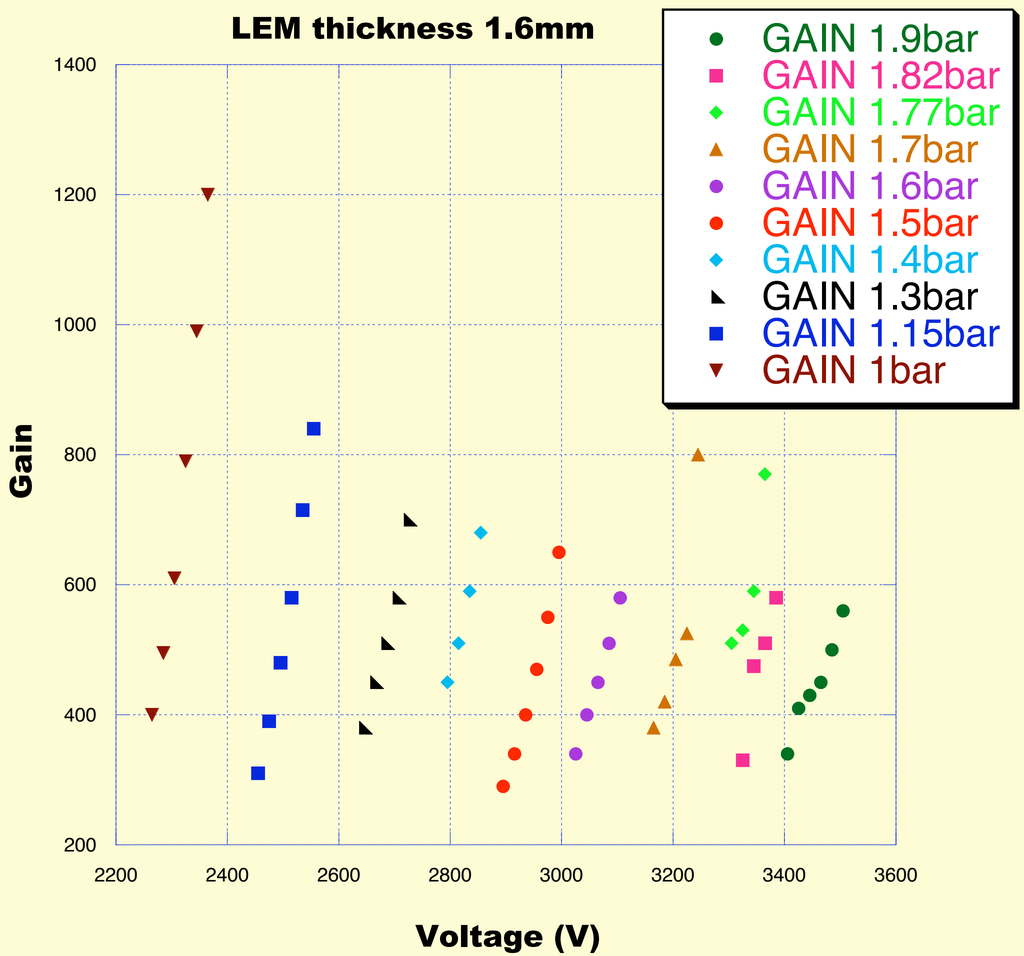


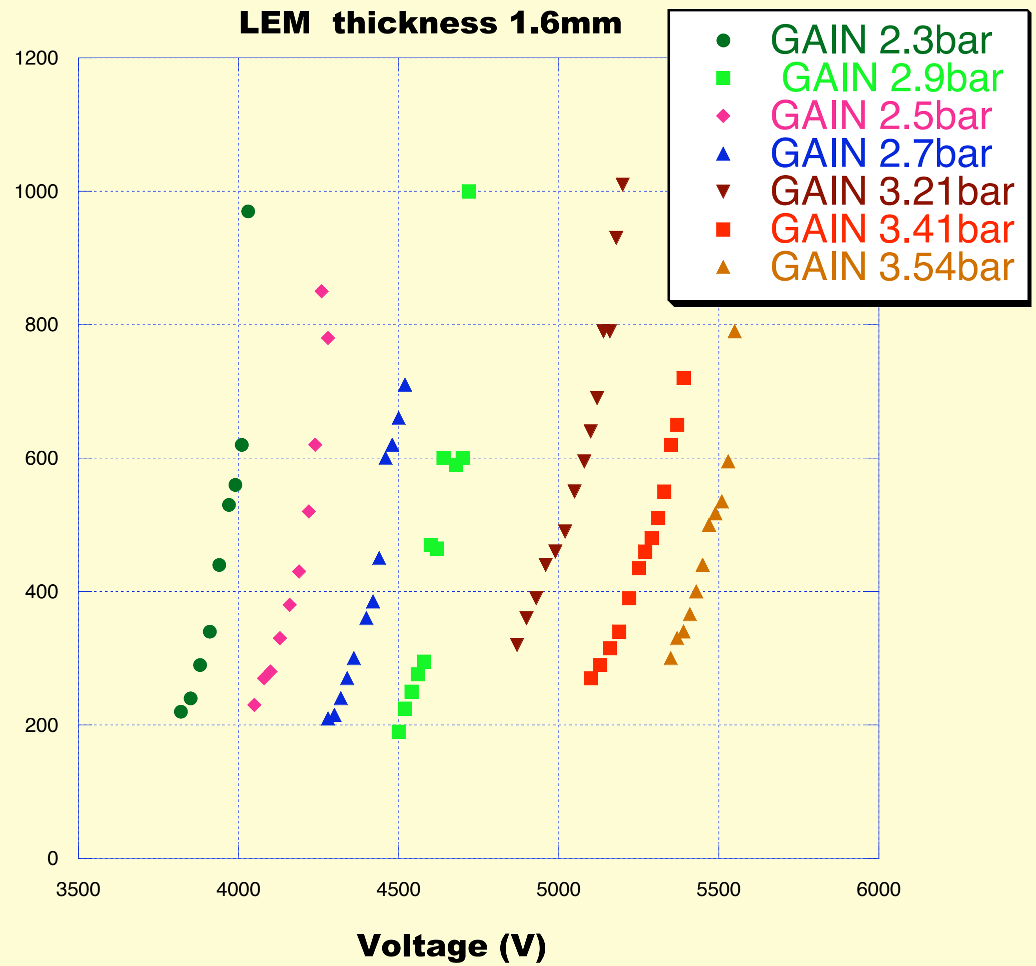
The typical spectrum (Fe55, 5.7 keV)



High gain operation of LEM in pure Ar at high pressure

Preliminary results, e-print in preparation

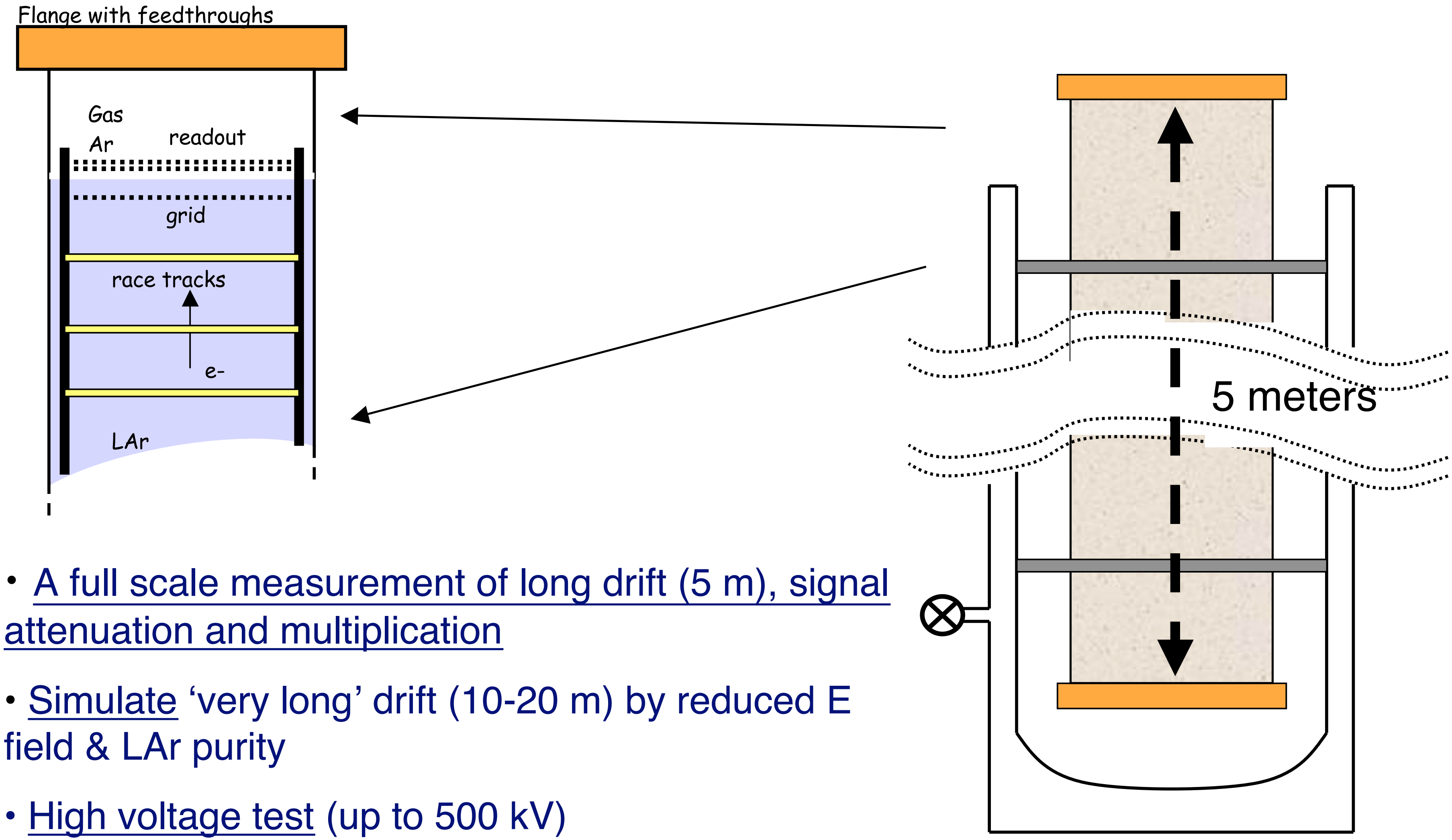




Gain up to ≈800 possible even at high pressure (good prospects for operation in cold)

Resolution ≈ 28% FWHM for Fe-55 source

Long drift, extraction, amplification: test module



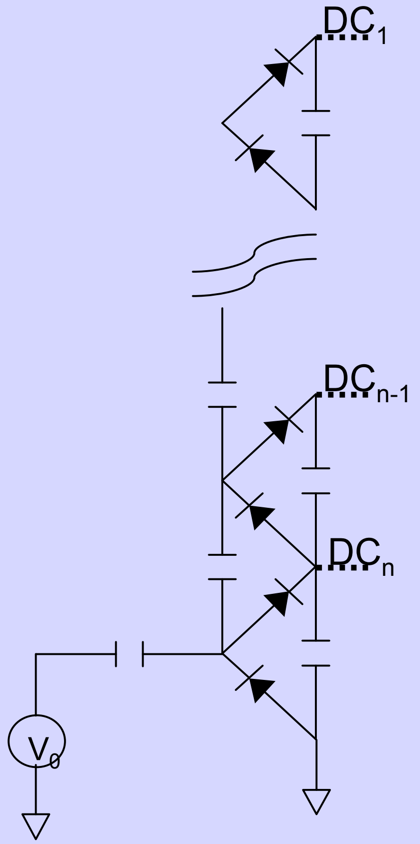
- A full scale measurement of long drift (5 m), signal attenuation and multiplication
- Simulate 'very long' drift (10-20 m) by reduced E field & LAr purity
- High voltage test (up to 500 kV)
- Design & assembly in progress: external dewar, detector container, inner detector, readout system, …

Results in ≈2006

Long drift, extraction, amplification: test module

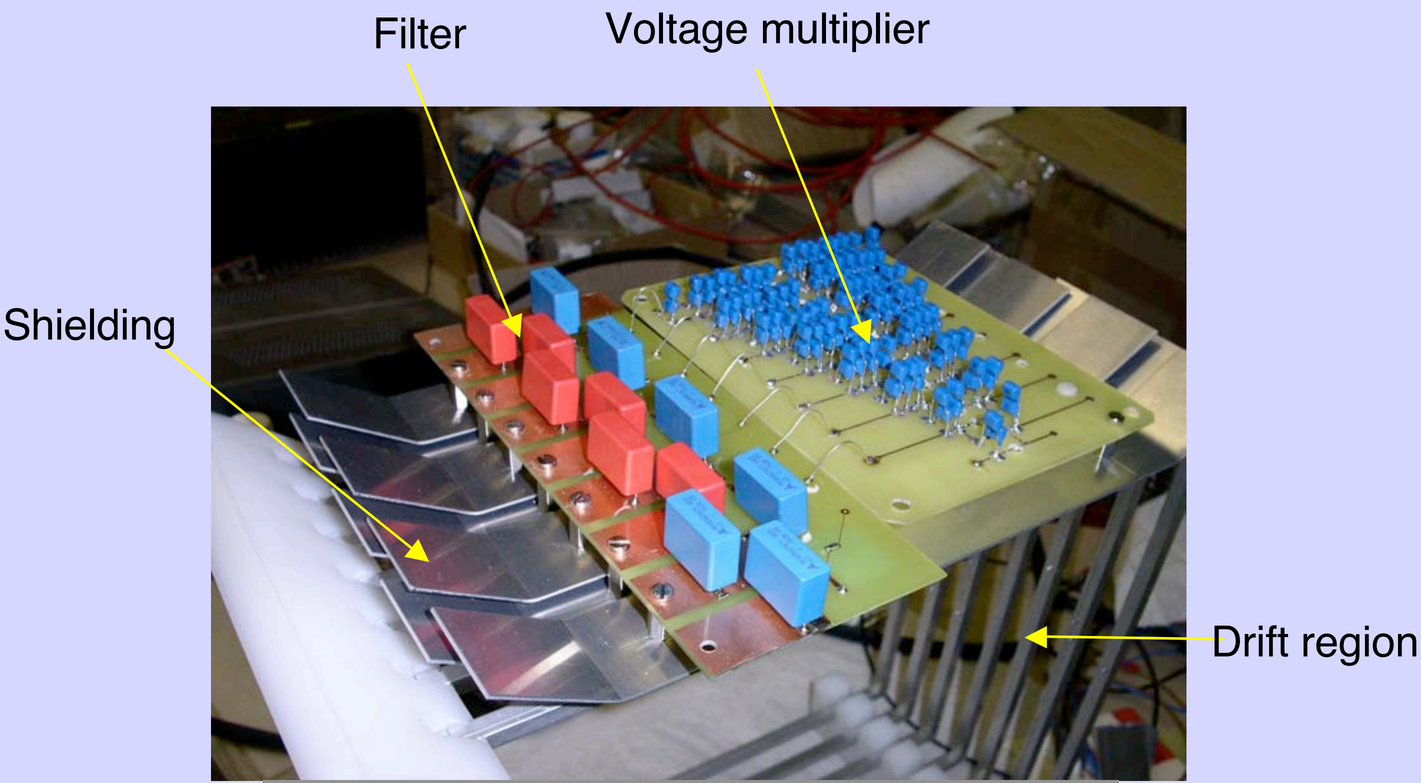
Inner diameter 250 mm, drift length 5000 mm
Drift H.V. up to 500 kV

Drift very high voltage: Greinacher circuit



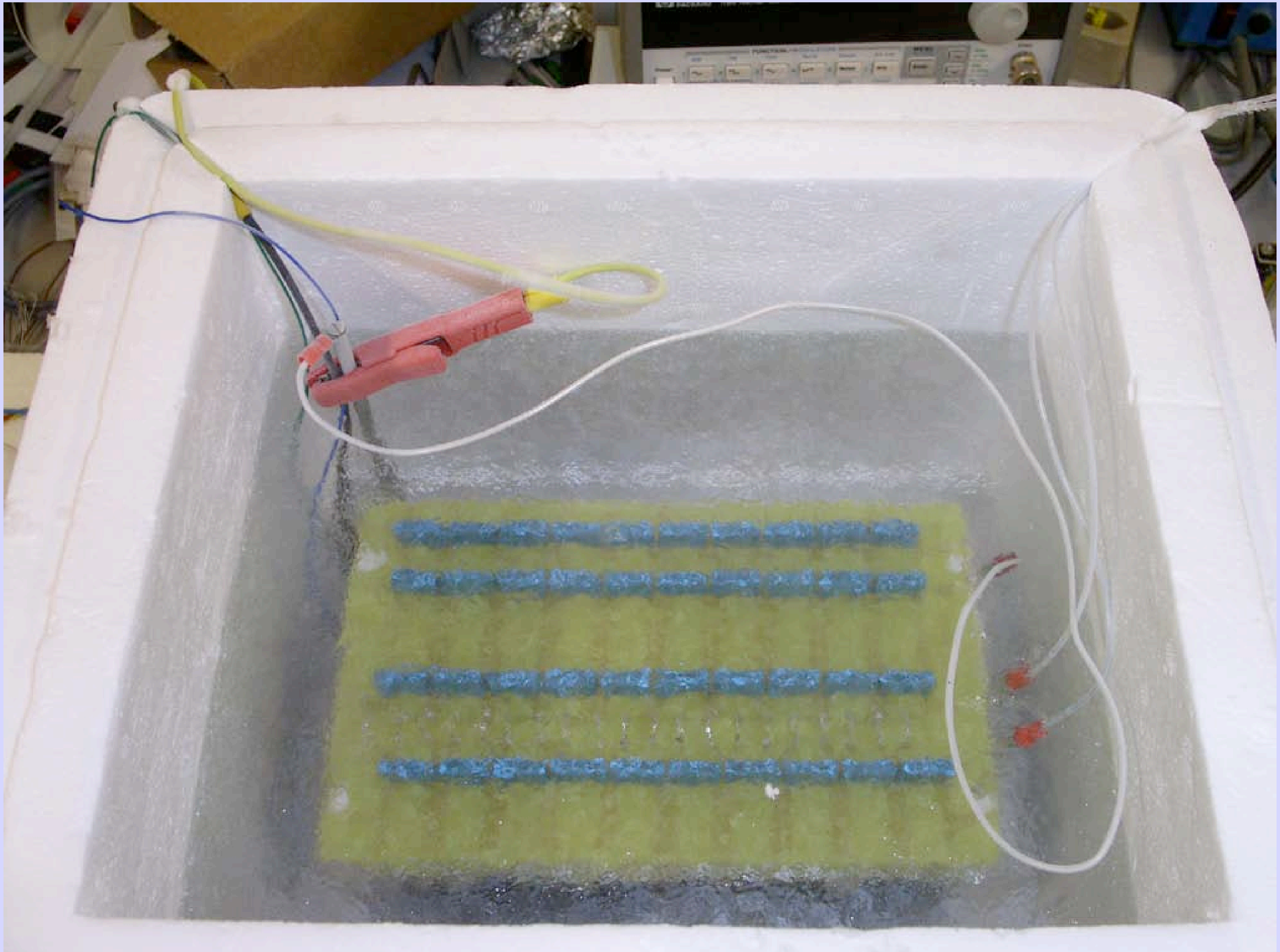
Greinacher or Cockroft/Walton voltage multiplier

Voltage of 0.1÷2 MeV can be reached with two possible solution: large number of stages with "small" V_0~1kV ÷5kV or higher voltage per stage V_0~5kV ÷25kV and less stages. Both solutions have positive and negative aspects. The final choice is driven by ripple conditions required, space availability and costs.



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

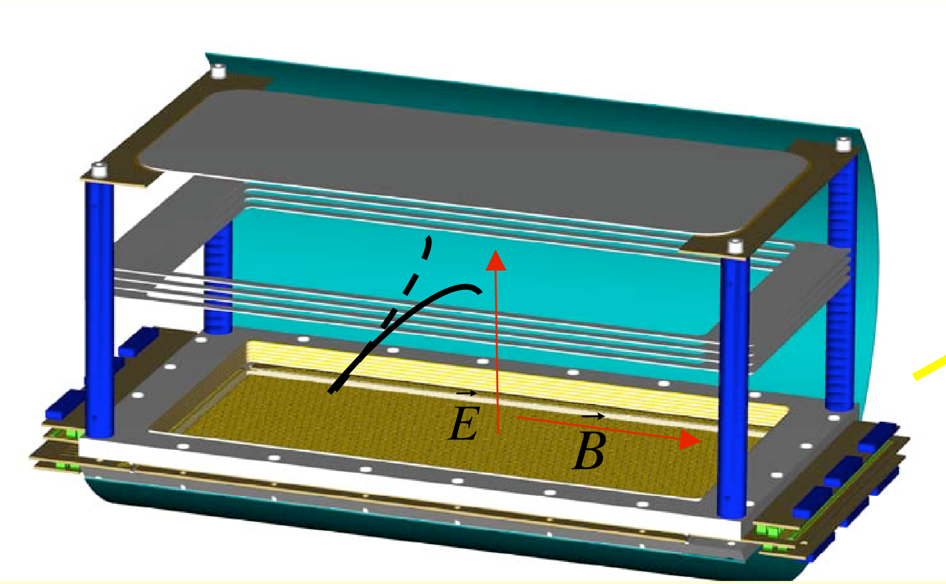
Drift very high voltage: 40 kV multiplier in LAr

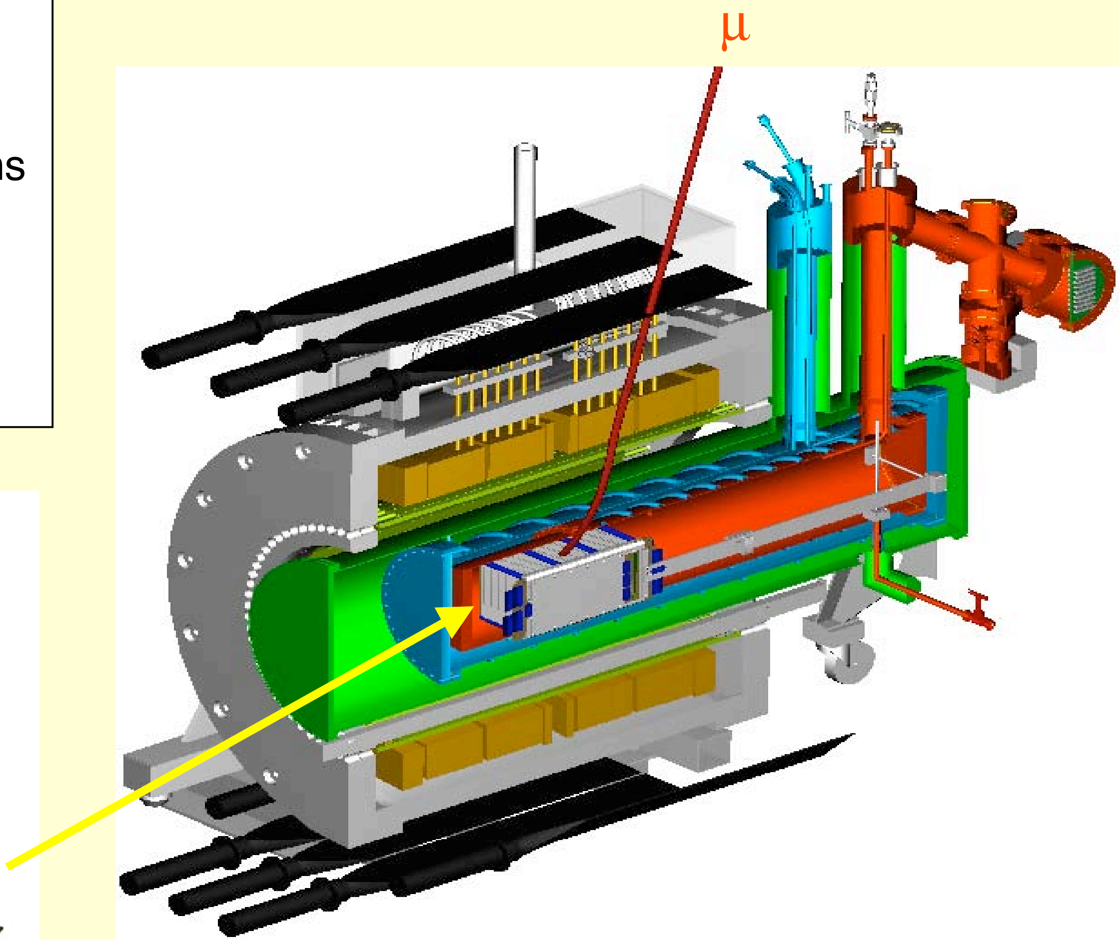


Liquid Argon imaging in B-field

E-print: physics/041280

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





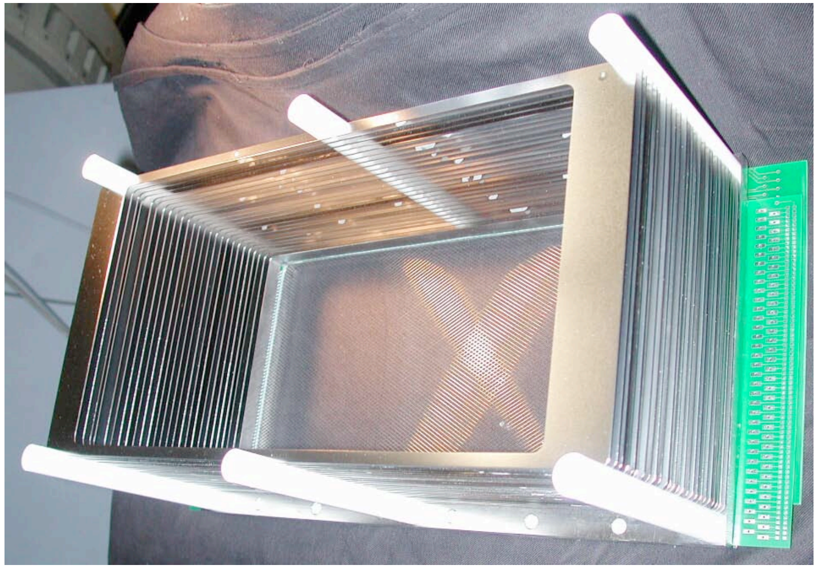
Width 300 mm, height 150 mm, drift length 150 mm

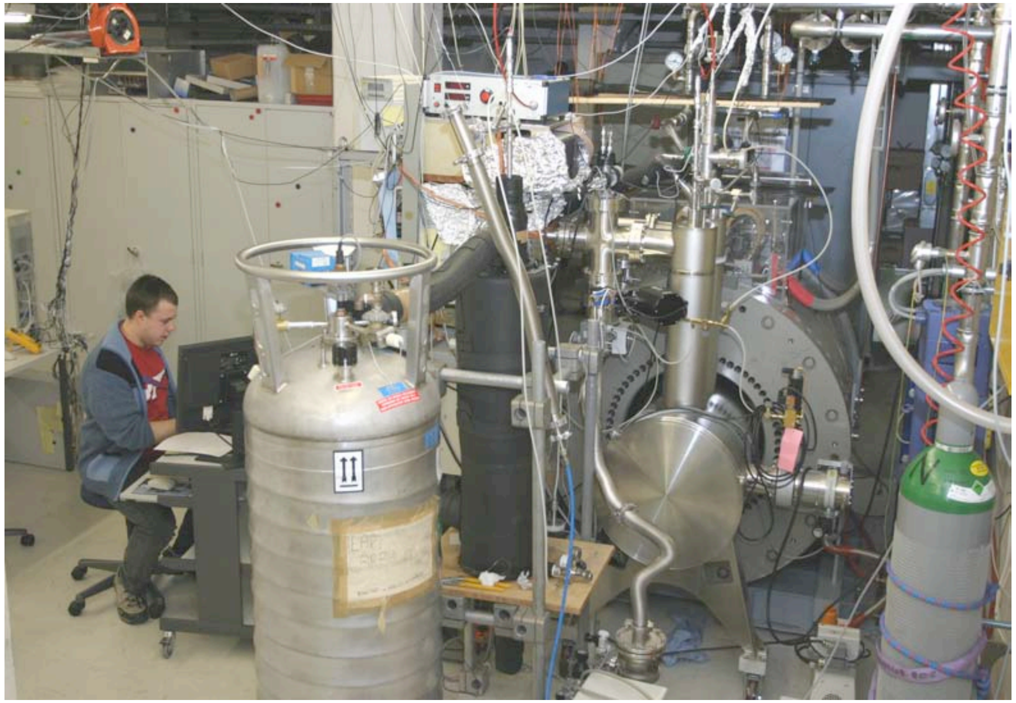
SINDRUM I Magnet (PSI)

B_{max} = 0.55 T

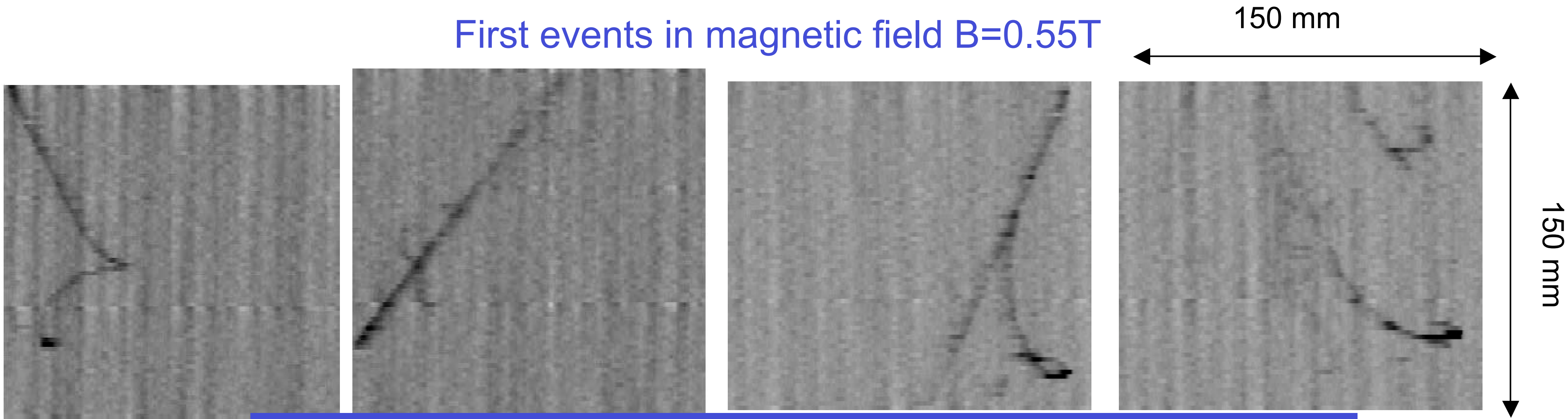
Power consumption 220 kW

Chamber detail, overall setup and first events





First events in magnetic field B=0.55T



E-print: physics/041280, accepted for publications in NJP

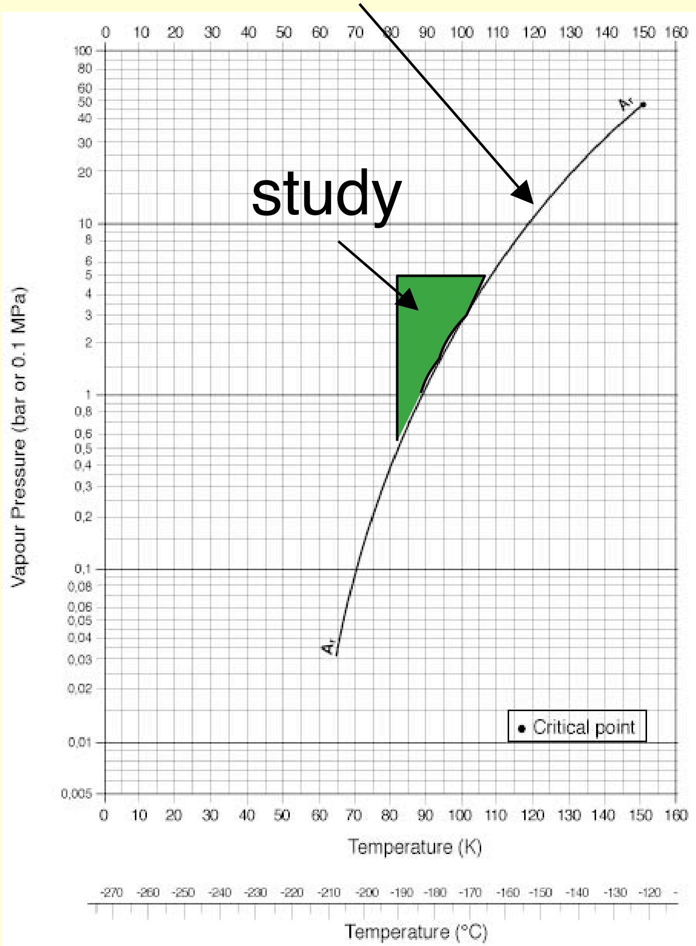
High-pressure drift properties in liquid Argon

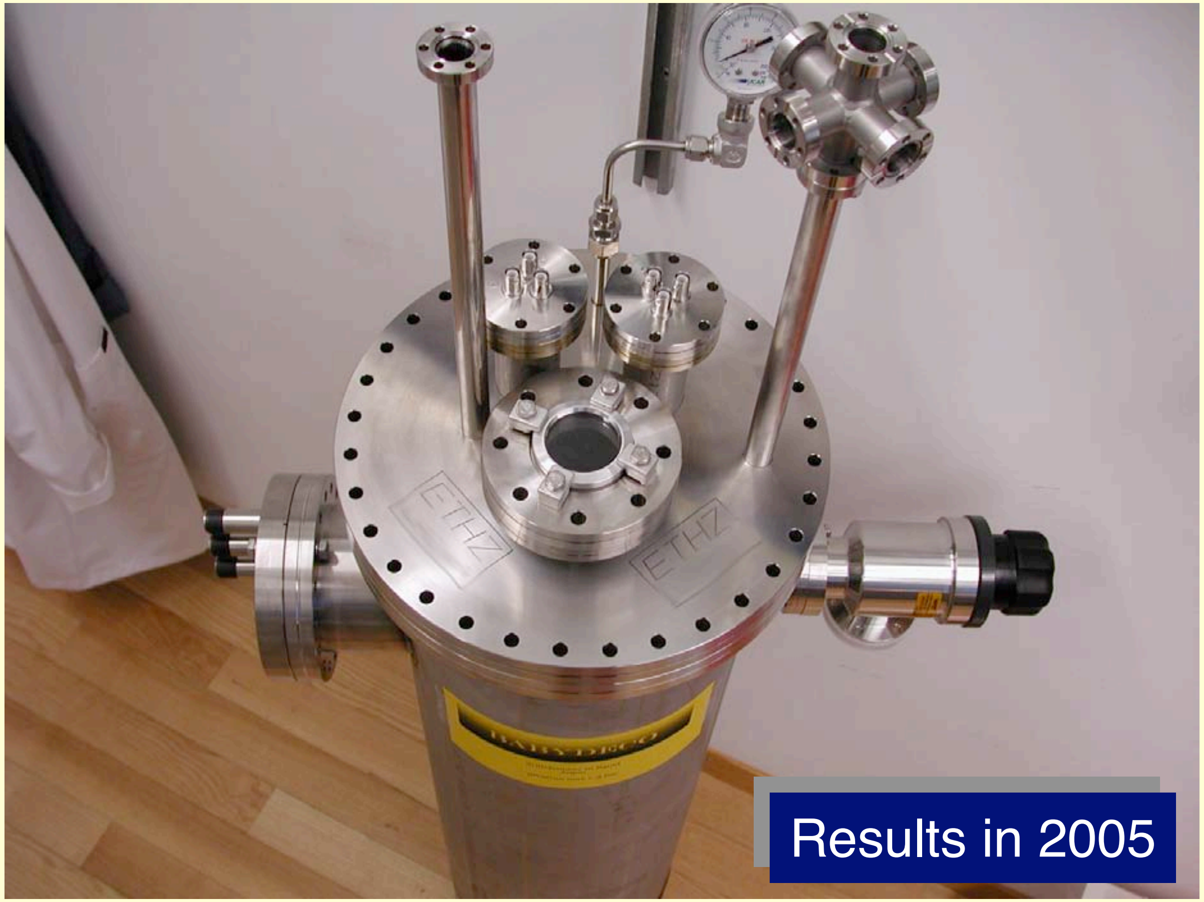
- **At the bottom of the large tankers:**

  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

Study of large underground storage tank

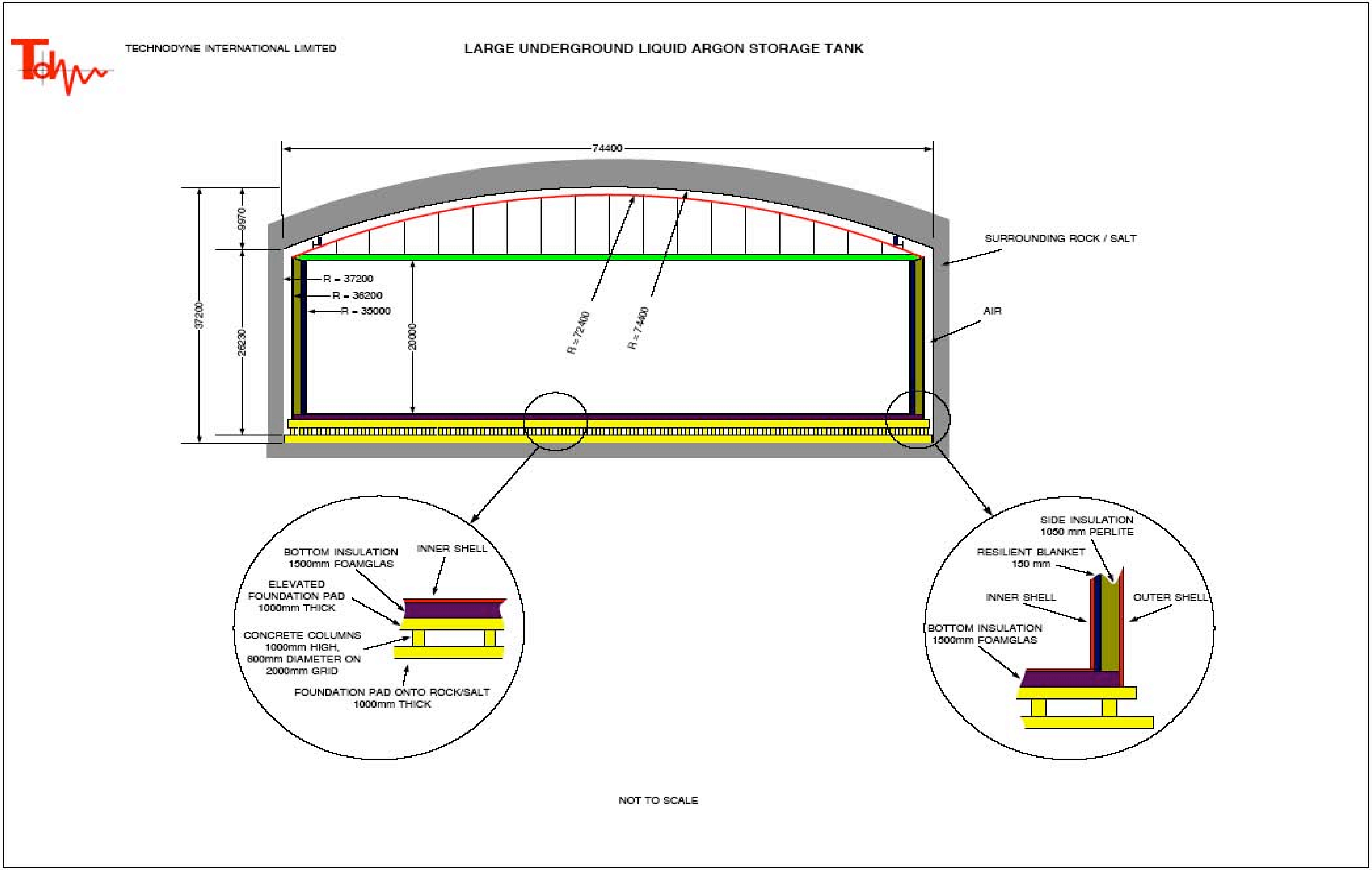
	Project: Large Underground Argon Storage Tank
Issued By: JMH	Document Title
Date:	

A feasibility study mandated to Technodyne LtD (UK)

Study duration:

February - December 2004

Technodyne baseline design

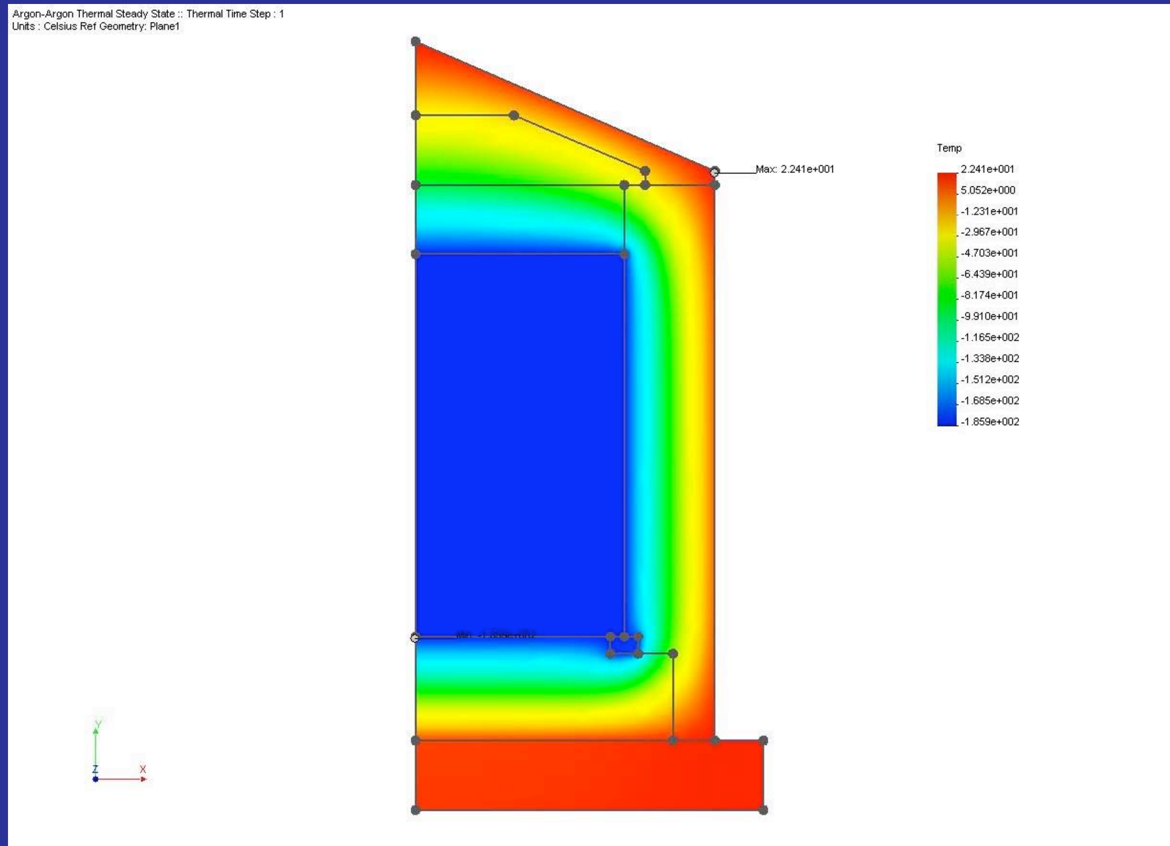


Technodyne baseline design

- 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

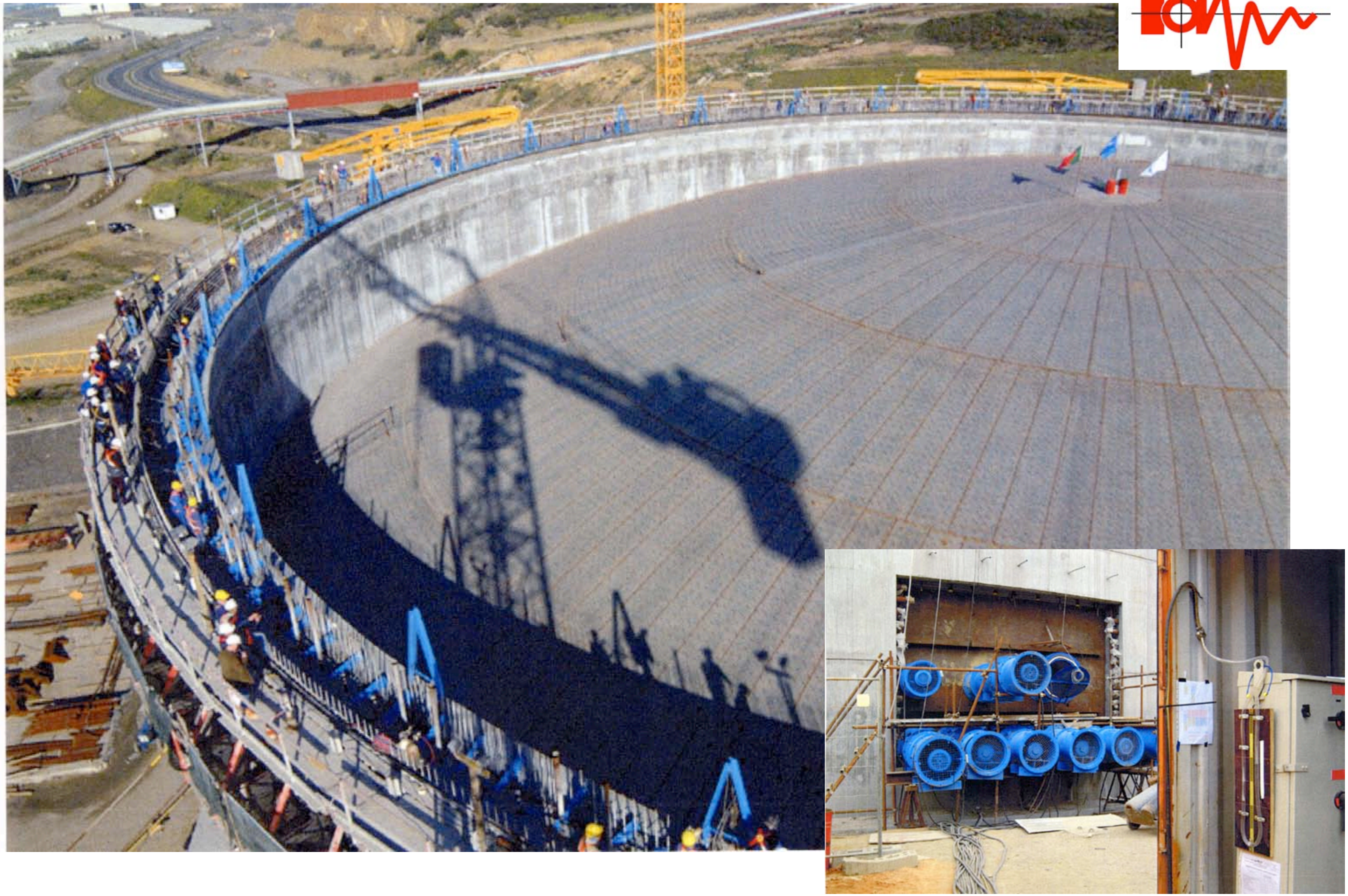
- *1.1 Stability of cavern*
  - The assessment of the stability of a large cavern must be considered. When designing cryogenic tanks for above ground factors such as wind loading and seismic effects are taken into account, however large rock falls are not. The structure in a working mine are well understood 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? (A) Concrete base

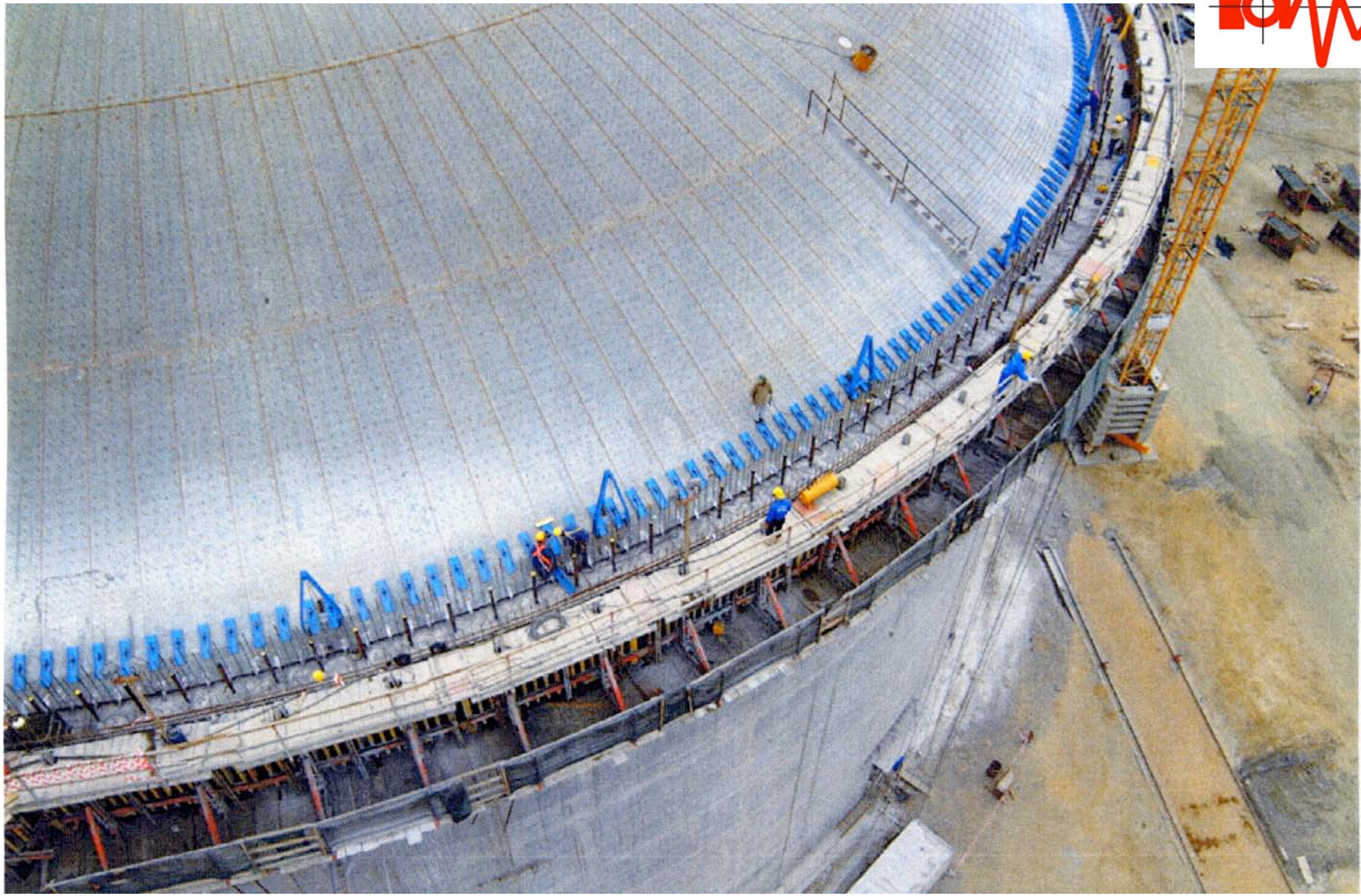
(B) Construction of the concrete outer-shell

(C) Roof construction (inside tank)

(D) Air-raising of the roof



(E) Roof welding



Tank budgetary costing

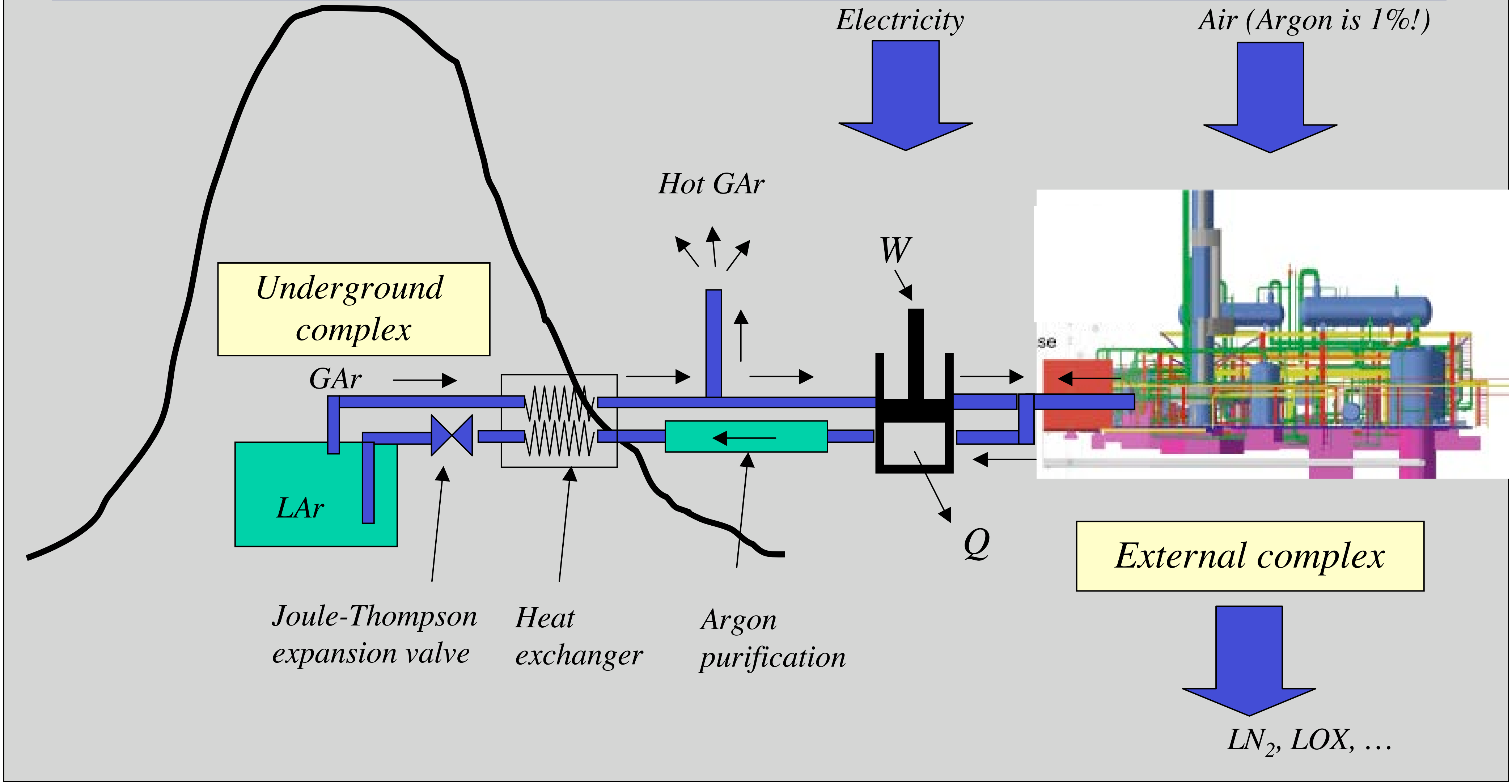
- The estimated costs tabulated below are for an inner tank of radius 35m and height 20m, an outer tank of radius 36.2m and height 22.5m. The product height is assumed to be 19m giving a product mass of 101.8 k tonnes.

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

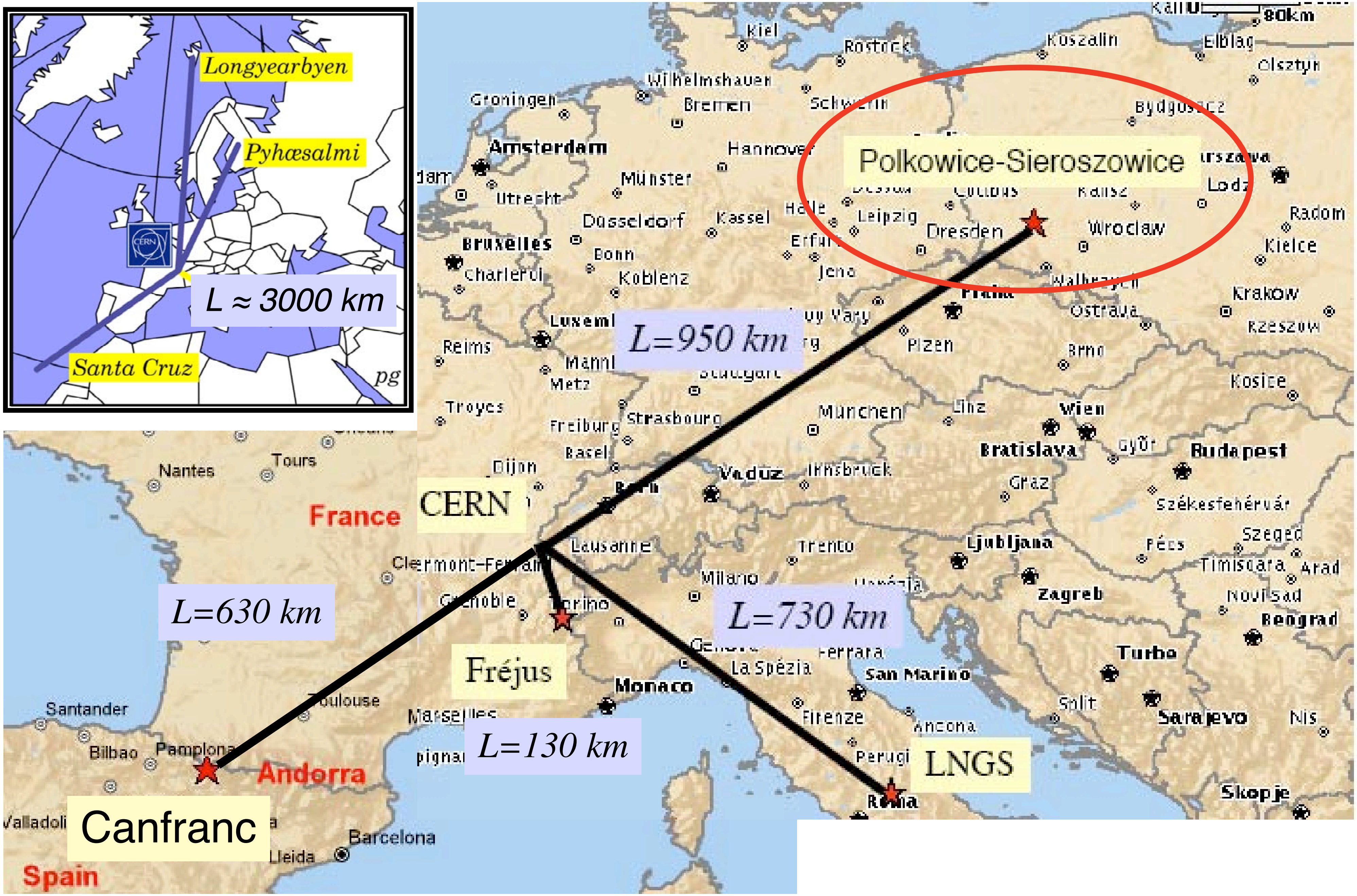
- There are three major items required for generating and maintaining the Liquid Argon needed in the tank. These are:
  - Filling the tank with the initial Liquid Argon bulk
  - Re- liquefaction of the gaseous Argon boil-off.
  - Continuous purification of the Liquid Argon.

- *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

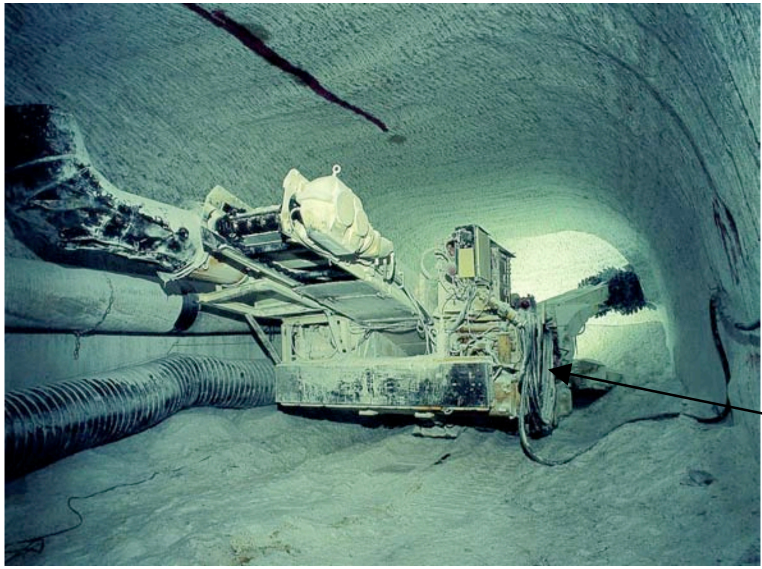
- *1.2 Cooldown*
  - ➥ Assuming a start temperature of 35 degrees C and using Liquid Argon to perform the cool-down then the amount of liquid Argon required for the cool-down process would be ≈1000 tonnes LAr. Assuming that the liquefaction plant can produce 150 tonnes / day of liquid argon then the 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 ?



Example: salt mine in Poland (Sierozowice)

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.



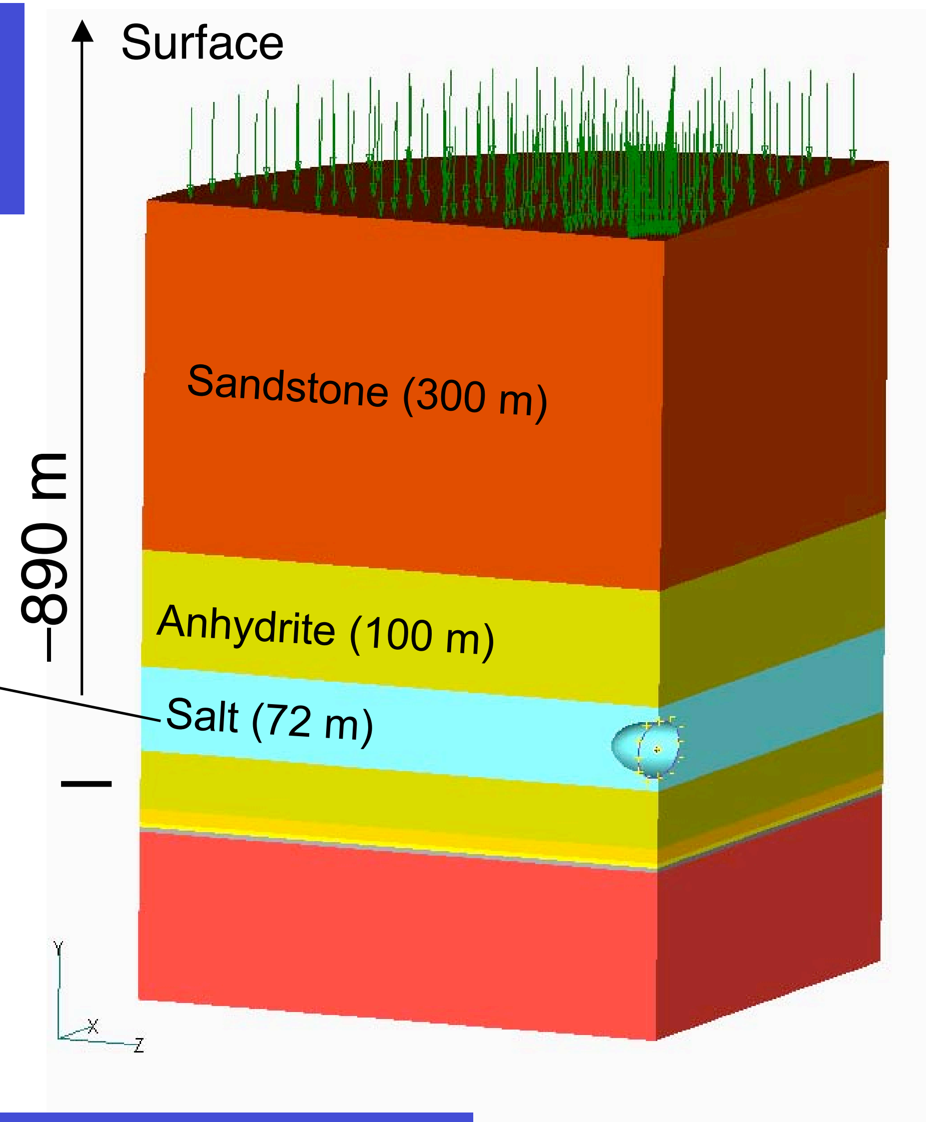


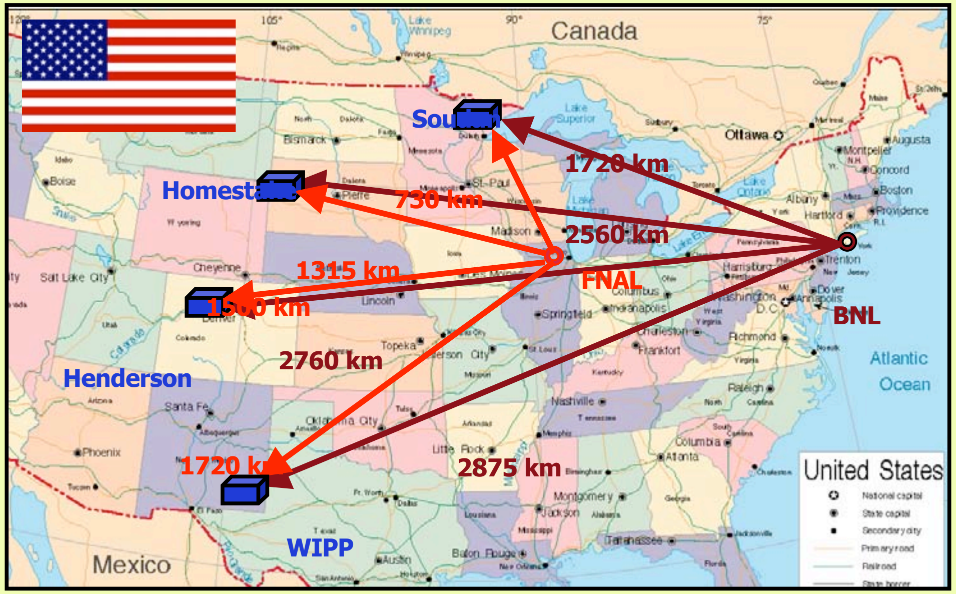
Tabela 1. Wyniki st__enia substancji radioaktywnych w badanych próbkach soli z kopalni Sieroszowice.

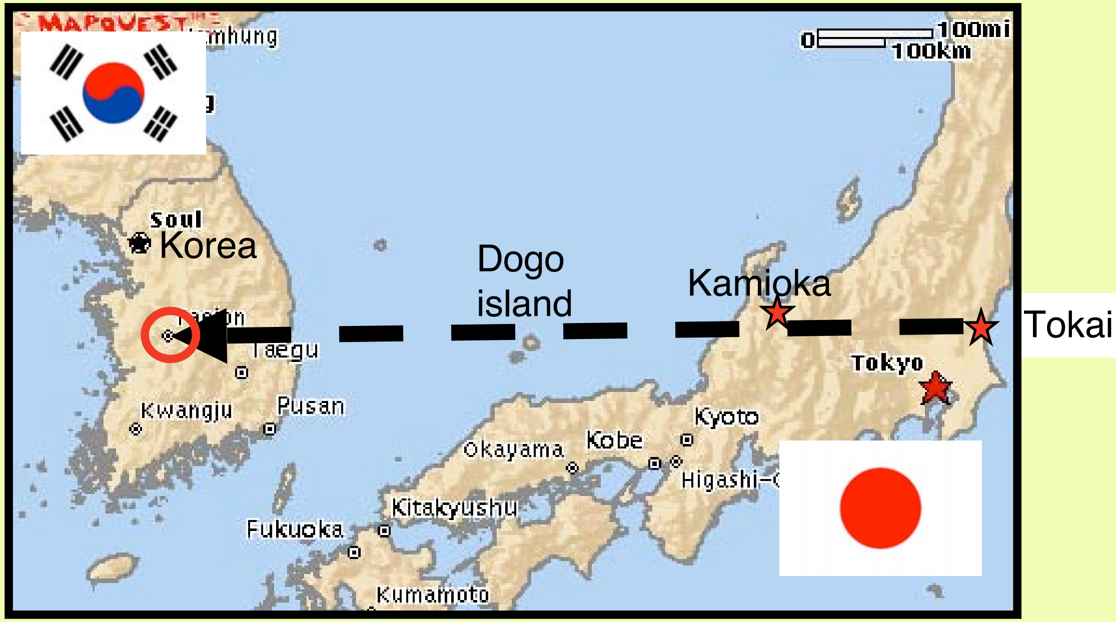
Radionuklid	Próbka nr: 1	2	3 [Bq/kg]	4
^{238}U	0.40±0.06	0.34±0.05	0.10±0.02	0.14±0.02
^{234}U	0.38±0.06	0.33±0.05	0.14±0.02	0.14±0.02
^{230}Th	0.29±0.05	0.34±0.06	0.10±0.03	0.19±0.03
_rednio sz. U	*0.357*	*0.337*	*0.113*	*0.157*
^{232}Th	0.09±0.03	0.08±0.02	0.03±0.02	0.11±0.02
^{235}U	0.015±0.006	0.015±0.007	<0.005	0.008±0.004
^{40}K	nd	nd	nd	2.1±0.3

Salt radiopurity test samples:

J.W.Mietelski, E.Tomankiewicz, S.Grabowska

Non-European sites for very large liquid argon TPC





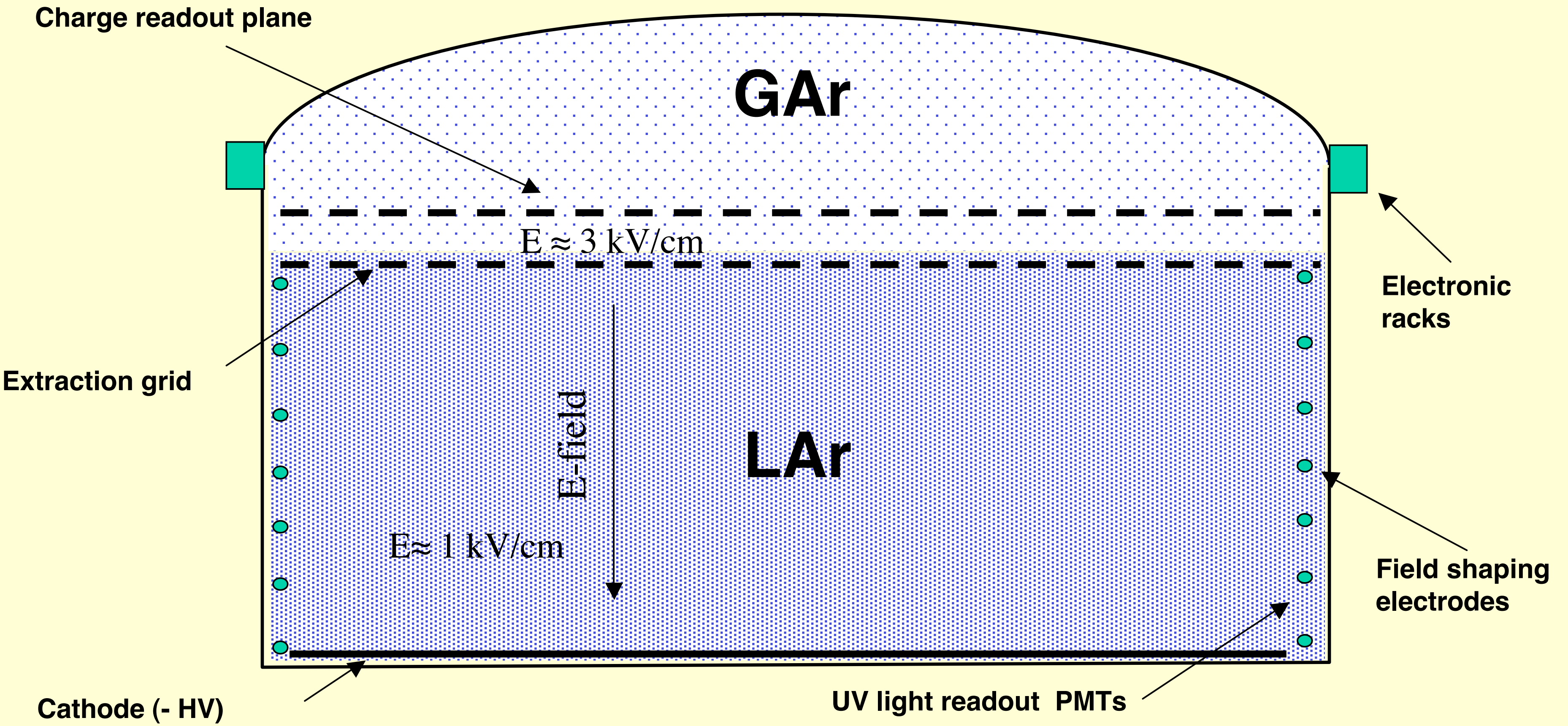
Liquid Argon TPC provides high efficiency for broad energy range: Flexibility in L & E choice

10 kton prototype

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

(e.g. sensitivity for p→νK: $\tau > 10^{34}$ 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



≈7000 m³ 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

- An extrapolation of the liquid Argon TPC concept to very large masses has been presented. It relies on
  - ➥ (a) industrial tanker developed by the petrochemical industry (no R&D required, readily available) and
  - ➥ (b) improved detector performance for very long drifts (R&D on-going, results expected for ≈2006)

- For such large scale projects, we must largely profit from connection with industry (e.g. Technodyne). In addition, a multi-disciplinary approach is also mandatory (geophysics, cryogenic engineering, …)

- As far as neutrino physics is concerned:
  - ➥ 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.
  - ➥ A 10% full-scale, cost effective prototype of the design on the scale of 10 kton could be 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.