The liquid Argon TPC:
a powerful detector for future neutrino experiments

…as well as for underground astroparticle physics and proton-decay searches

HIF05, La Biodola, ELBA
29-31 May 2005

A. Ereditato, INFN Napoli
A. Rubbia, ETH Zurich

Foreword

Strategy for accelerator neutrino oscillation experiments (a personal point of view)

We can schematically identify three phases of experiments:

present generation (2005-2011): CNGS: unambiguously establish $\nu_\mu - \nu_\tau$ oscillations
NuMI: reduce errors on Δm^2_{23} and $\sin^2\theta_{23}$
glance at θ_{13} if …just around the corner… (~10 degrees)

next generation (2009-2013): T2K, NoVa: pick up θ_{13} (and matter effects ?)
machines should keep their promises on intensity !
(if not, troubles for further projects ?)

next-to-next (> 2015): hard to predict, physics says CP and mass hierarchy, but nothing can be firmly decided today…ready for the unexpected!

…However, some considerations could be made:

- a further step in intensity will be required, conventional beams obsolete ?, new Super-B, βB or Nufact.

- cost/complexity of facilities: wise choices on detectors: multi-task and large mass;
we have > 10 years ahead of us: avoid premature decisions, invest on research, graded strategy, seek for high technological added-value (detectors have to run for many years, state-of-the-art technologies).

- world-wide coordination: optimize resources, exploit existing infrastructure, seek for complementarity

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

The physics goals depend on the value of θ_{13} for which there is no theoretical input

↓

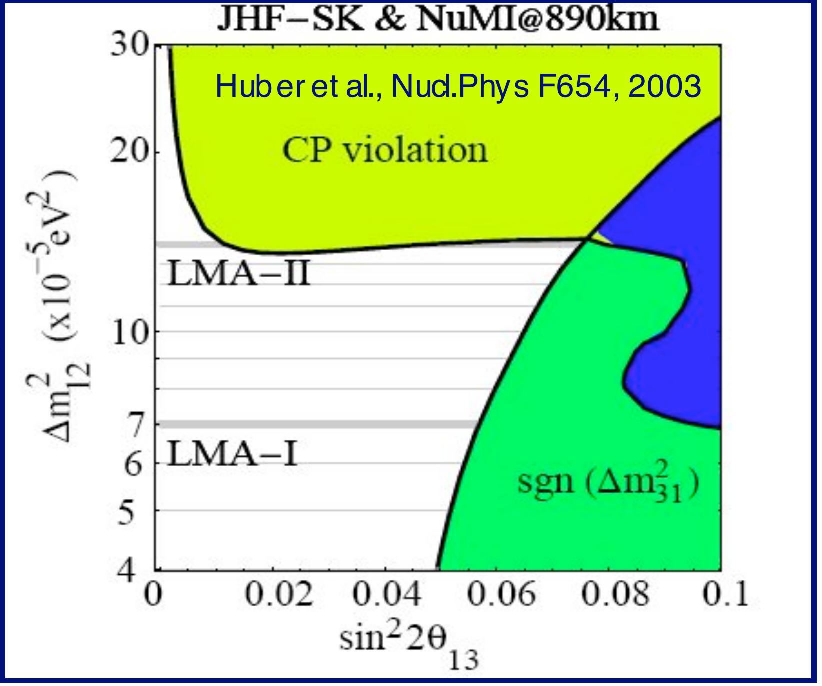
must conservatively wait for feedback from T2K & NovA and commission the following generation of detectors with astroparticle sources

θ_{13} : comparison between CNGS, MINOS, T2K and NovA

Experiment	Run	p.o.t.	90% limit	3σ evidence
CNGS	2006-2010	2.25×10^{20}	~ 0.1	
MINOS	2005-2008	16×10^{20}		> 0.080
T2K	2009-2013	50×10^{20}		> 0.018
NovA (Booster) NovA (p driver)	2010-2014 ?	32.5×10^{20} 125×10^{20}		> 0.015-0.020 > 0.005-0.007

Assume 5 years running, $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2
(90% limit or 3σ evidence for non zero $\sin^2 2\theta_{13}$)

With some chance, next generation experiments on θ_{13} could measure mass hierarchy and CP effects

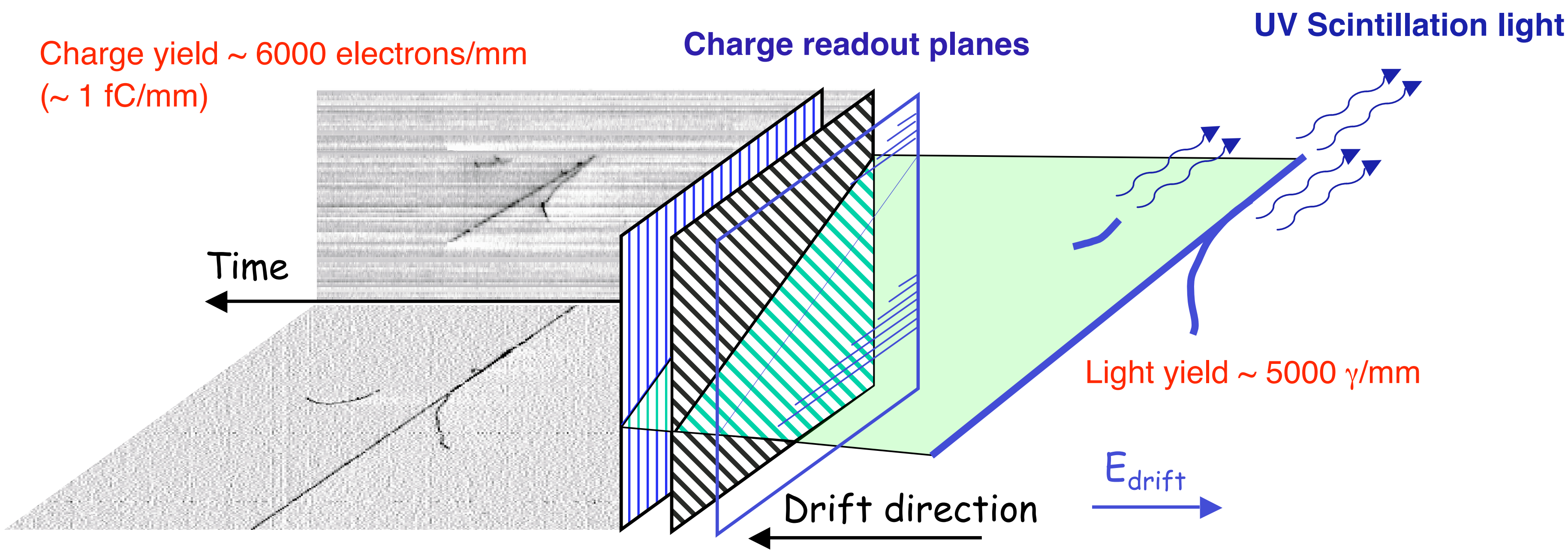


ICARUS: the mother of all liquid Argon TPC

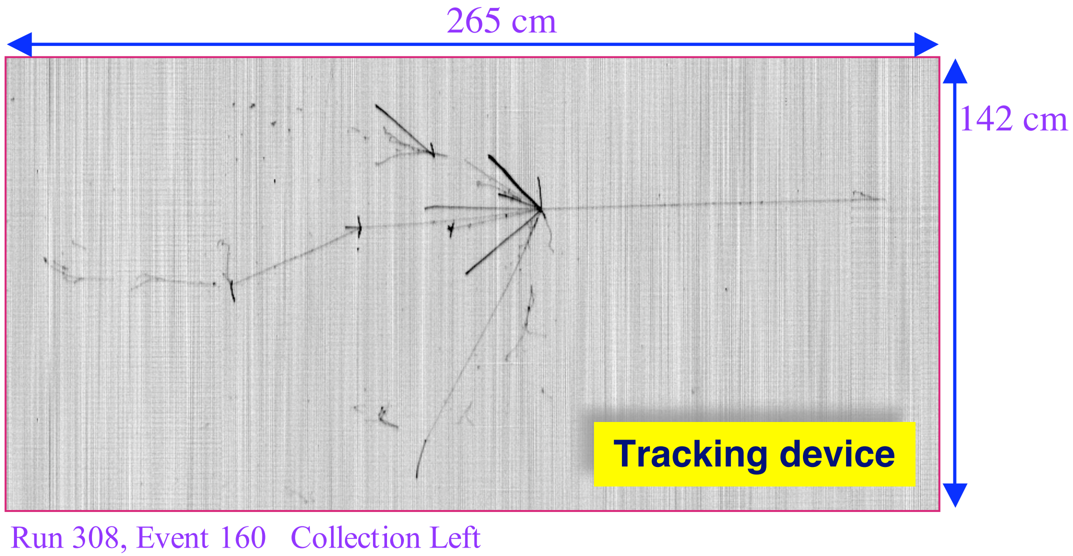
The largest liquid Argon TPC ever built is the ICARUS T600 detector. Its assembly culminated with its full test on surface in 2001.

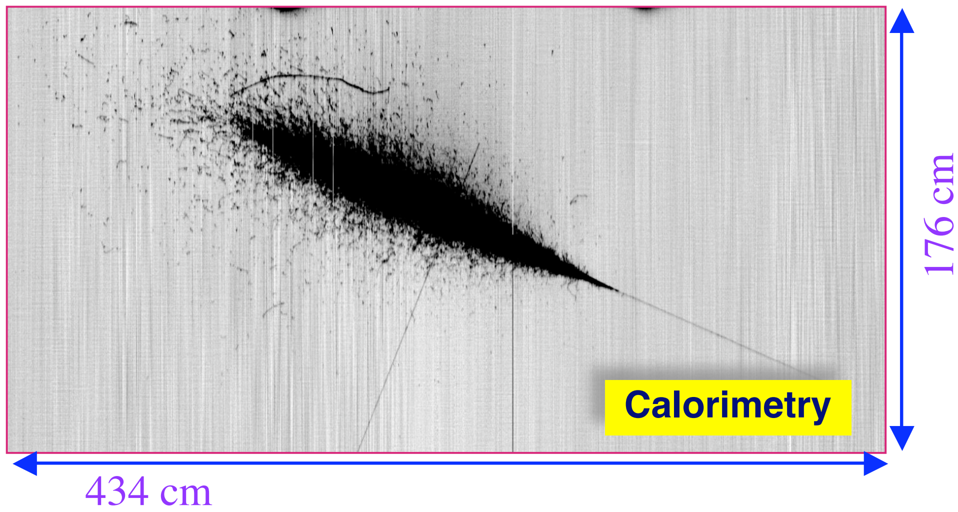
The detector is now at LNGS.
Aim at a prompt commissioning.

Application at LNGS: modular structure.
Cloning to reach the 1800 ton mass scale.



Cosmic-ray events in the T600 detector





Recent developments

Since 2003 we have been investigating possible applications of the liquid Argon TPC technique, successfully developed within the ICARUS Collaboration under the auspices of INFN, for future experiments on neutrino physics and nucleon decay searches.

(Initial work plan identified and started, see next slides)

- 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. of NUINT04, LNGS, **Nucl. Phys. Proc. Suppl. 139:301,2005,** 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, SPSC-CERN

- Very massive underground detectors for proton decay searches,

  A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, 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, July 2004

Envisaged strategy

- more than 20 years old ICARUS project: huge amount of knowledge and experience
- ICARUS at LNGS: on the way of being commissioned. Actual implementation dictated by logistics.
- no ‘black magic’ needed to exploit the technique; detector technology @ 600 ton scale is fully proved
- though, further optimization might be required for mass scale increase (~100 kton and more) (as for any other detector technique at that scale !)
- graded strategy identified:

  1) laboratory prototypes to acquire expertise and perform specific measurements

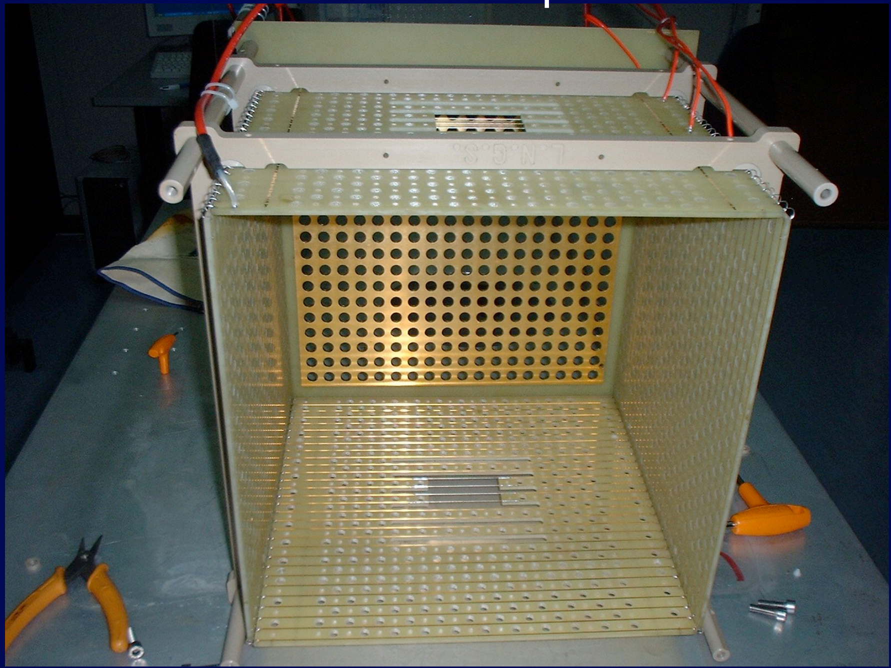
  2) order of ~100 ton applications for next generation experiments (e.g. T2K) on low energy neutrino physics and oscillation studies

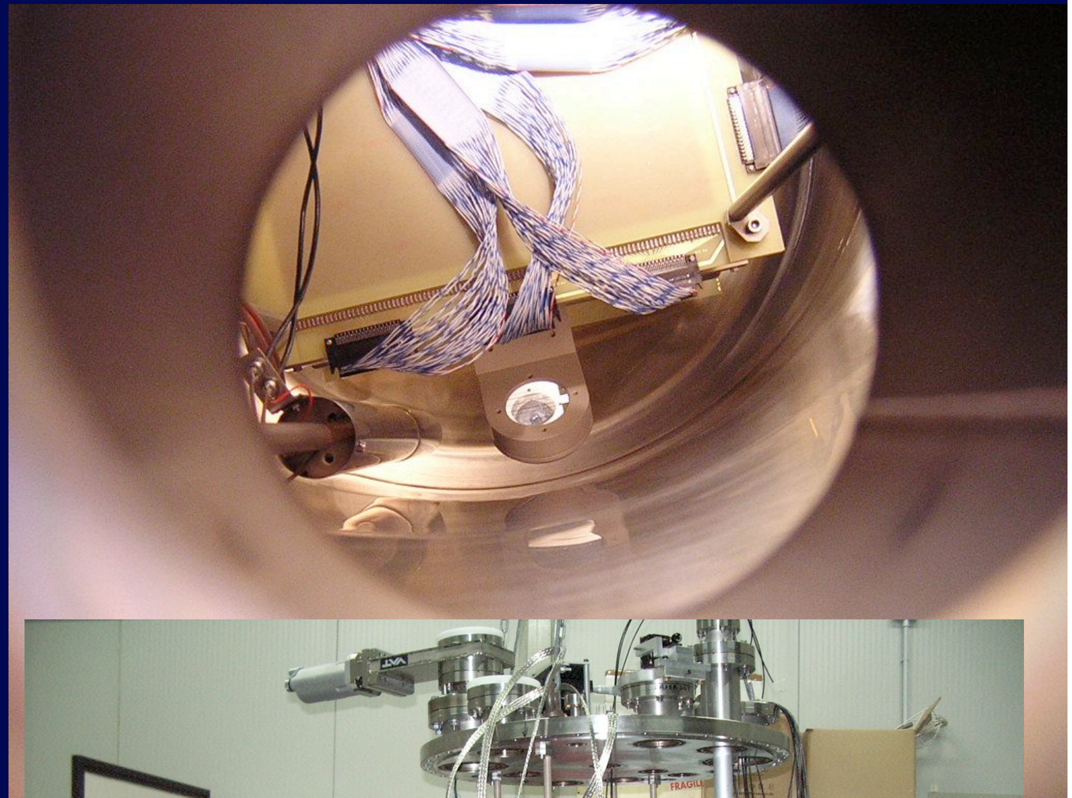
  3) O(10 kton) neutrino observatory with double-phase for improved proton decay search, neutrino beams and astroparticle physics (note: equivalent to a 100 kton WC). Magnetized ?

  4) O(100 kton) ‘very large’ detector for ultimate p-decay sensitivity, SN detector, CP violation studies. Magnetized ?

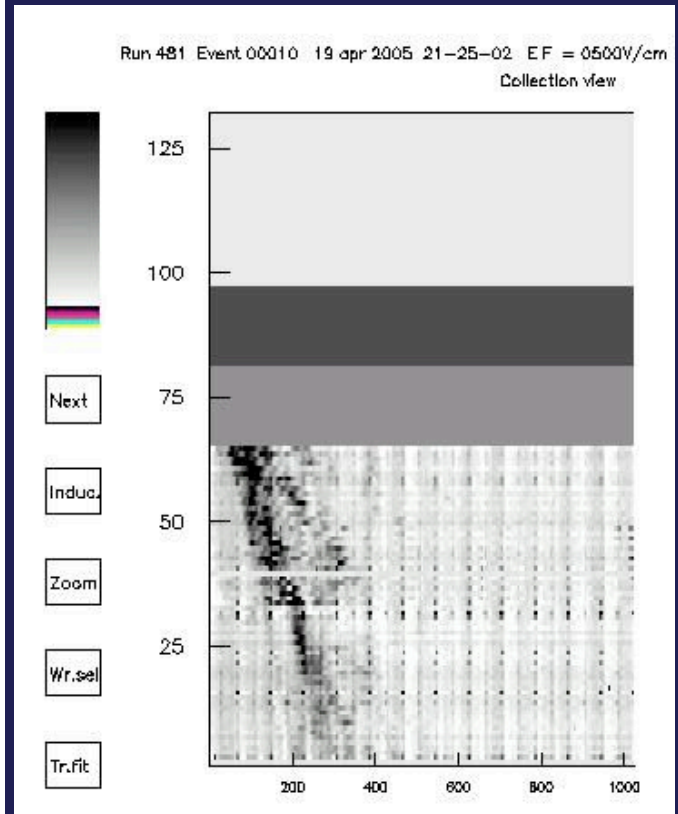
In parallel, start studies, prototyping, laboratory measurements, collaboration with industry

30 liter TPC at INFN Napoli. Studies on calibration and LAr purity monitoring by UV-lasers

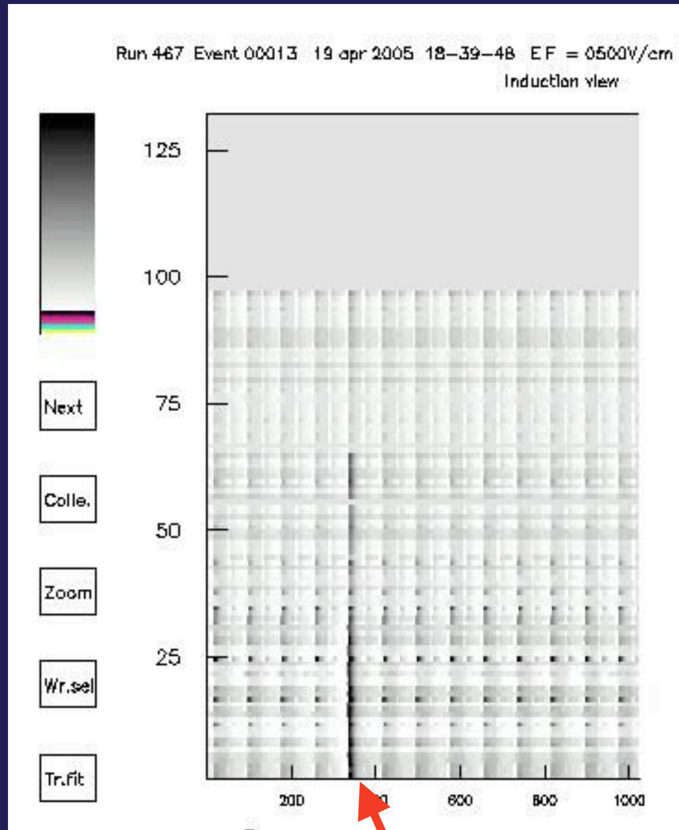




First events collected with the TPC in Napoli



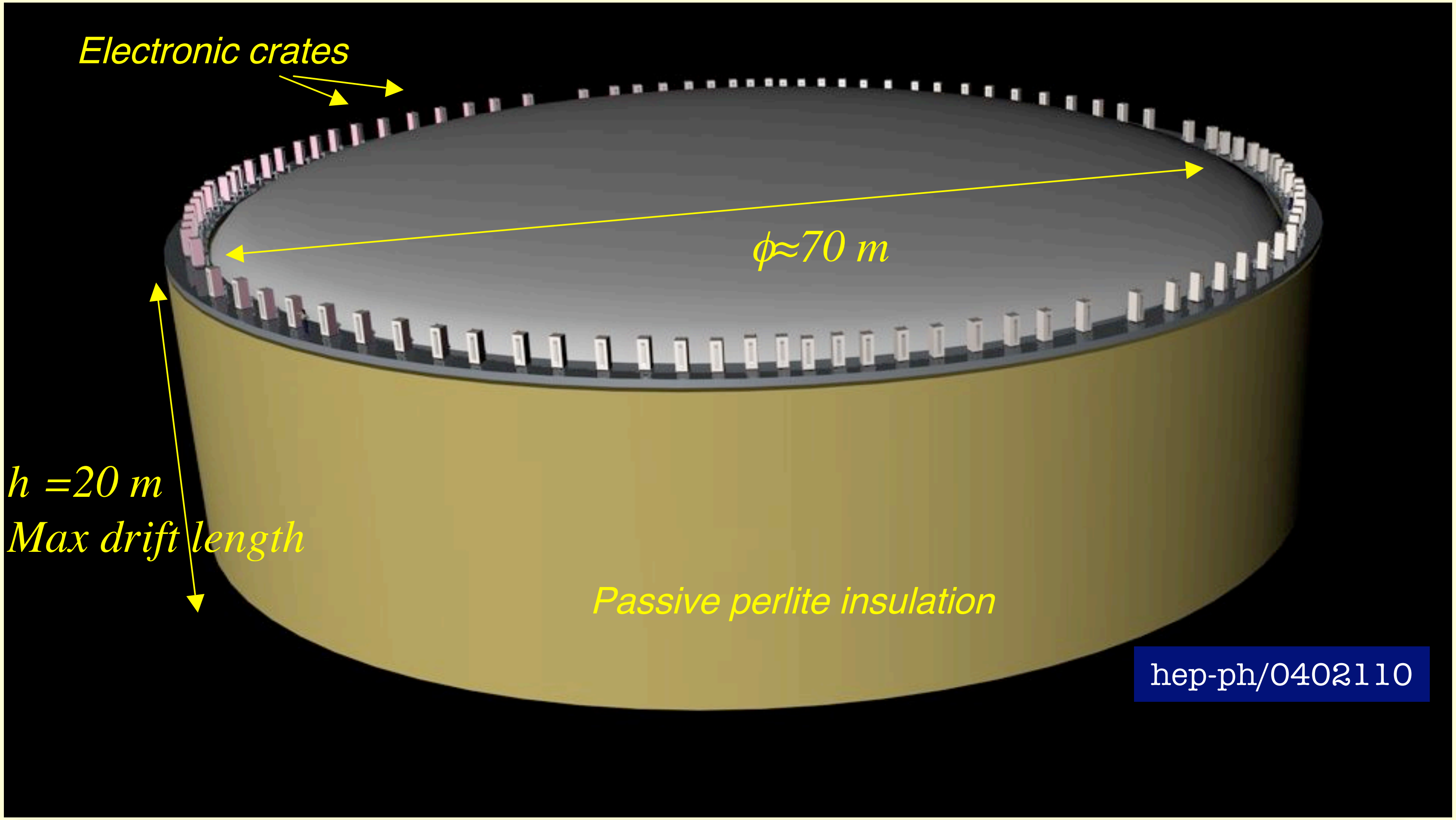
cosmic-ray shower



UV laser induced track

Conceptual design of a very large liquid Argon TPC detector

A "general-purpose" detector for Super-beams, beta-beams and neutrino factories in addition to a broad non-accelerator physics program (solar and SN ν, p-decay, atmospheric ν, …)



Single module cryo-tanker (10-100 kton of LAr) based on industrial LNG technology

	Water Cerenkov (UNO)	Liquid Argon TPC
Total mass	**650 kton**	**100 kton**
$p \to e\,\pi^0$ in 10 years	**1.6×10^{35} years** **ε = 17%, ≈ 1 BG event**	**0.5×10^{35} years** **ε = 45%, <1 BG event**
$p \to \nu\,K$ in 10 years	**0.2×10^{35} years** **ε = 8.6%, ≈ 37 BG events**	**1.1×10^{35} years** **ε = 97%, <1 BG event**
$p \to \mu\,\pi\,K$ in 10 years	**No**	**1.1×10^{35} years** **ε = 98%, <1 BG event**
SN cool off @ 10 kpc	**194000 (mostly $\bar{\nu}_e p \to e^+ n$)**	**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**

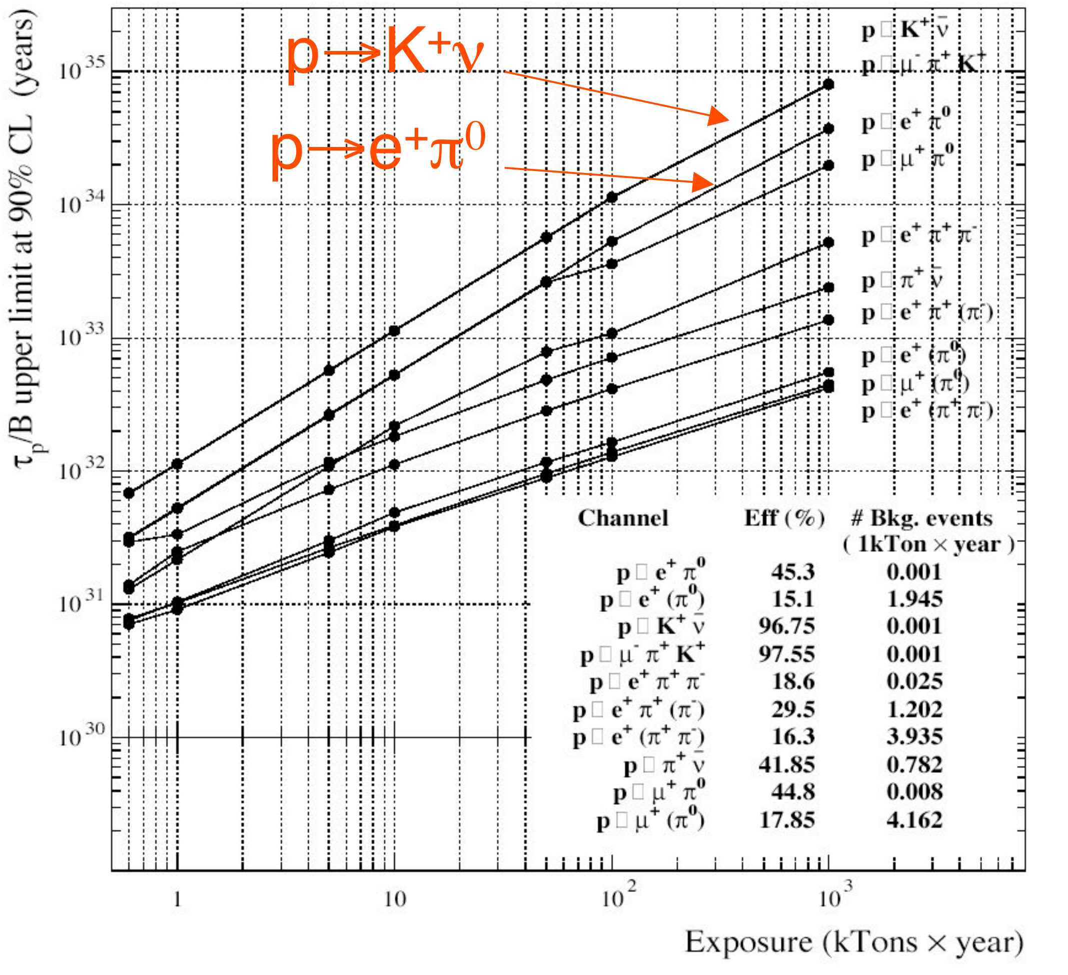
Operation of a 100 kton LAr TPC in a future neutrino facility:

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 γ=75

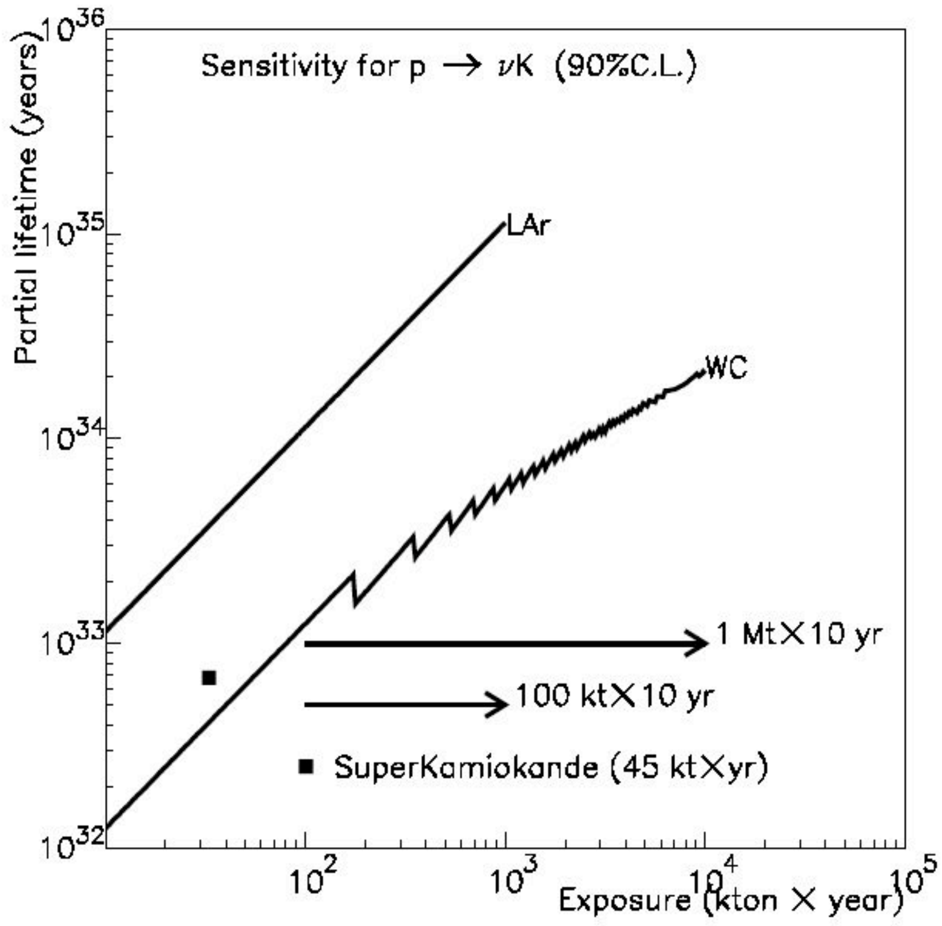
Proton decay sensitivity

Many channels accessible



Channel	Eff (%)	# Bkg. events (1kTon × year)
p□ e+ π0	45.3	0.001
p□ e+ (π0)	15.1	1.945
p□ K+ ν̄	96.75	0.001
p□ μ- π+ K+	97.55	0.001
p□ e+ π+ π-	18.6	0.025
p□ e+ π+ (π-)	29.5	1.202
p□ e+ (π+ π-)	16.3	3.935
p□ π+ ν̄	41.85	0.782
p□ μ+ π0	44.8	0.008
p□ μ+ (π0)	17.85	4.162

Complementarity

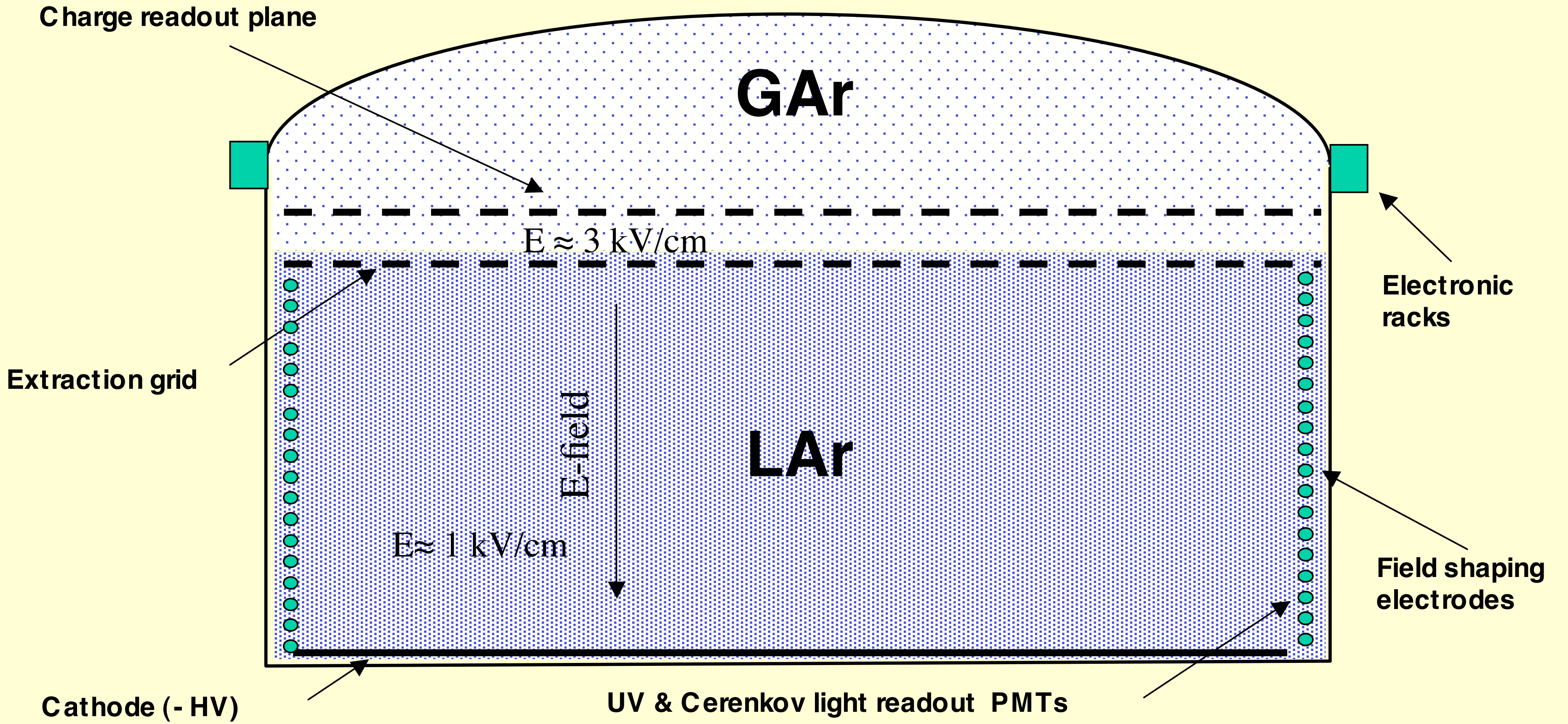


LAr TPC provides ultimate fine-grain tracking and calorimetry as necessary for proton decay searches

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



LNG = Liquefied Natural Gas

Cryogenic storage tankers for 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

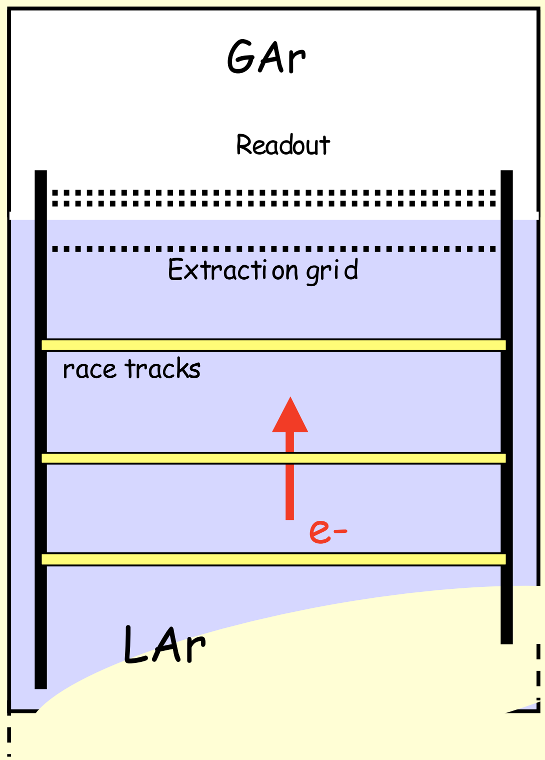
Cooling by "auto-refrigeration"

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 m.i.p. 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 cm^2/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 m^2**



Work in progress: laboratory measurements, studies on specific technical issues, detector optimization, collaboration with industry on infrastructure and equipments,…

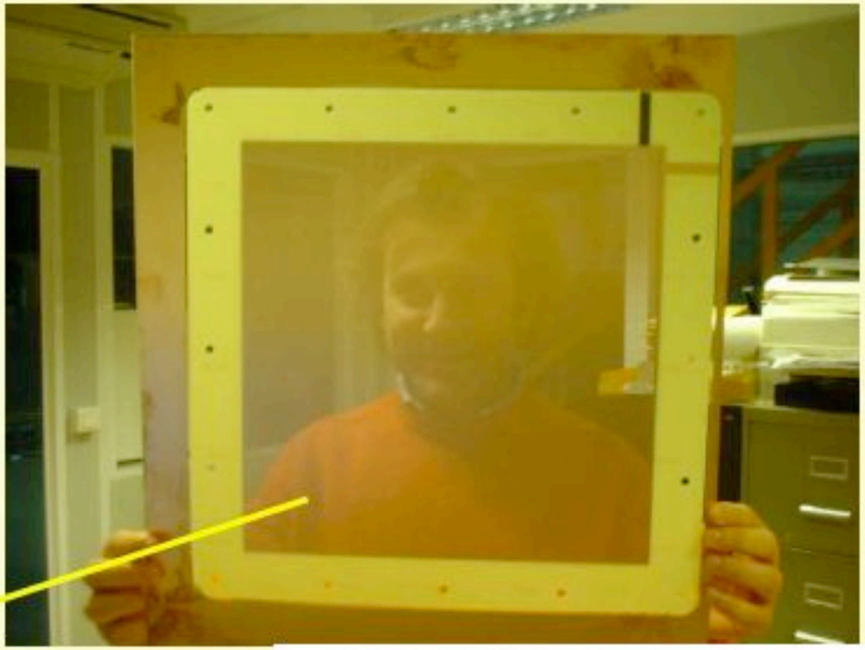
- **Study of suitable charge extraction, amplification and imaging devices**
- **Improved method for HV supply**
- **Understanding of charge drift properties under high hydrostatic pressure**
- **Study of LAr TPC prototypes immersed in a magnetic field**
- **Realization and test of a 5 m long detector column-like prototype**
- **Engineering study of large liquid underground storage tank**
- **Study of logistics, infrastructure and safety issues for underground sites**

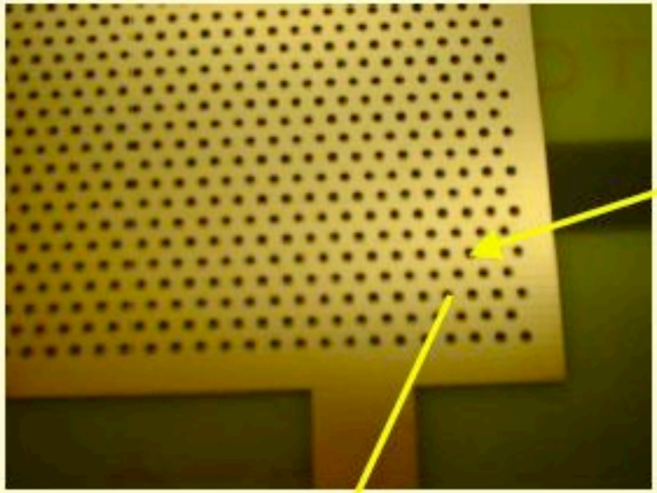
Thick Large Electron Multiplier (LEM)

Thick-LEM (vetronite Cu coated + holes)

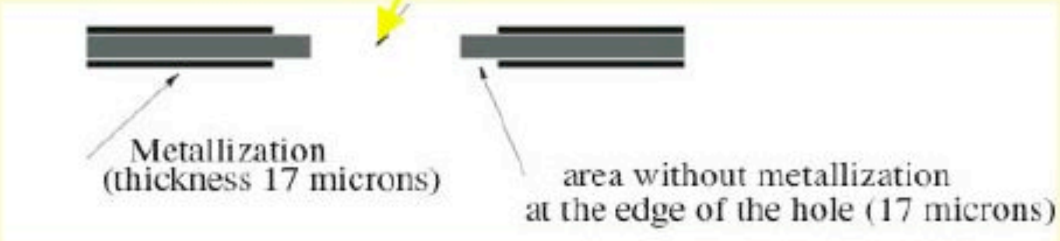
Sort of macroscopic GEM

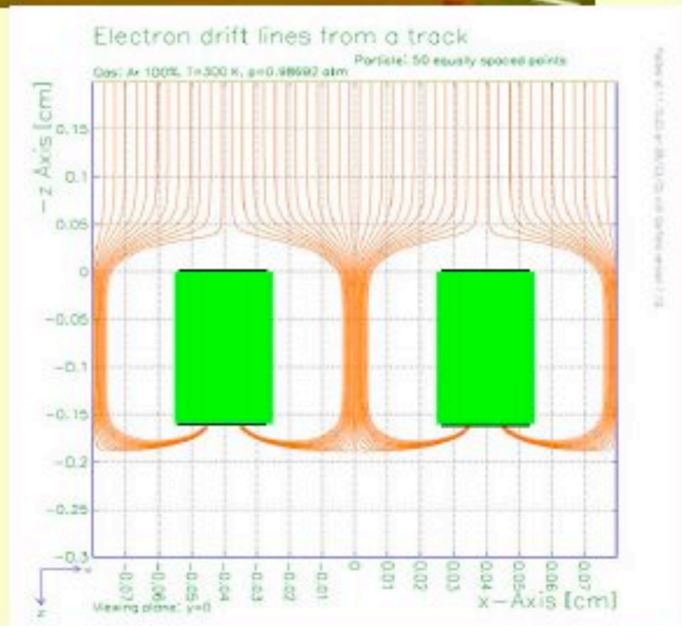
A priori more easy to operate at cryogenic temperature





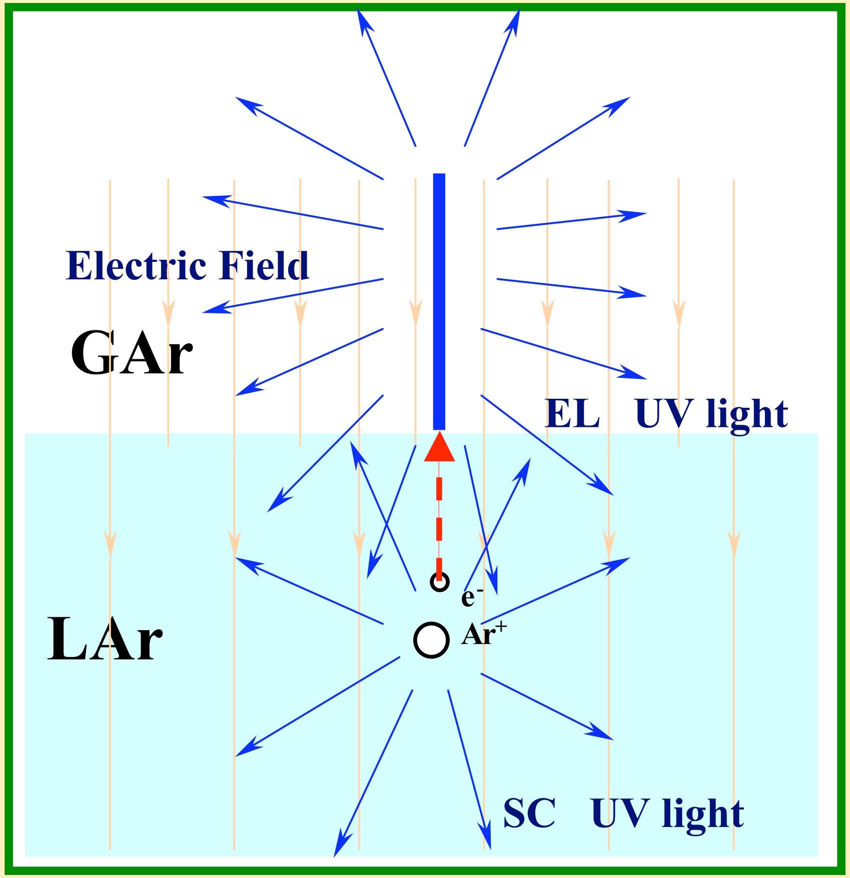
- Three thicknesses: 1, 1.6 and 2.4 mm
- Amplification hole diameter = 500 μm





Electron extraction in LAr double-phase

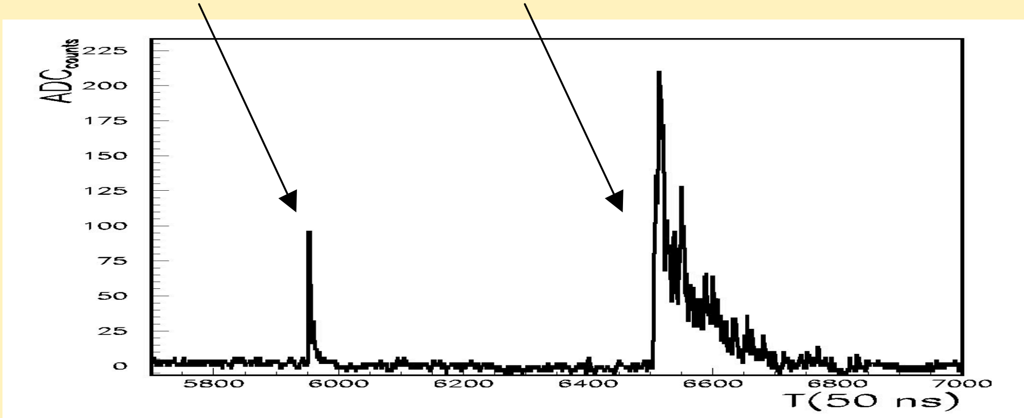
Particle produces excitation (Ar*) and ionization (Ar⁺, e)

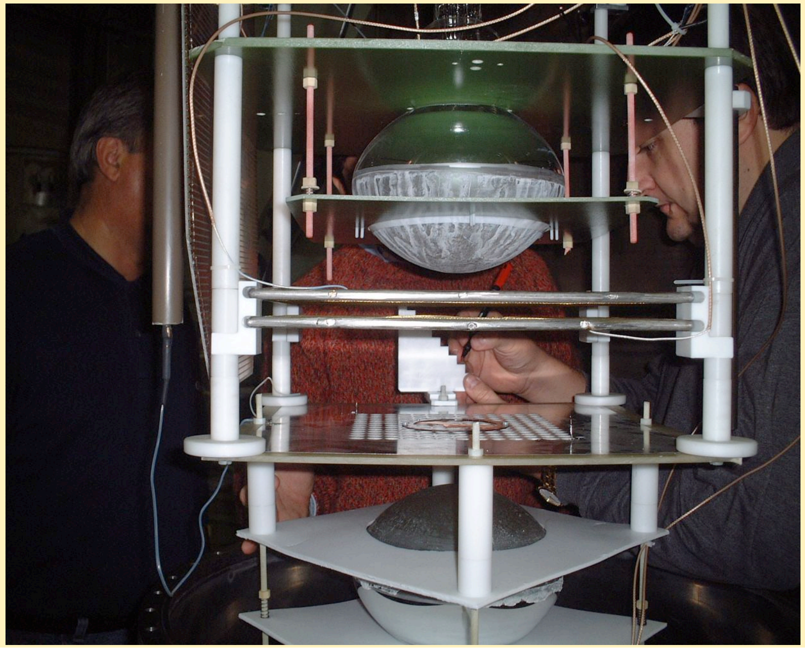


Both SC and EL can be detected by the same photo-detector

Scintillation SC is a result of direct excitation and recombination

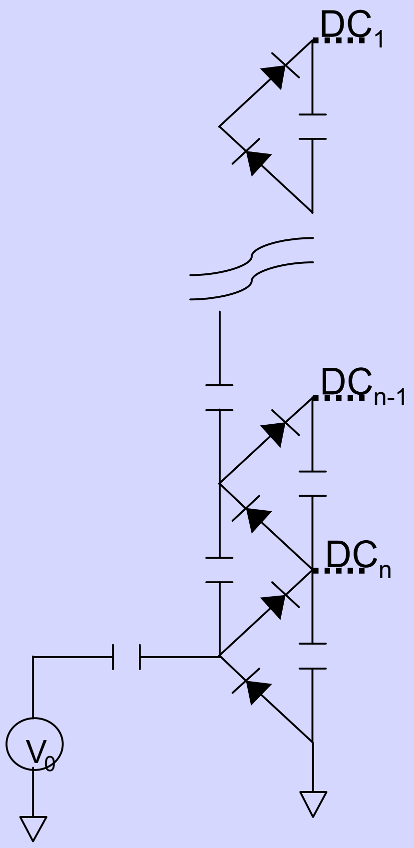
Electro-luminescence EL (proportional scintillation) is a result of electron acceleration in the gas



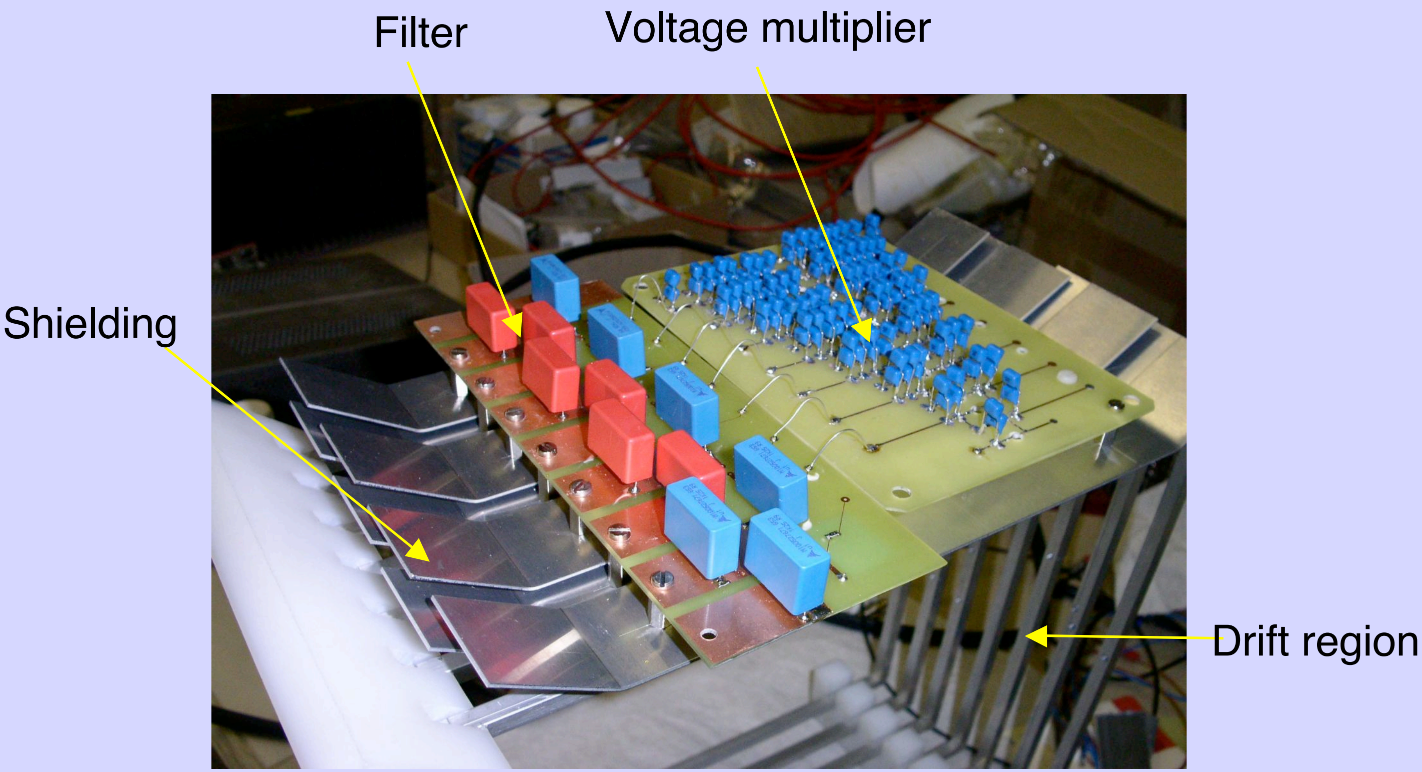


Drift very high voltage: Greinacher circuit

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

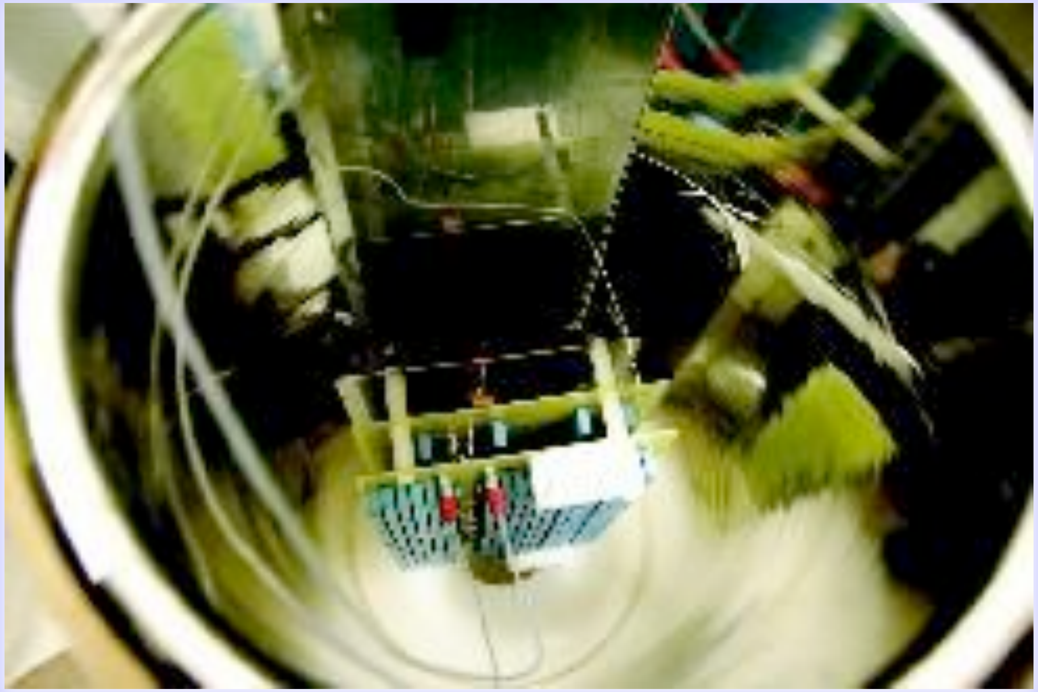


Greinacher or Cockroft/Walton voltage multiplier

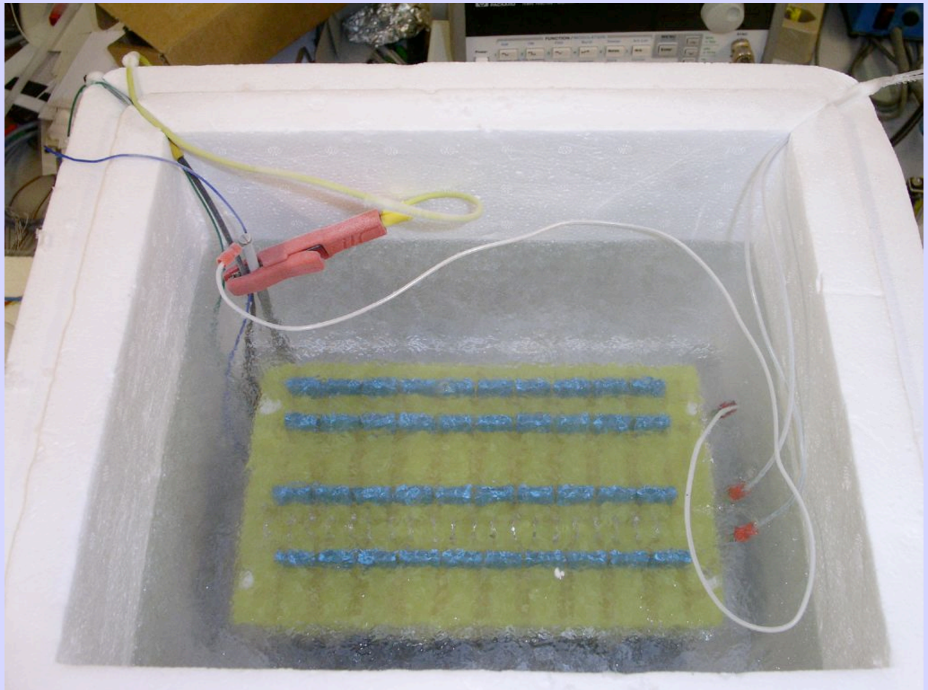


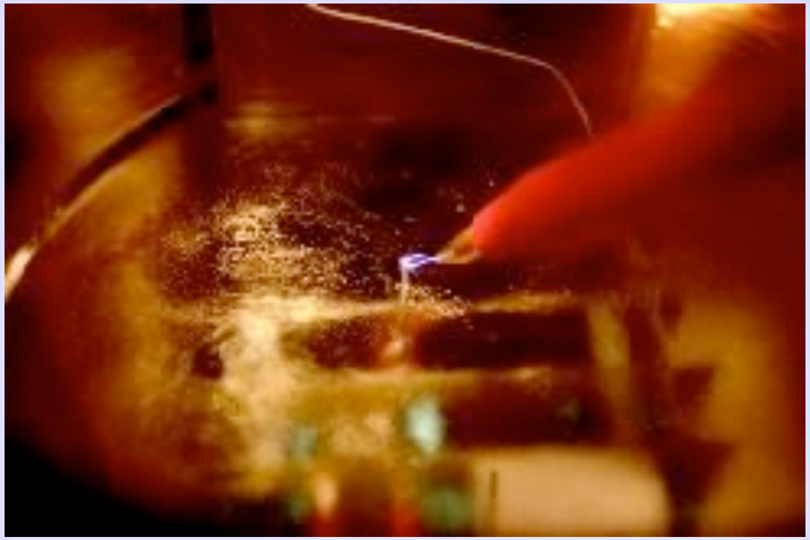
Prototype connected to actual electrodes of 50 liter TPC (ripple noise test) Successfully tested up to 20kV

Drift very high voltage: 40 kV multiplier in LAr



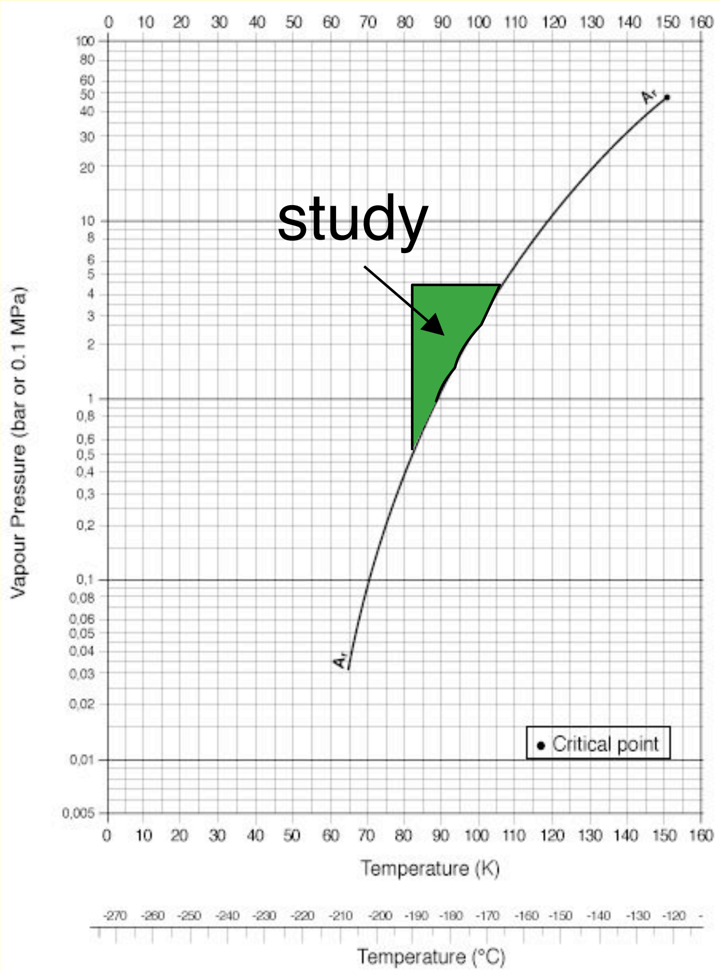
NOVACAP NP0 dielectric capacitors, stable in temperature and against discharge.
HV diodes from Vishay/Phillips

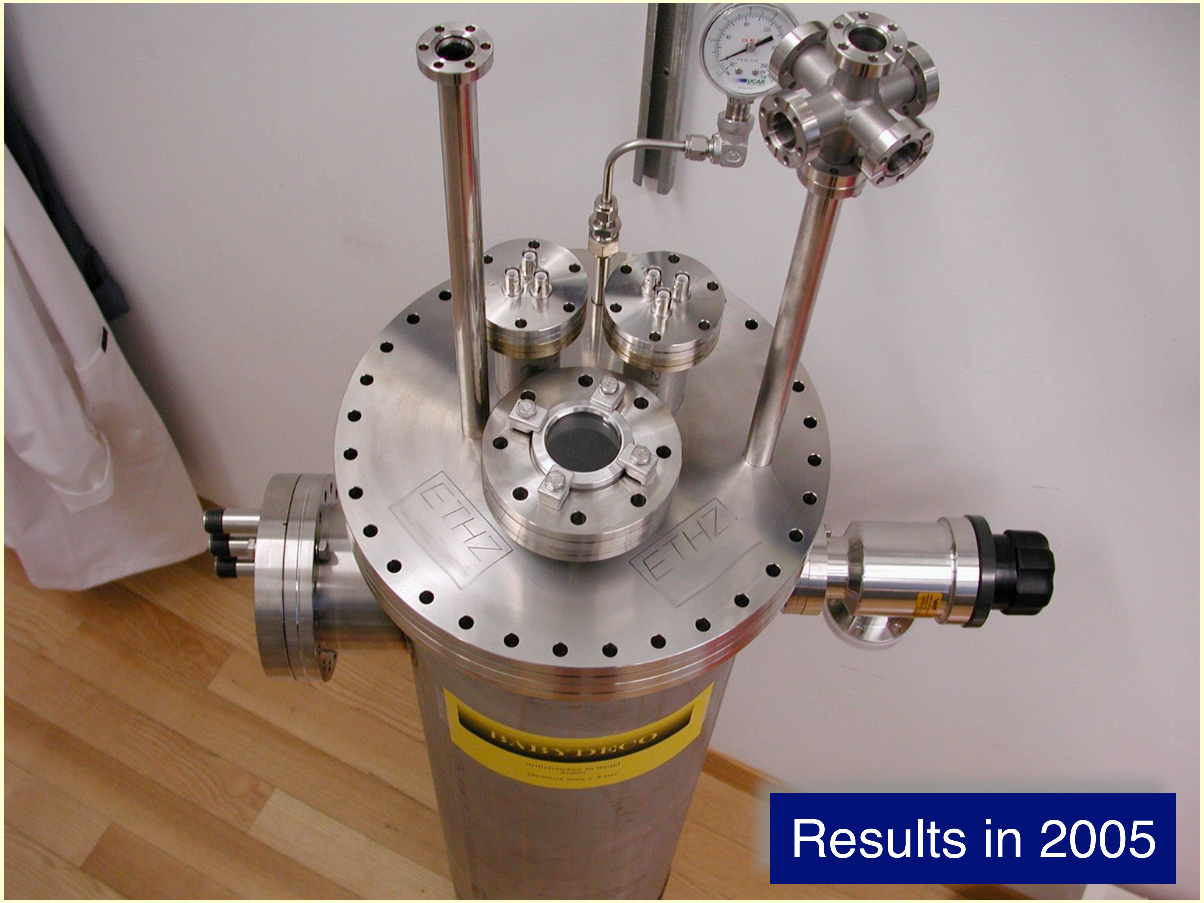




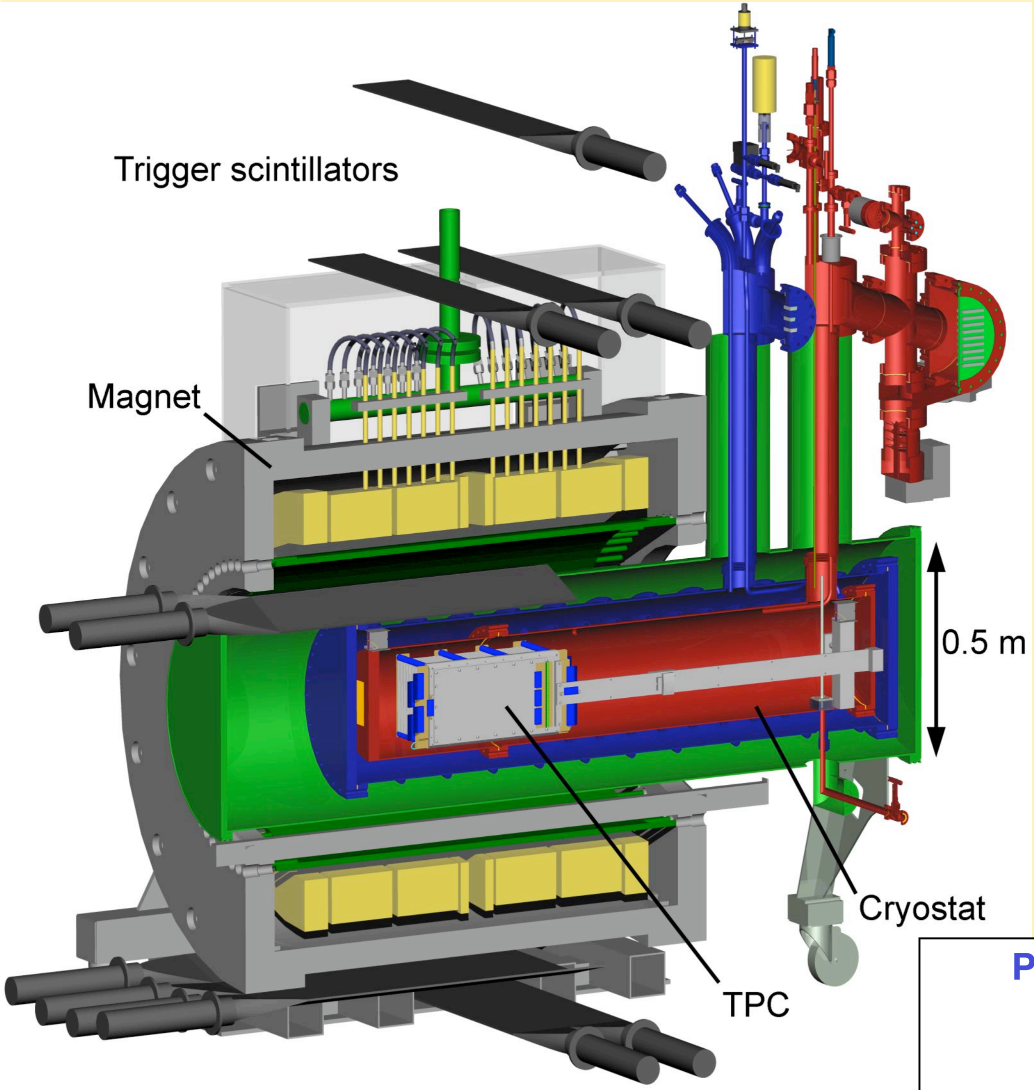
High-pressure drift properties in liquid Argon

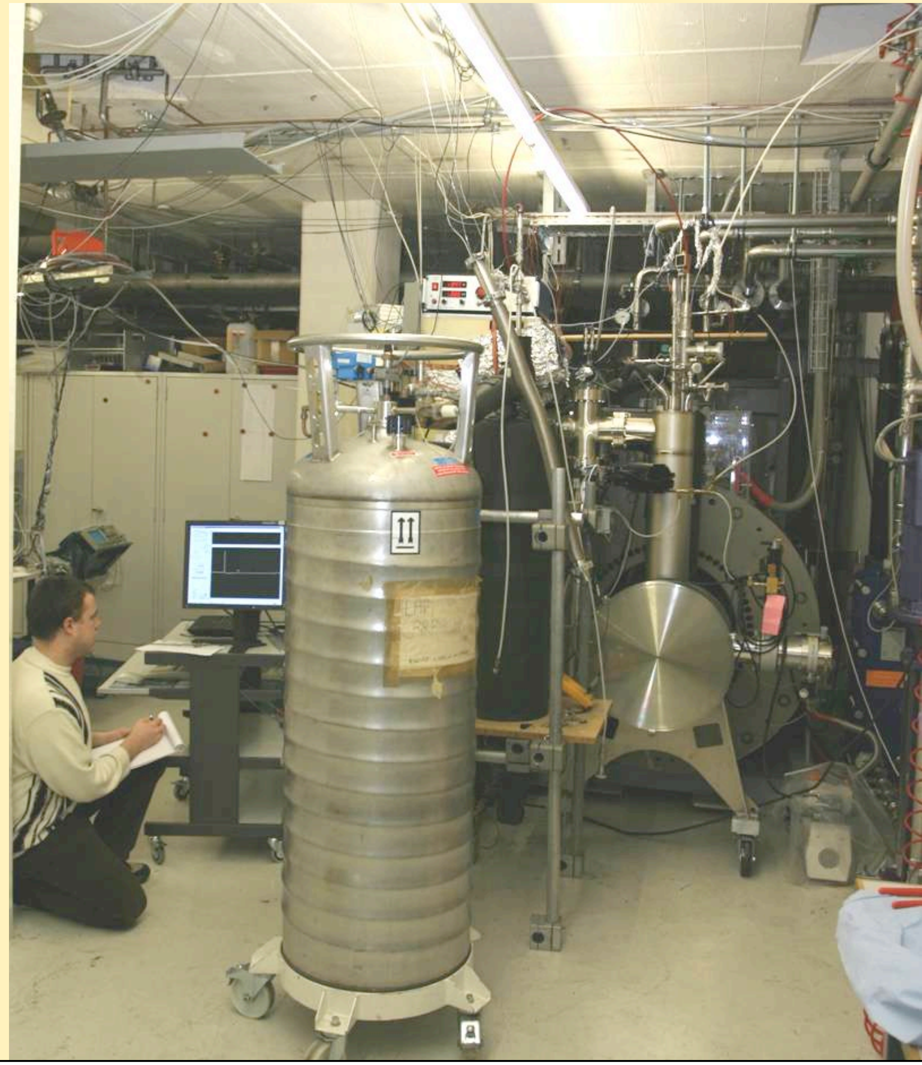
- **At the bottom of the large LAr tankers:**
  hydrostatic pressure could be quite significant (up to 3-4 atmosphere)
- **Test of electron drift properties in high pressure liquid Argon**
  understand electron drift and imaging properties under pressure above equilibrium vapor pressure





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

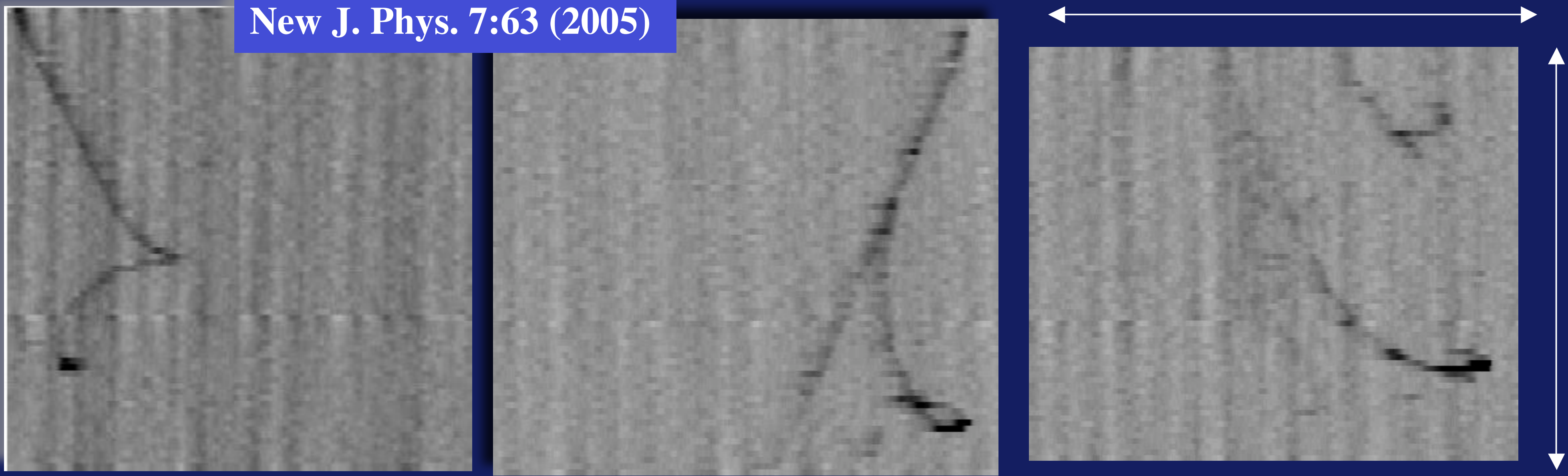




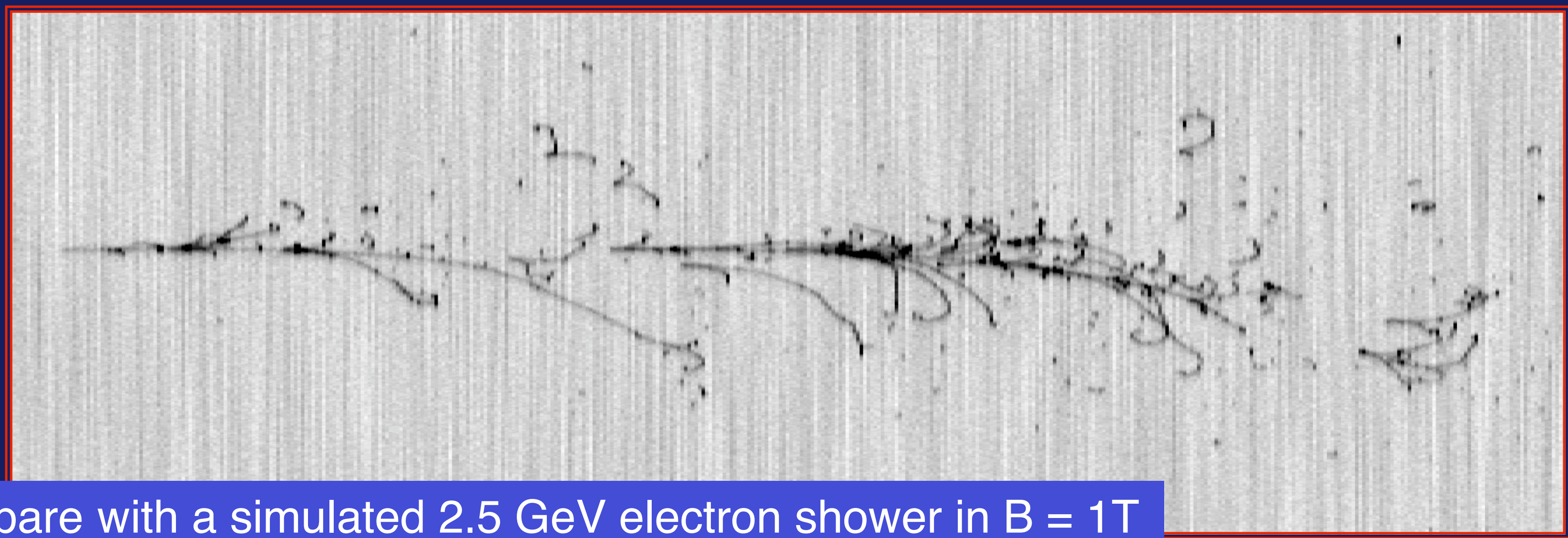
Prototype chamber magnetic field; test program:

- ➥ 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)

Cosmic-ray events in magnetic field (B=0.55 T)

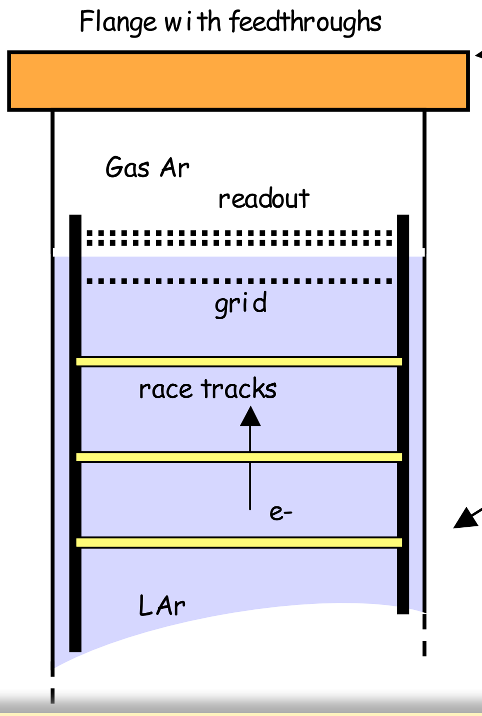


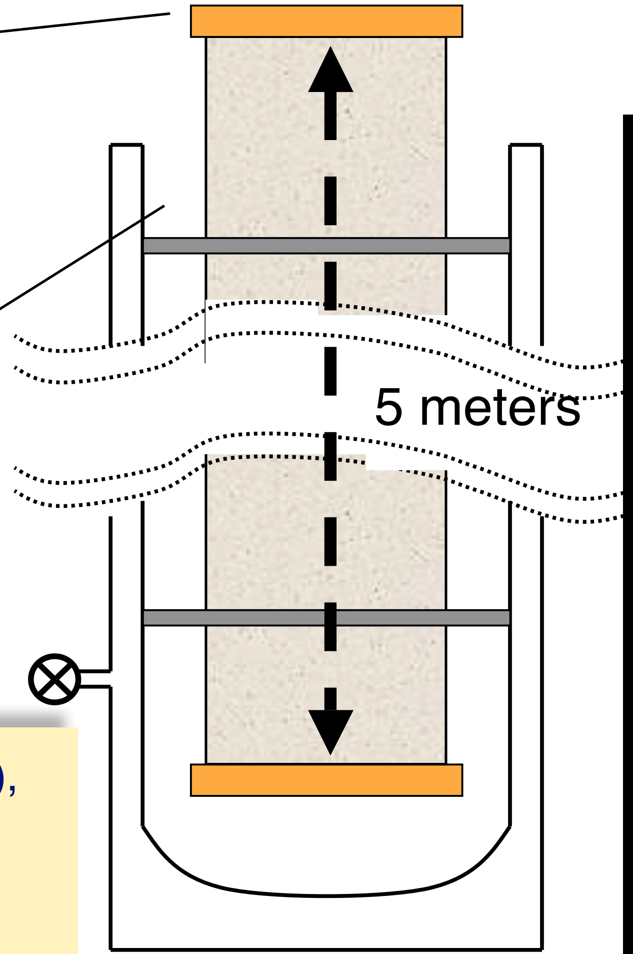
New J. Phys. 7:63 (2005)

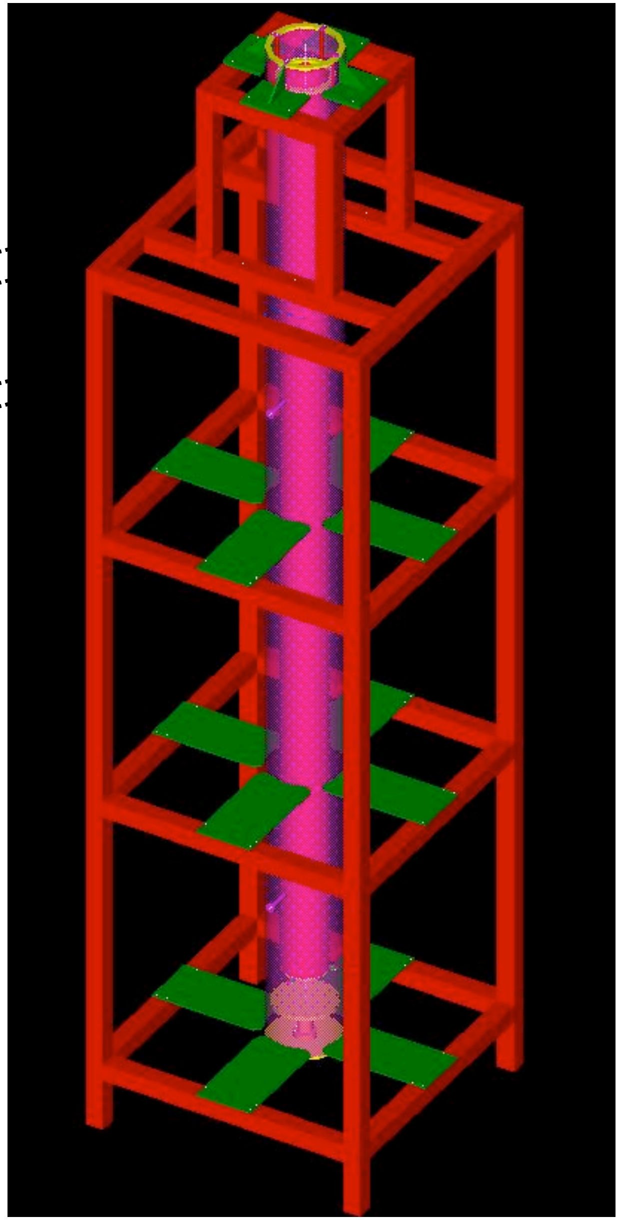


compare with a simulated 2.5 GeV electron shower in B = 1T

Long drift, extraction, amplification: test module



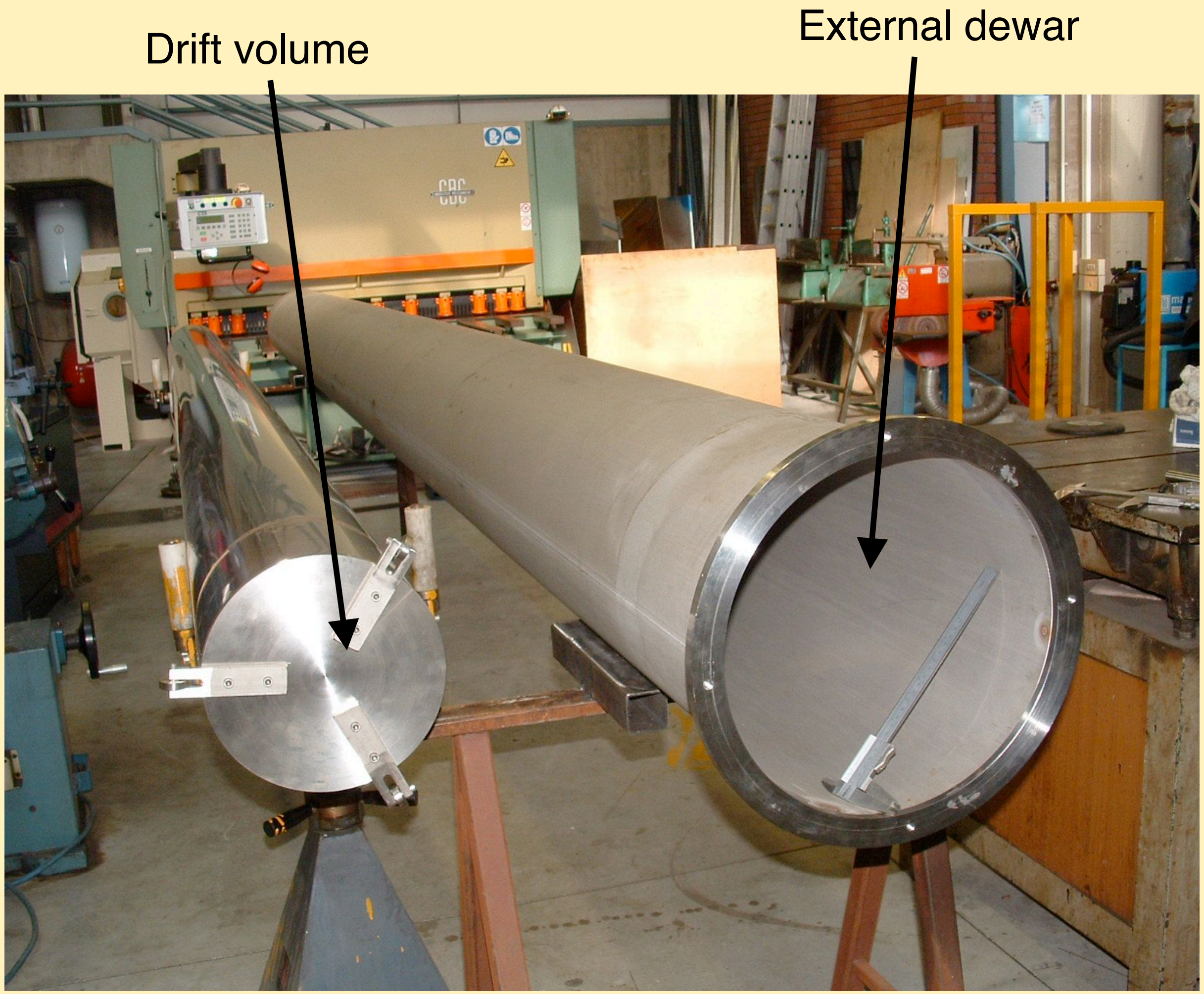




- Full scale measurement of long drift (5 m), signal attenuation and multiplication
- Simulate ‘very long’ drift (10-20 m) by reduced E field & LAr purity
- High voltage test (up to 500 kV)
- Design & assembly:

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

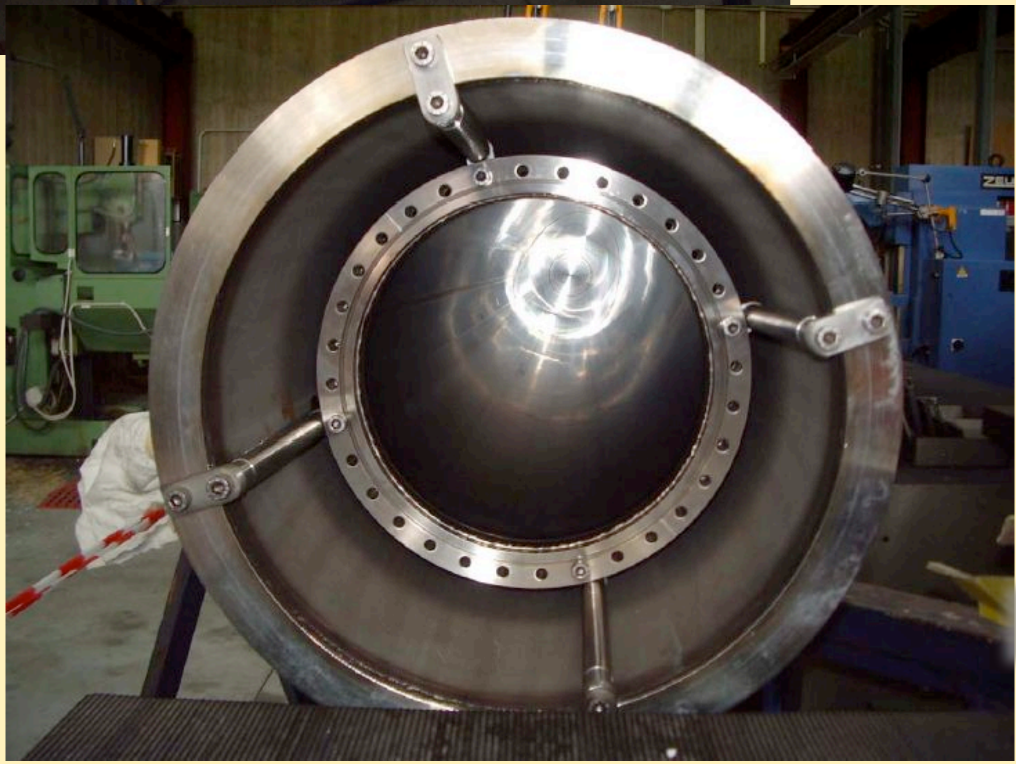
Results in 2006



Inner diameter 250 mm, drift length 5000 mm
drift HV up to 500 kV

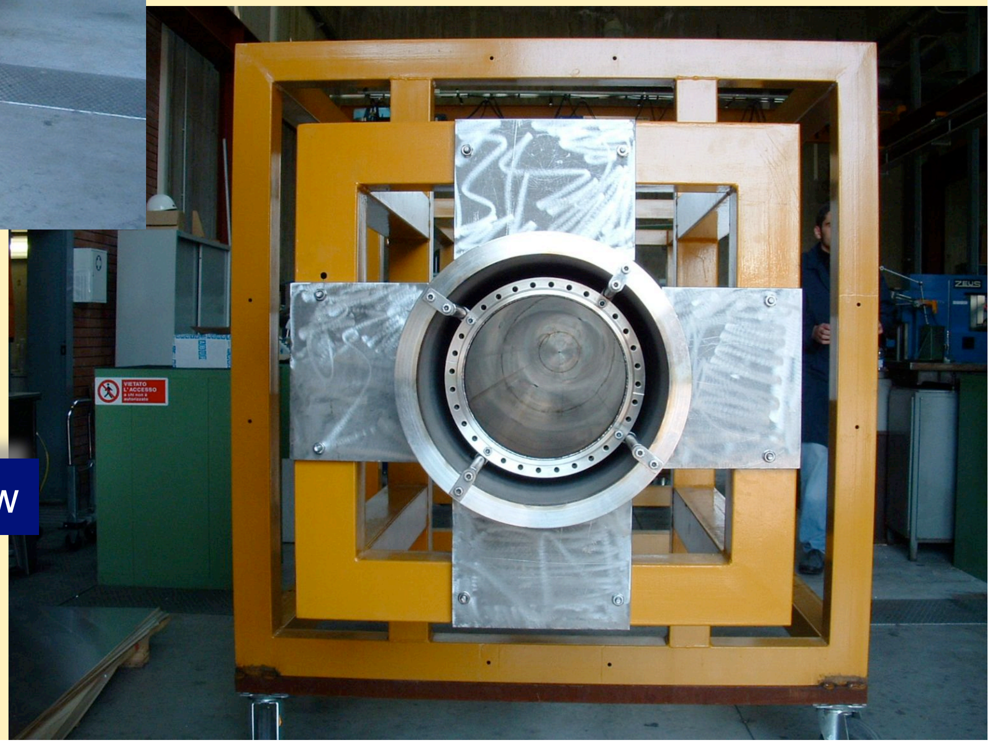
Vacuum leak tests

Super-insulation



Assembled detector

Detector in the support structure (horizontal garage position)



Front view

Engineering of large underground storage tank

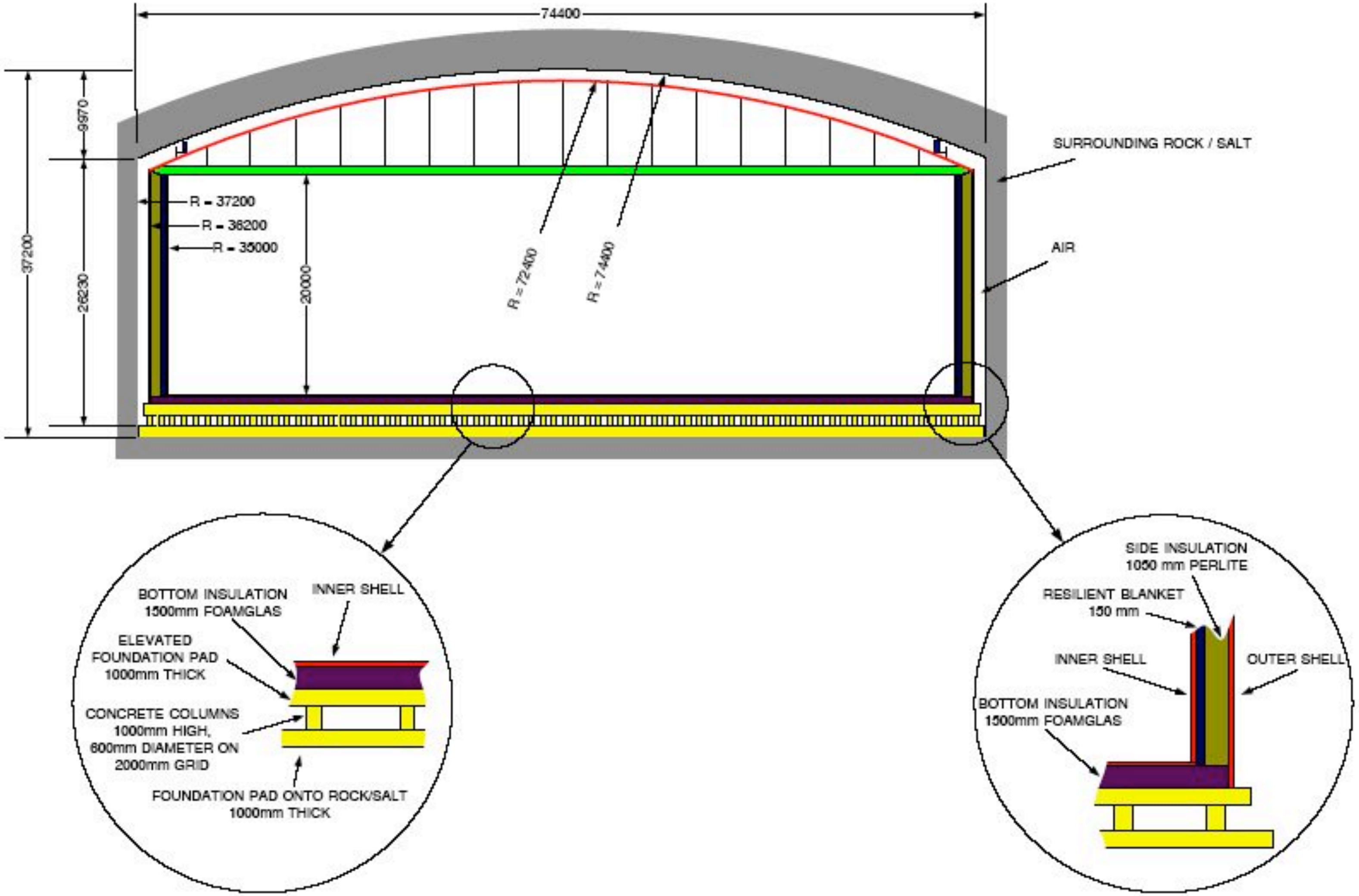
	Project: Large Underground Argon Storage Tank
Issued By: JMH	Document Title
Date:	

A feasibility study mandated to Technodyne LtD (UK)

Study duration:

February - December 2004

Technodyne baseline design



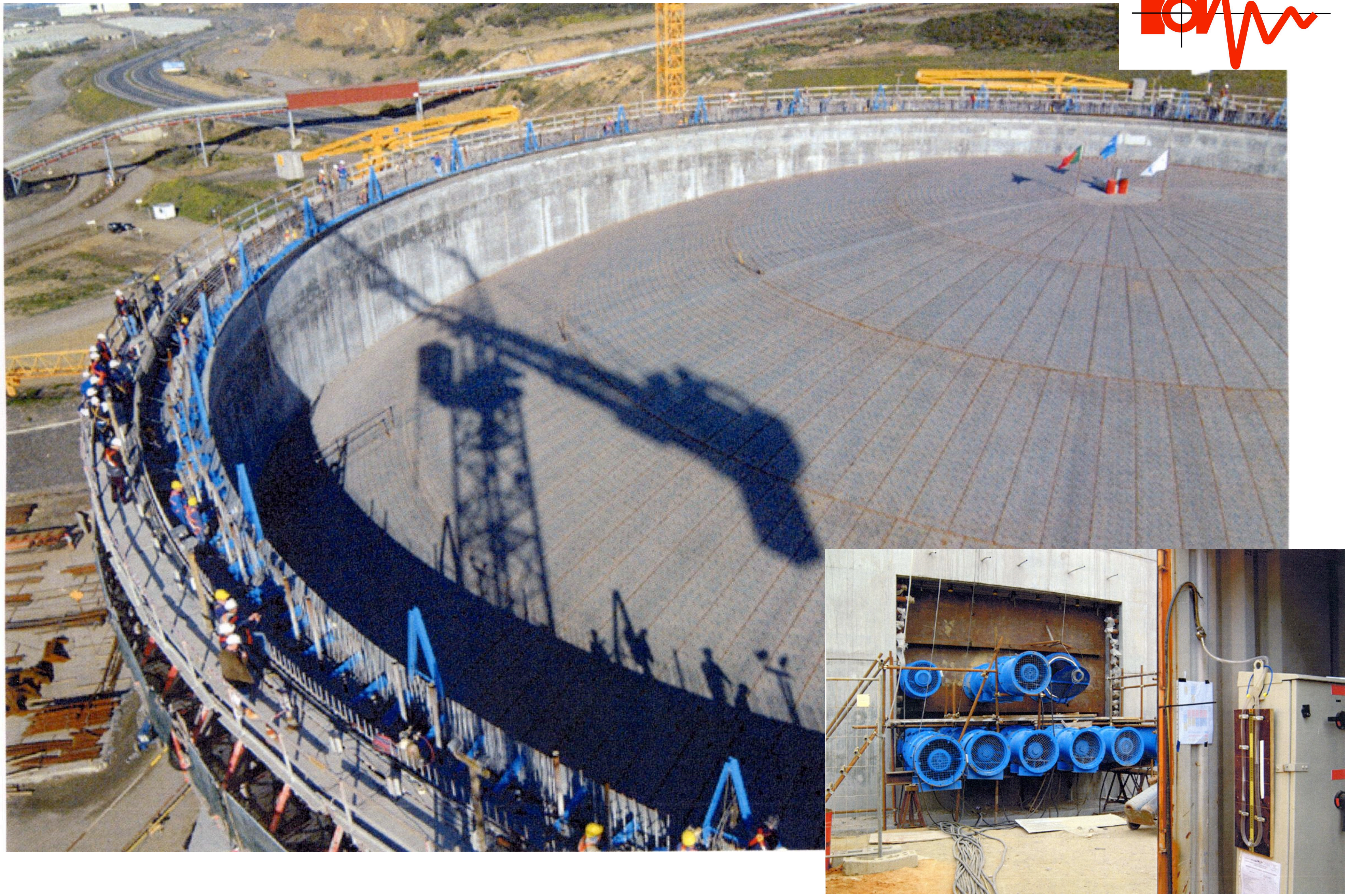
NOT TO SCALE

A dream come true? (A) Concrete base

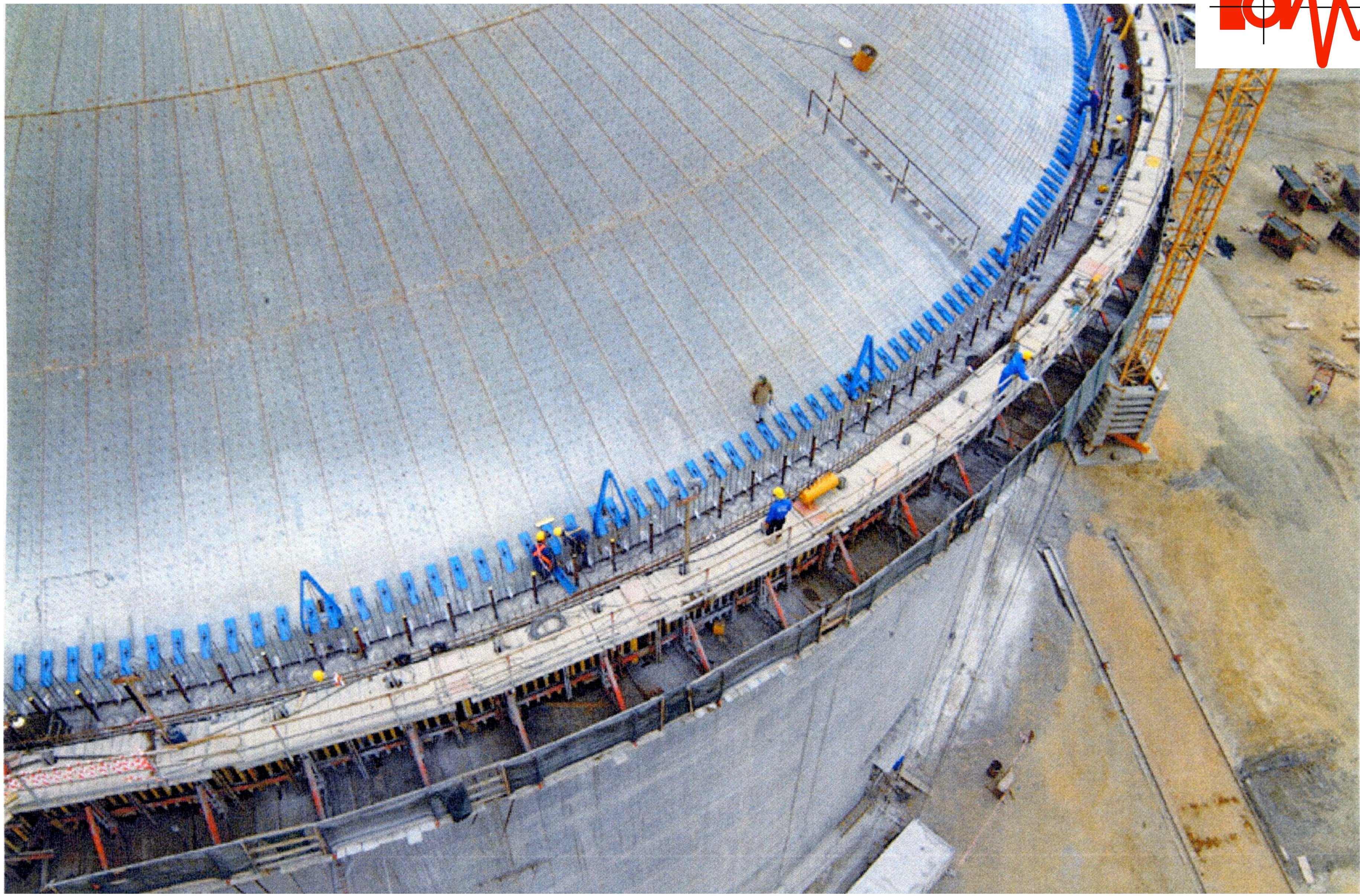
(B) Construction of the concrete outer-shell

(C) Roof construction (inside tank)

(D) Air-raising of the roof

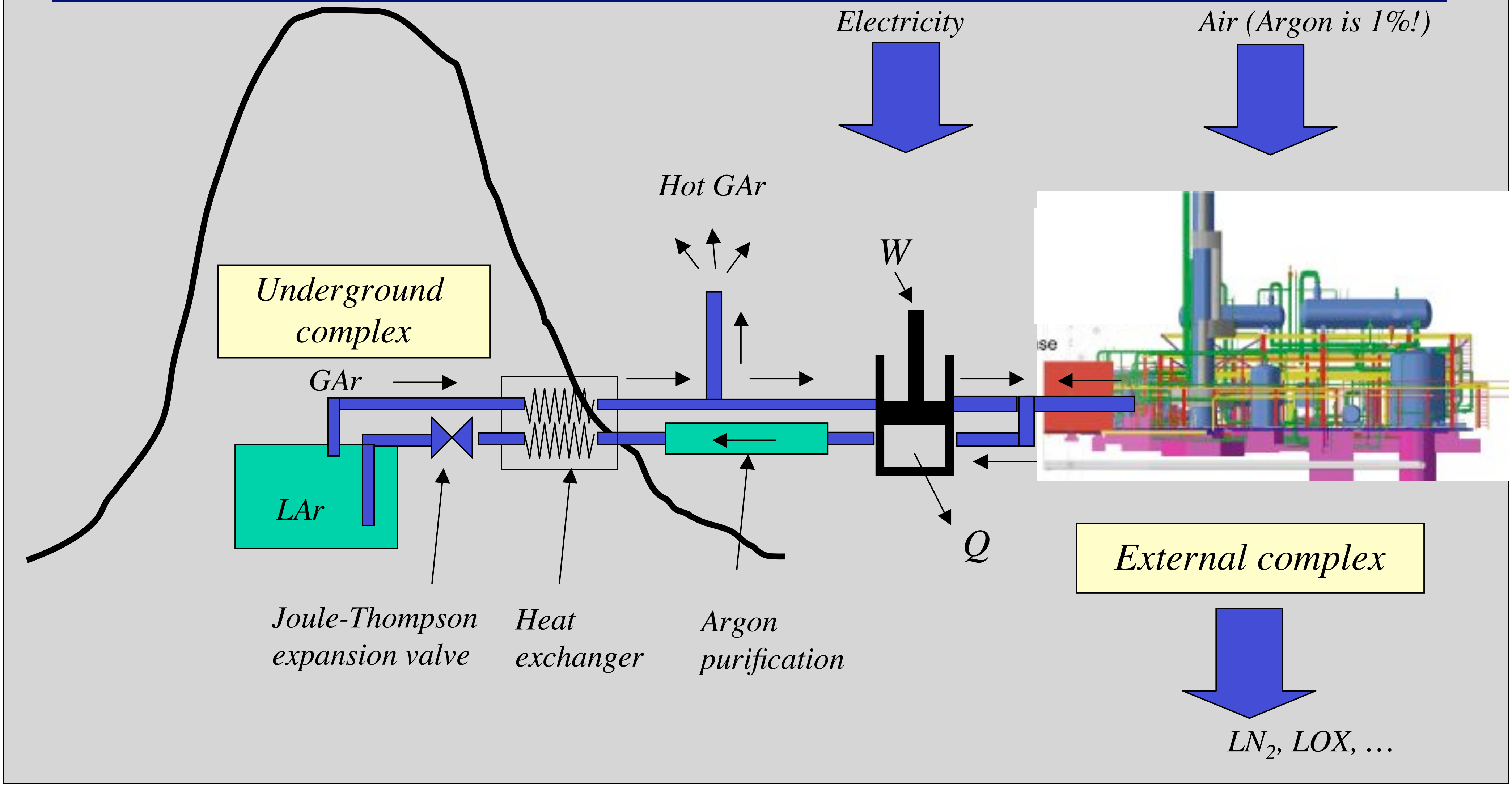


(E) Roof welding



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)

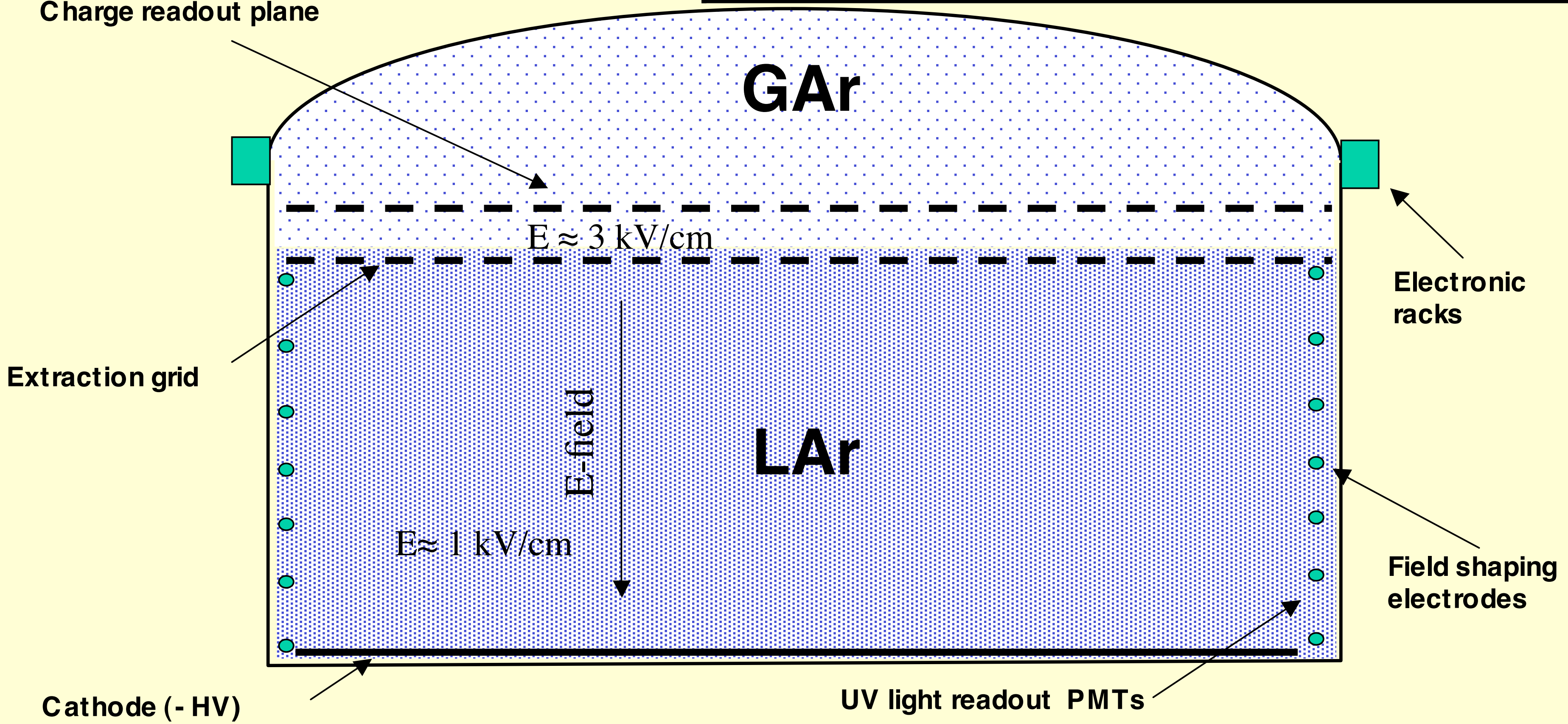


10 kton 'prototype'

- 10% full-scale prototype
- **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



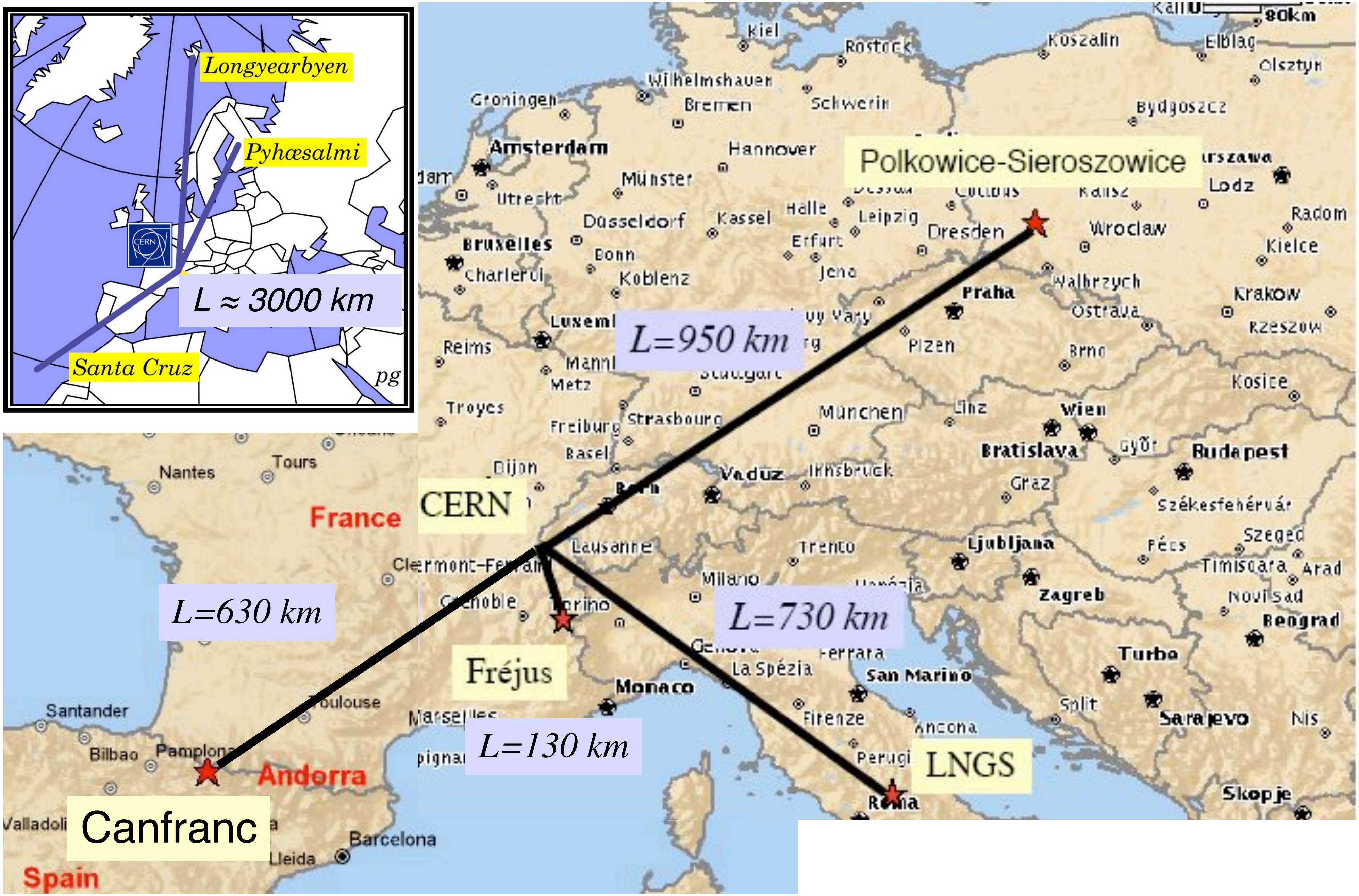
~ 7000 m^3 cryogenic tanker (without outer shell)

Approximate cost estimate in MEuro : 100 & 10 kton

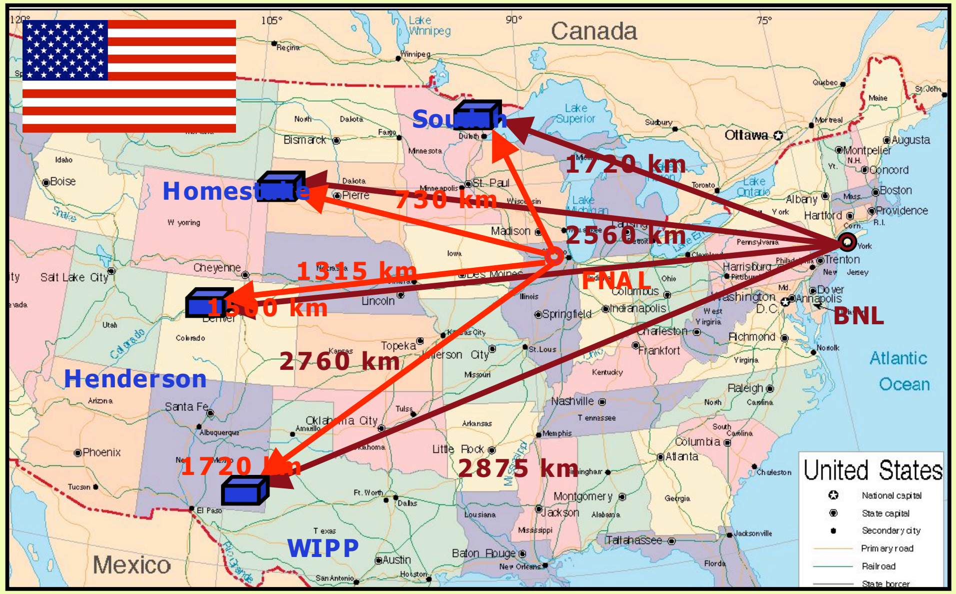
Detector	100 kton	10 kton
LNG tanker (see notes 1-2)	50÷100	20 ÷ 30
Merchant cost of LAr (see note 3)	100	10
Refilling plant	25	10
Purification system	10	2
Civil engineering + excavation	30	5
Forced air ventilation	10	5
Safety system	10	5
Inner detector mechanics	10	3
Charge readout detectors	15	5
Light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

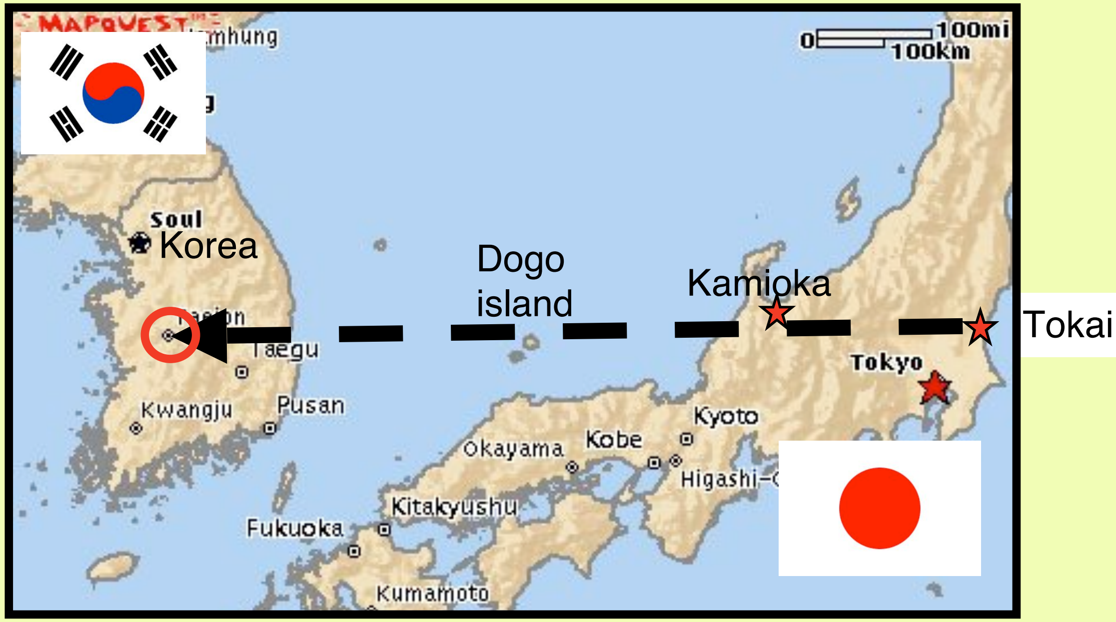
Notes:
(1) Range in cost of tanker comes from site-dependence and current uncertainty in underground construction
(2) Cost of tanker already includes necessary features for LAr TPC (surface electro-polishing, hard roof for instrumentation, feed-throughs,…)
(3) LAr merchant cost ≠ production cost. Fraction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

Possible underground sites in Europe ?



Non-European sites for very large liquid Argon TPC

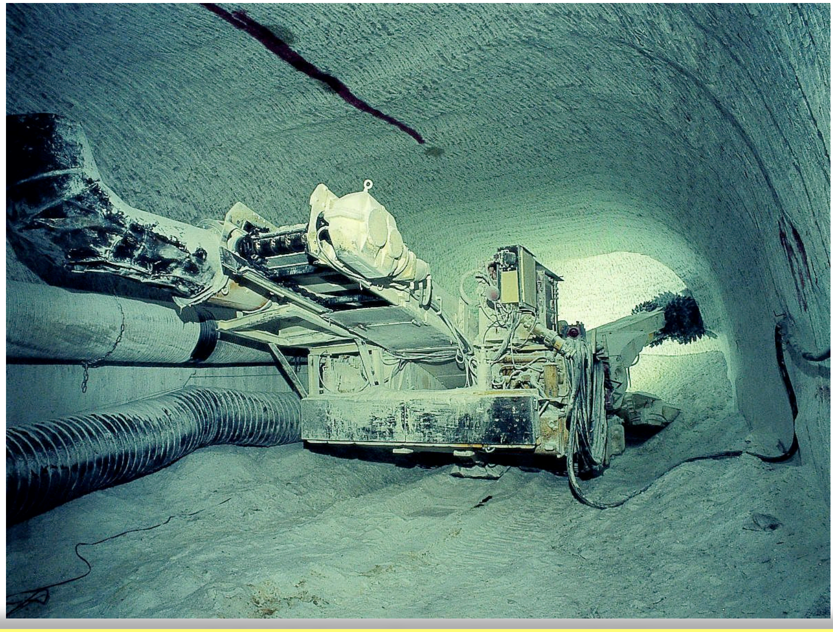




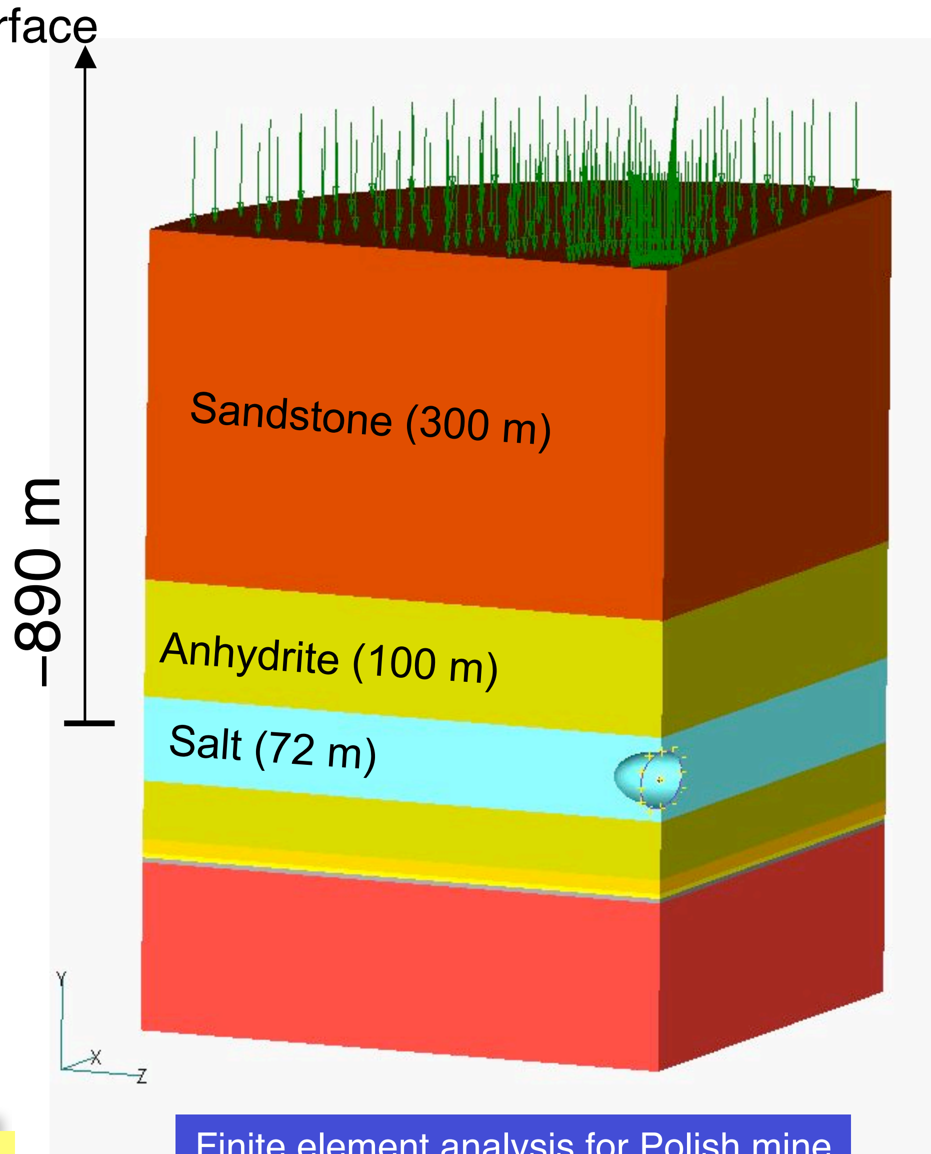
Liquid Argon TPC provides high efficiency for a broad energy range: flexibility in L & E choice

Example: Sieroszowice salt mines

- Geophysical instabilities limit the size of the underground cavern
- Actual size limits depend on details of rock and depth and on the wished cavern geometry
- Contact with Mining and Metallurgy department (Krakow University) and with mining companies (A. Zalewska)
- Finite element analysis calculation for Polish mine (courtesy of Witold Pytel, CBPM "Cuprum" OBR, Wroclaw)



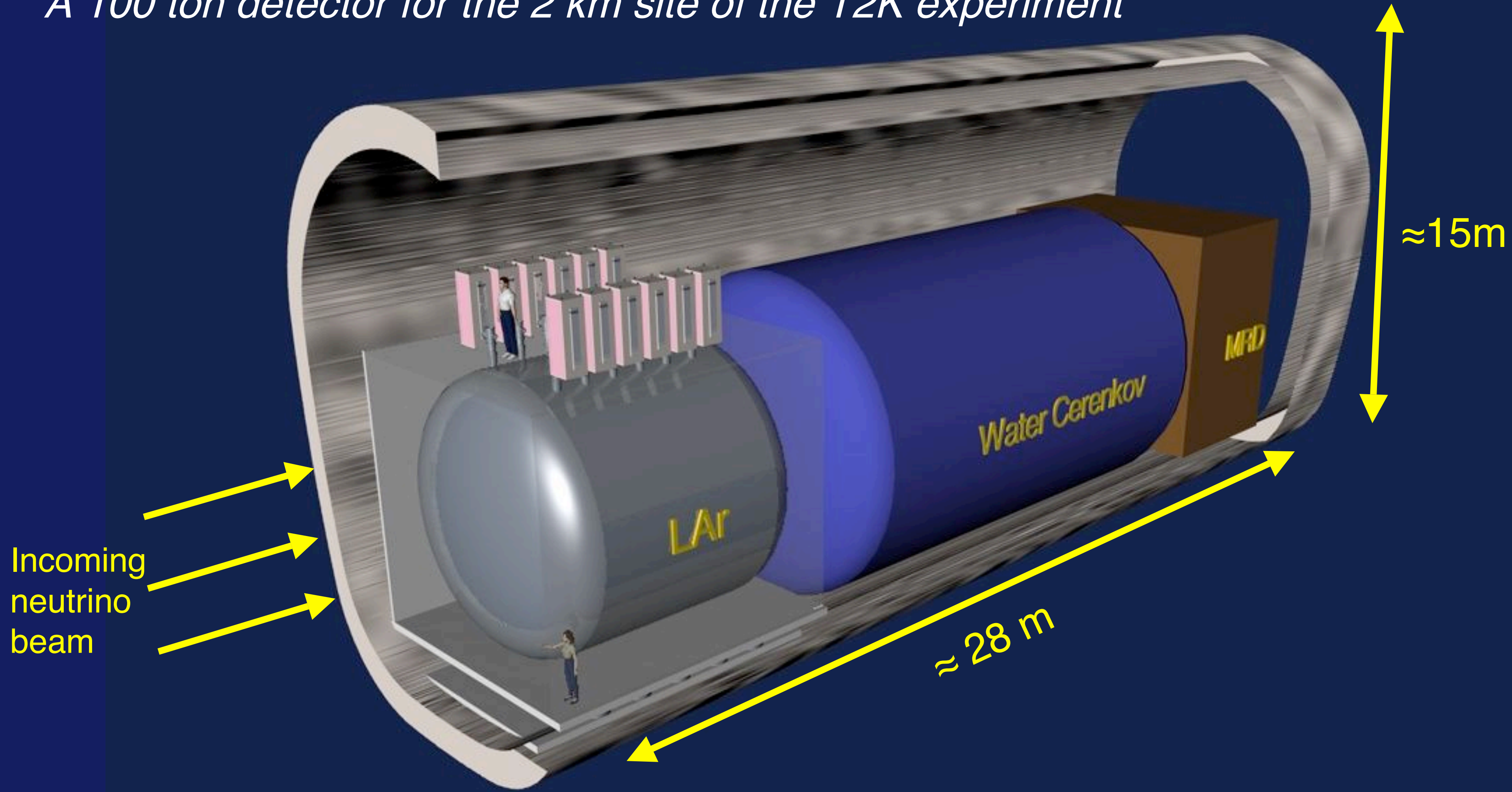
cavern ≈ 100000 m^3 or tunnel-like geometry



Finite element analysis for Polish mine

Next-to-come application of the LAr TPC technique ?

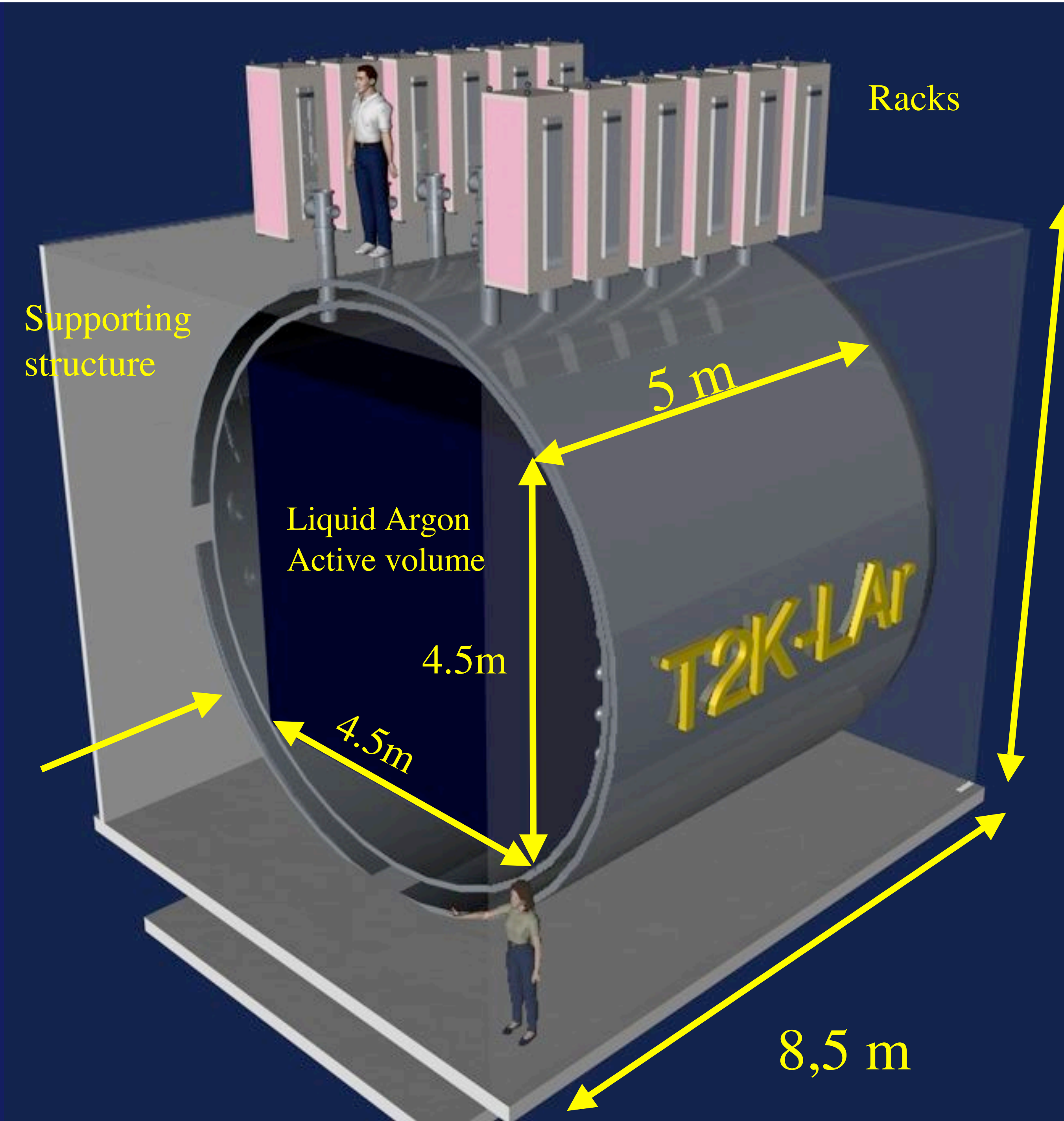
A 100 ton detector for the 2 km site of the T2K experiment



EoI from 25 groups for a detector complex at the intermediate site (EU, Japan, USA)

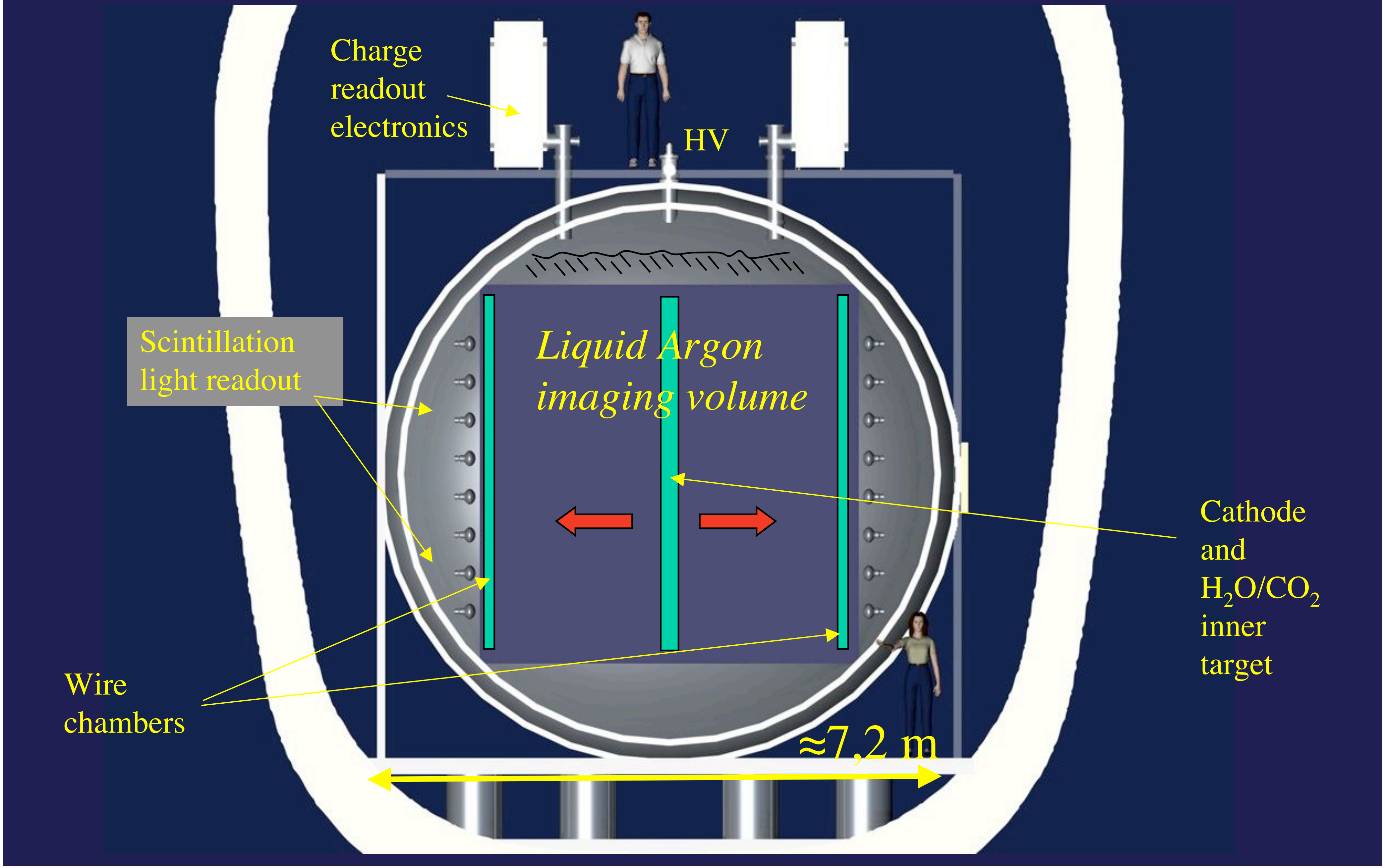
http://www.phy.duke.edu/~cwalter/nusag-members/2km-proposal-05-05-20.pdf

Side view



Racks
Supporting structure
5 m
Liquid Argon
Active volume
4.5m
4.5m
T2K-LAr
7,2 m
8,5 m

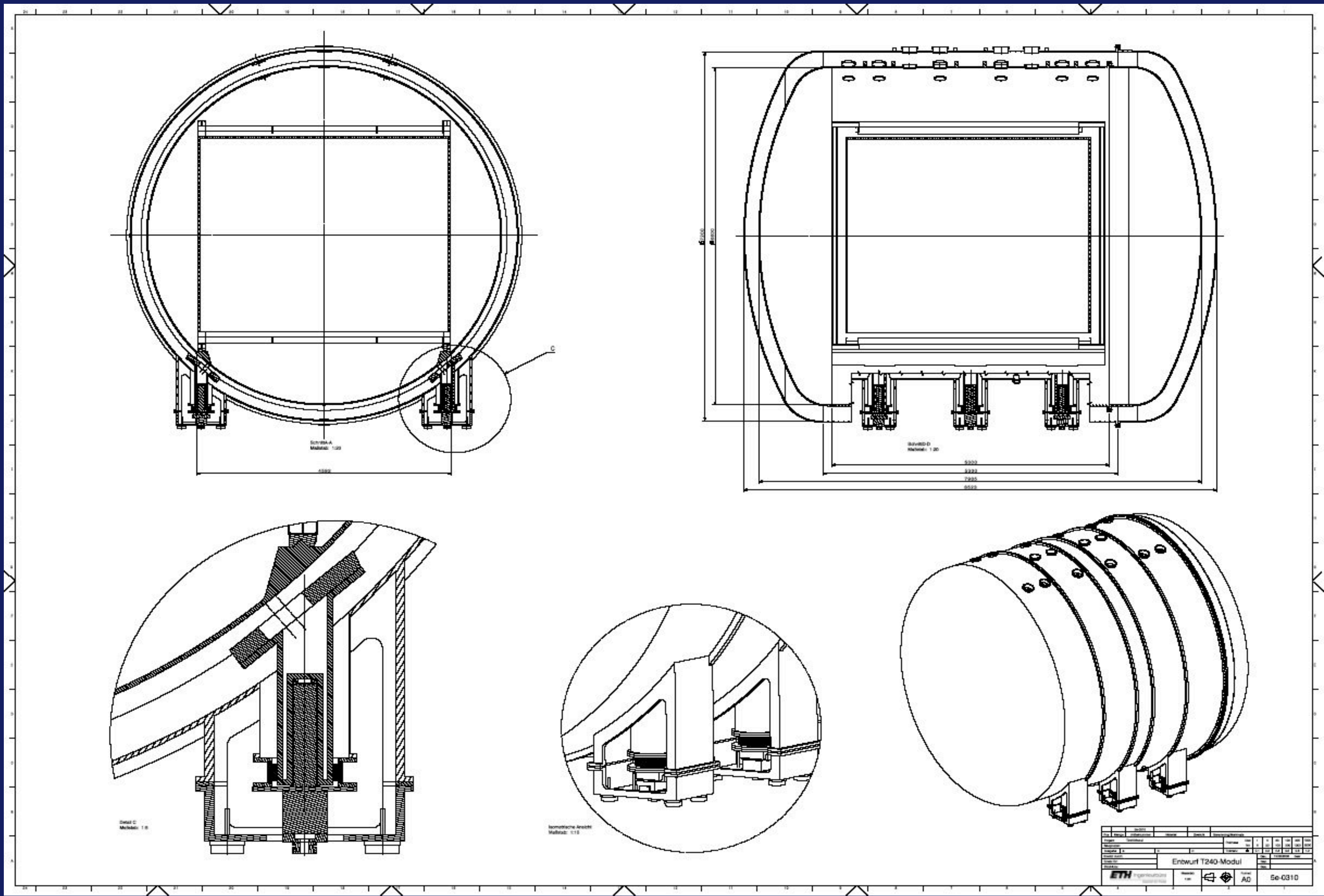
Front view



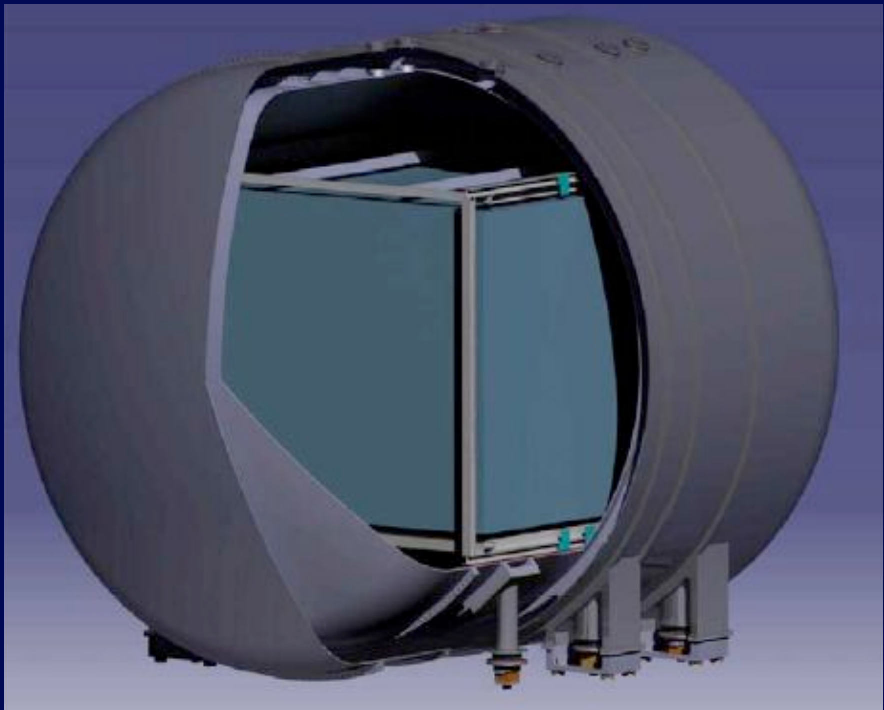
Charge readout electronics
HV
Scintillation light readout
Liquid Argon imaging volume
Cathode and H_2O/CO_2 inner target
Wire chambers
≈7,2 m

Engineering design of cryostat

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

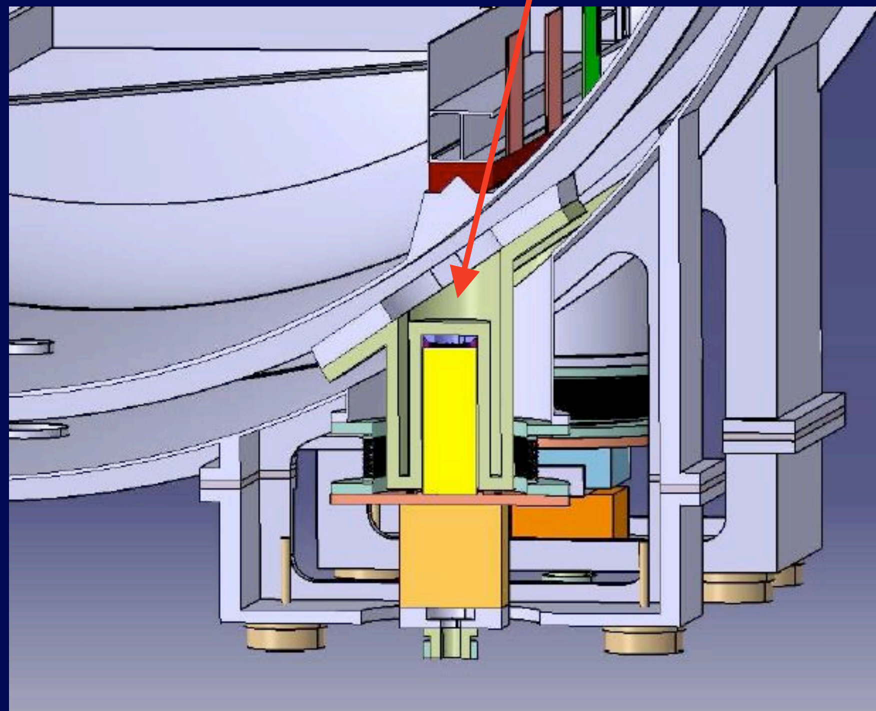


3D engineering

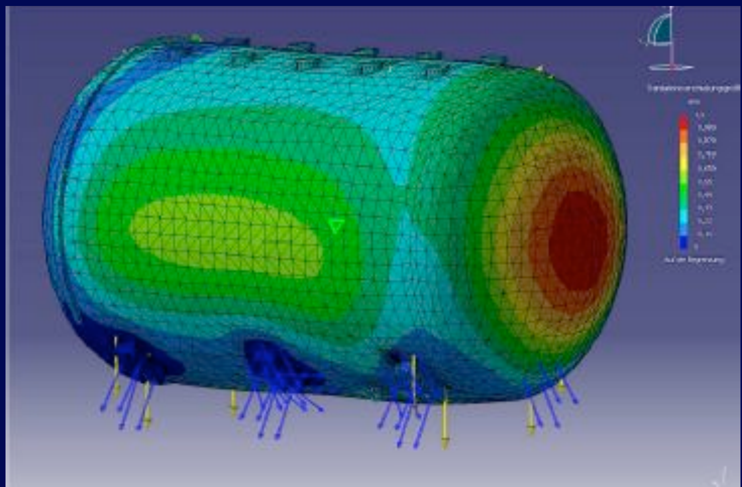


Thermal analysis

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



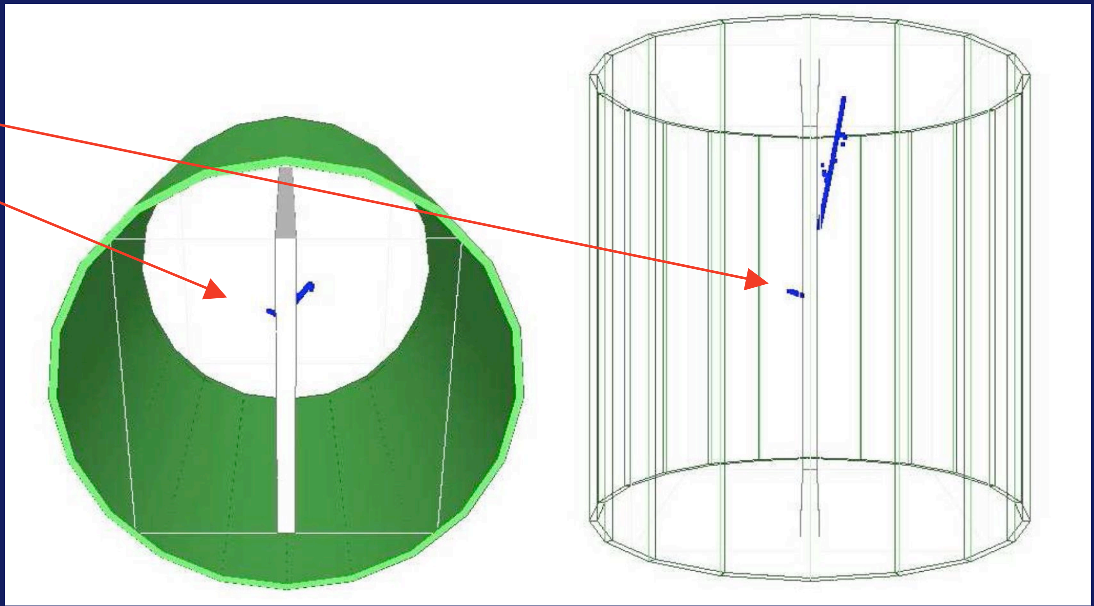
Finite element analysis



Reconstruction of MC events in the inner target

mass **width**	2.69 ton 12.5 cm	5.37 ton 25 cm	10.74 ton 50 cm
QE protons **QE full rec.**	50% 36%	30% 22%	19% 14%
QE per 10^{21}pot	**1178**	**1440**	**1832**
nonQE protons **nonQE π^+** **nonQE π^0** **nonQE full rec.**	32% 94% 95% 27%	22% 85% 85% 17%	16% 71% 76% 9%
nonQE per 10^{21}pot	**500**	**630**	**670**

Recoil proton
p = 660 MeV



QE event

Inner detector structure

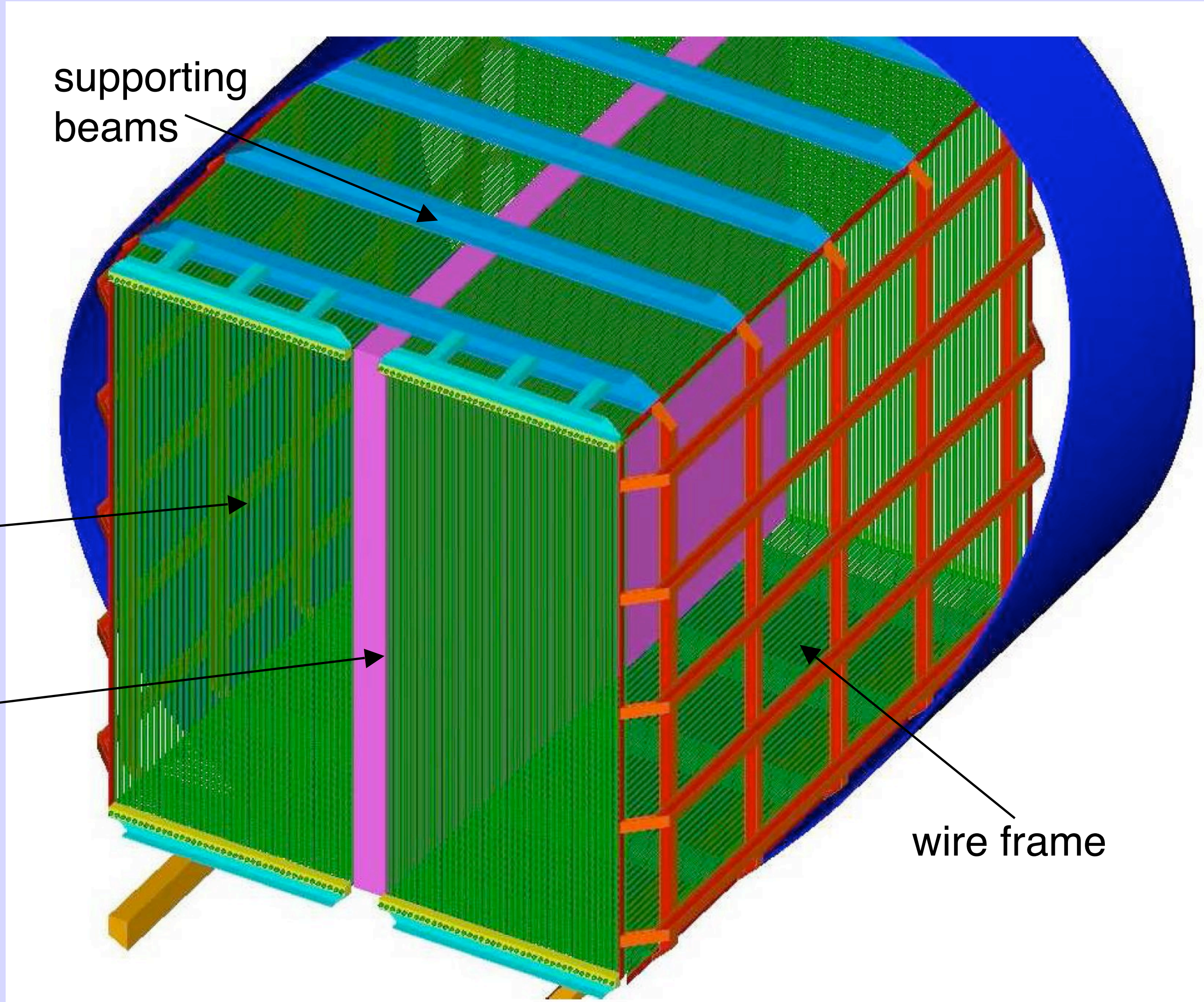
4.5 m x 4.5 m x 5 m stainless-steel supporting structure for wire planes, PMTs, auxiliary systems, cathode, inner target. Two independent readout chambers.

Conceptual design, stress calculation.

Engineering design in progress.

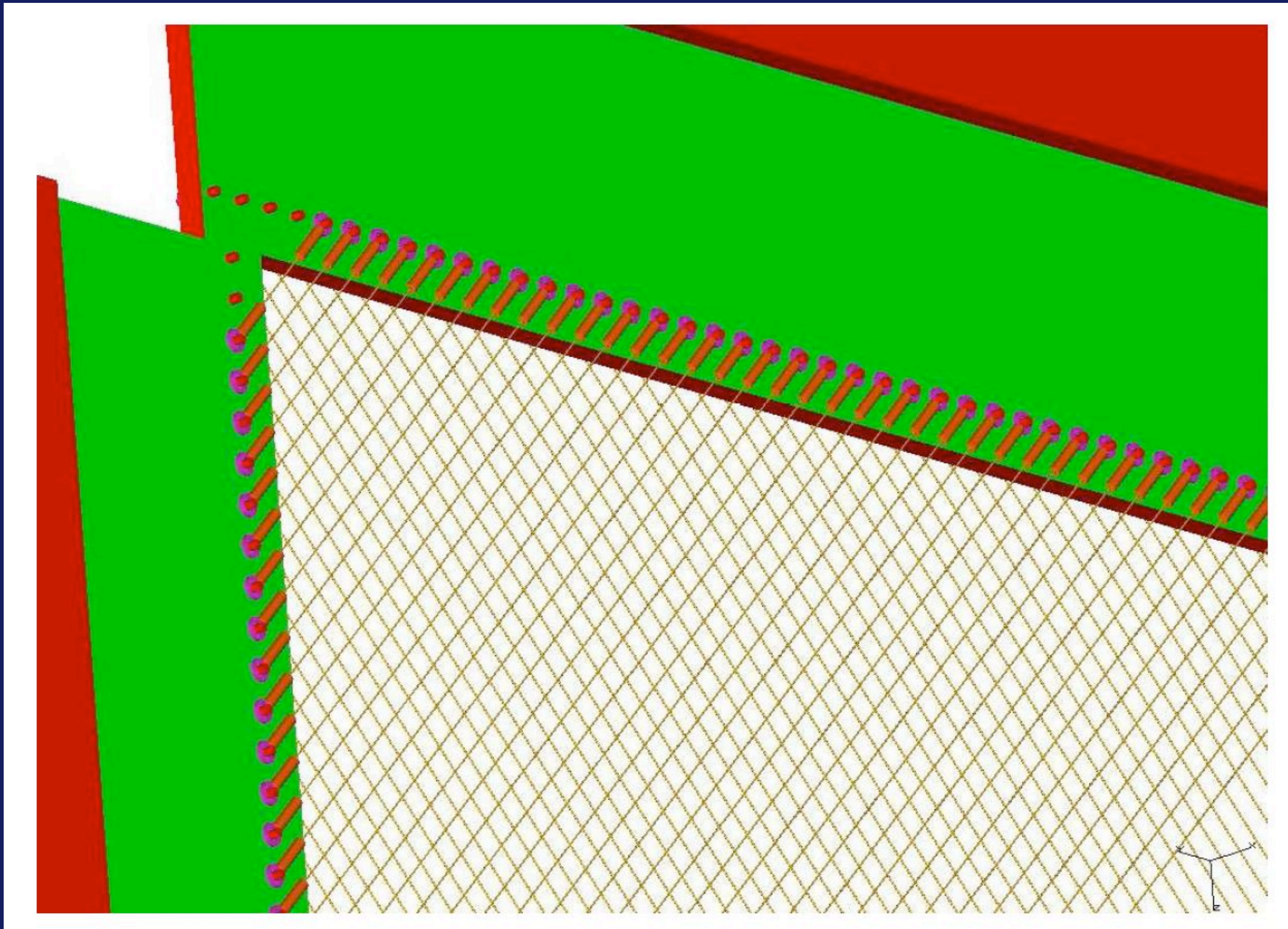
field shaping electrodes

cathode + inner target

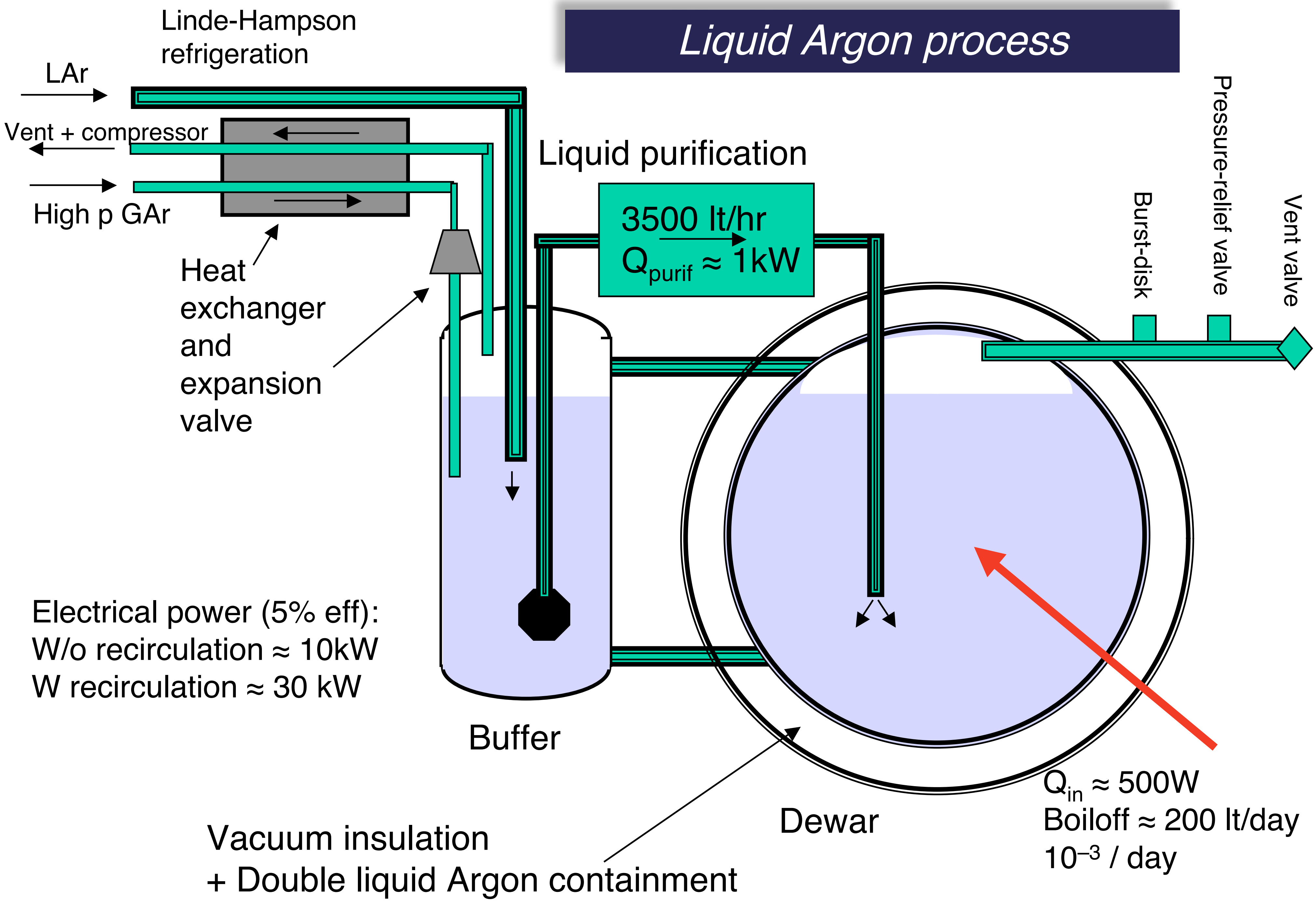


Details of the wire planes

Baseline option: two perpendicular planes per chamber; simple wire sustaining design with wire pre-tensioning anchored by slipknots and pins onto wire frame. Optional third vertical plane under study.

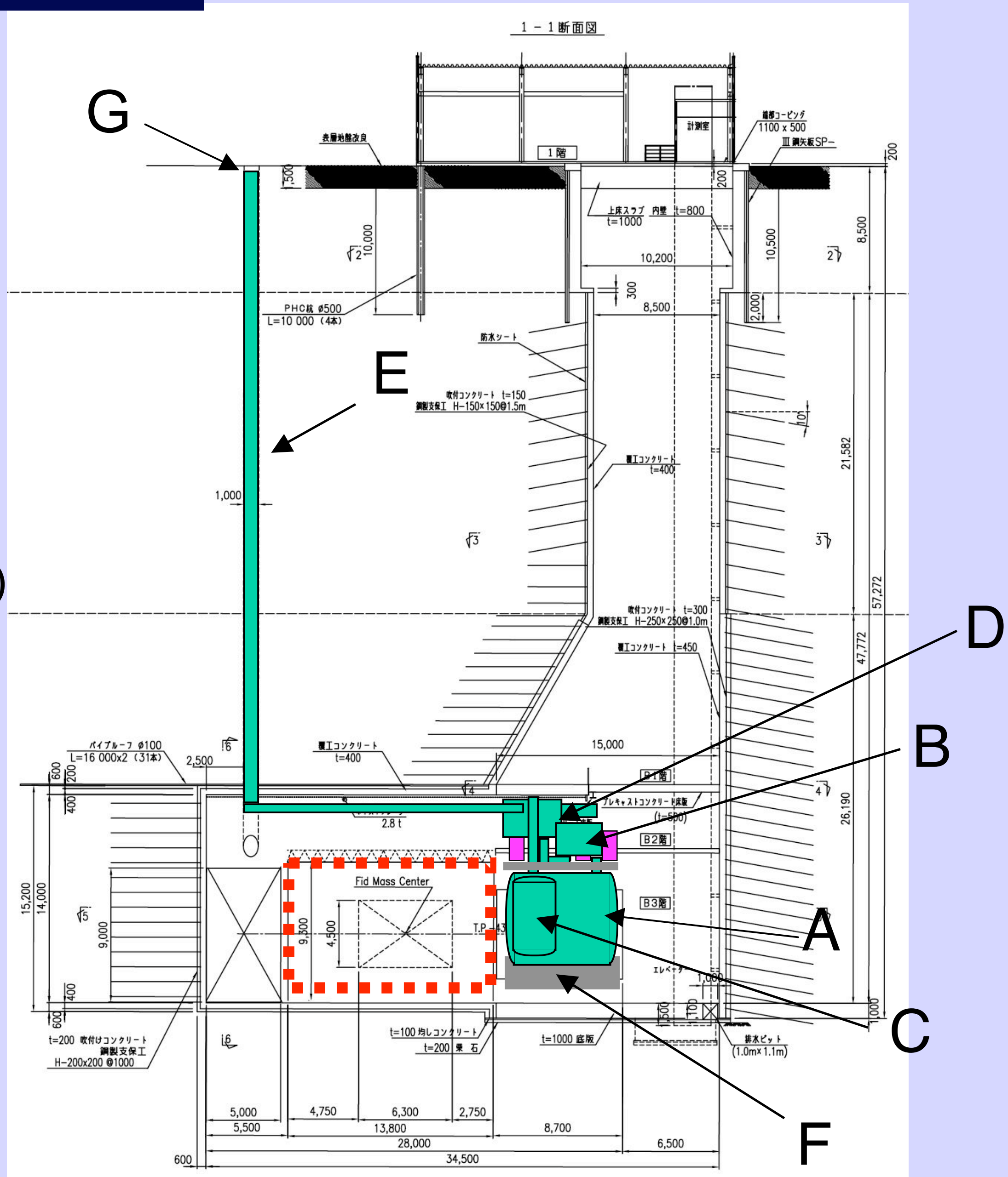


Liquid Argon process

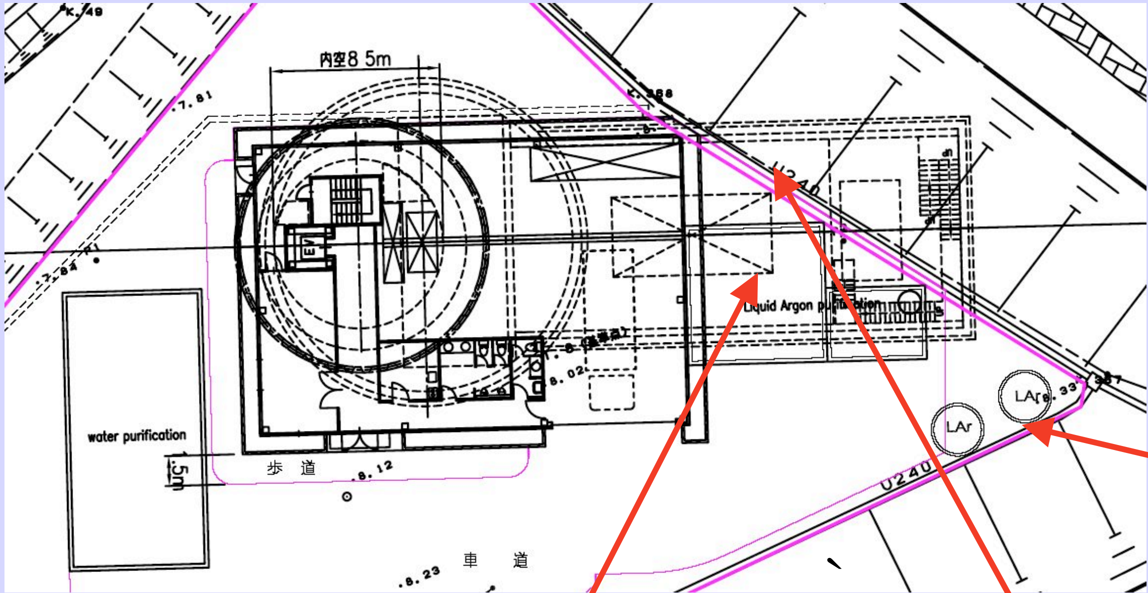


Underground cryogenic infrastructure

A: Detector dewar
B: LAr Purification
C: Buffer
D: Heat exchanger and expansion valve
E: Argon pipes
F: Shock absorbers
G: Dedicated shaft (ventilation and piping)



Surface infrastructure



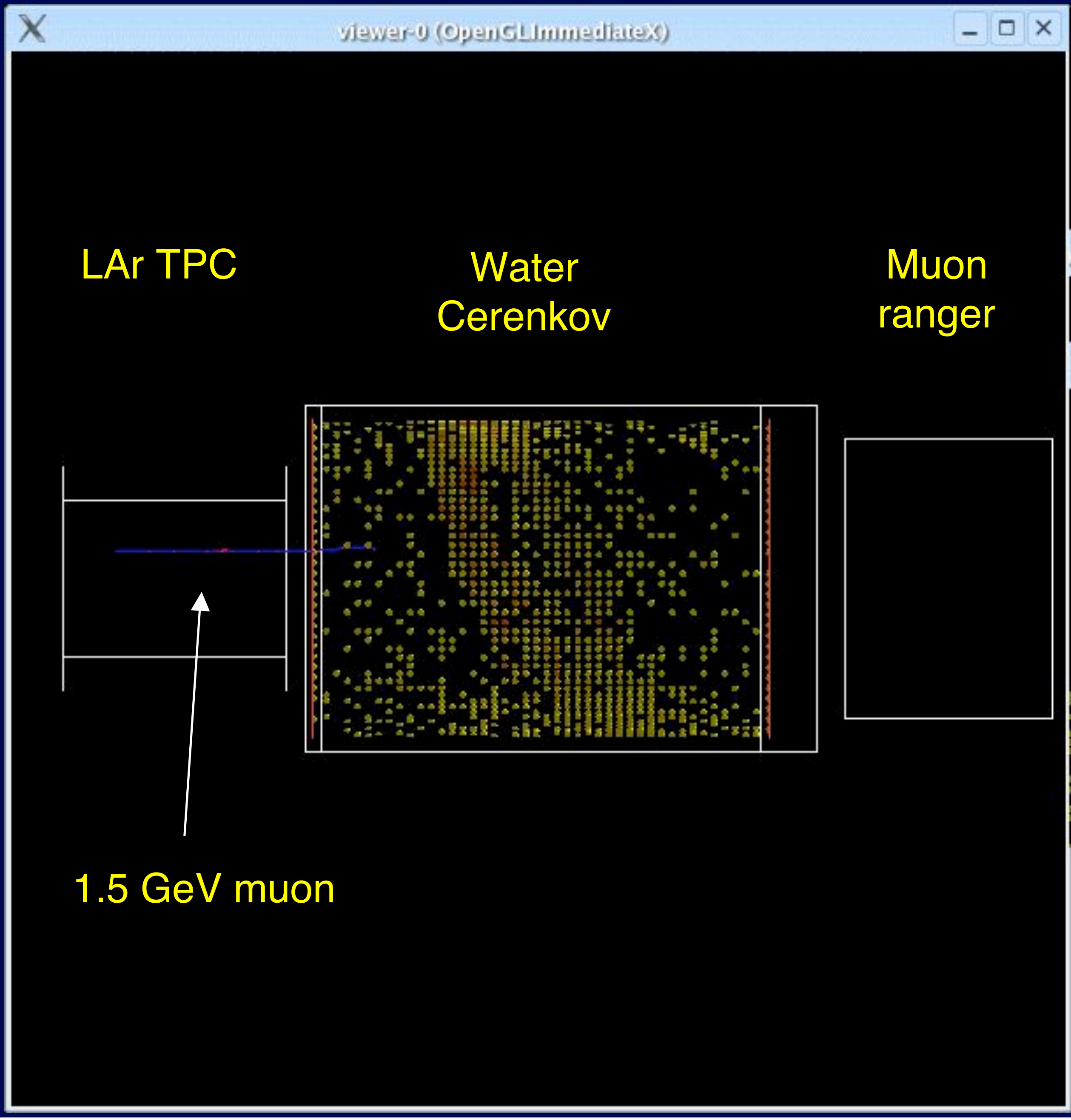
A preliminary layout of the surface equipment has been outlined

Compressors

Vaporizers

LAr storage

Software 2 km detector integration



Outlook

• Neutrino physics will benefit from present (< 2010) and next generation (< 2015) of beam experiments to assess the atmospheric oscillation signal and to measure the third (so far) unknown mixing angle.

• New detectors will be required for the next-to-next generation (> 2015 ?) to cope with the (needed!) boost in beam intensity, and able to fight against low expected signals (CP, matter effects) and in parallel to conduct neutrino astroparticle physics and proton decay experiments.

• After the long standing ICARUS R&D project and the specific application to the LNGS experiment, the LAr TPC technique is ready for future applications to neutrino and astroparticle physics experiments. Within a few years the ICARUS data will provide additional, valuable insights about the physics potential.

• We have tentatively identified a road-map, including milestones some of which already met:

1) dissemination and diffusion of the technical knowledge on LAr TPC detectors
2) applications at 'small' scale (~100 ton), e.g. for the T2K experiment (ν oscillations and low-E studies)
3) conceptual and engineering design of a 'very large' general-purpose detector (~100 kton)
4) start-up of the required collaboration with industry on logistics, infrastructure and equipments
5) realization of a 'test' module (~10 times ICARUS) with physics program on its own (matter stability, astroparticle physics, oscillation studies). Underground operation, possibly magnetized.

In parallel, a coherent and cooperative effort of the community for the actual implementation of these ideas has be triggered and supported.