F. Sergiampietri
"On the possibility to extrapolate Liquid Argon Technology to a super massive detector for a future Neutrino Factory"

LANNDD

Liquid Argon Neutrino and Nucleon Decay Detector in Magnetic Field

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Physics issues for a large-mass magnetized liquid Argon TPC

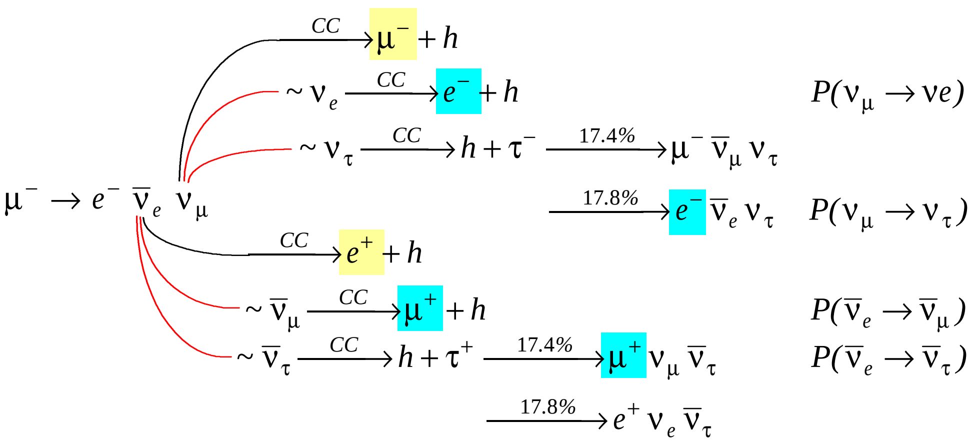
- Use as Far Detector for Neutrino Factories located in the USA, Japan or Europe
  - Neutrino oscillations
  - CP and T violation
  - Matter effect parameters

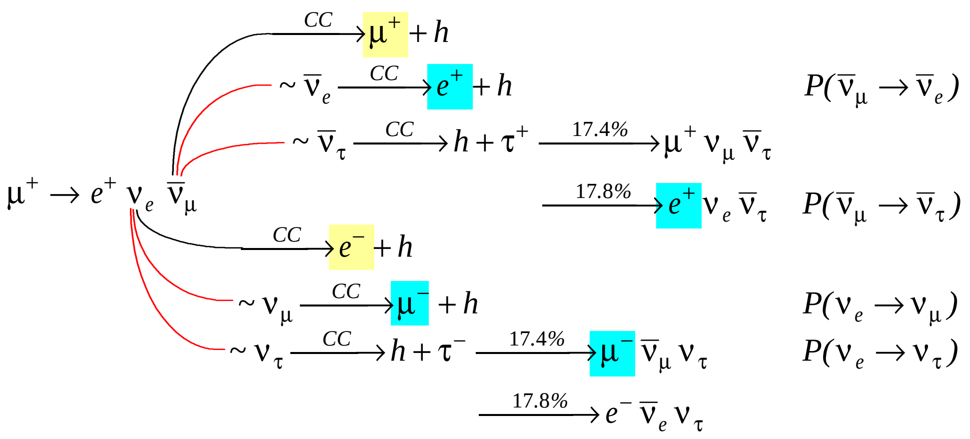
See M. Campanelli, *Study of effects related to the delta-phase (CP/T violation) in neutrino oscillations at a neutrino factory*, this workshop.

- Nucleon decay (Search for $p \to K^+ \bar{\nu}$ to 10^{35} years lifetime)
- Study of atmospheric neutrinos
- Detection of large numbers of solar neutrino events and supernova events

ν-oscillations, Δ*T*, Δ*CP*

ν-oscillations





$$\Delta T \therefore P(\nu_e \rightarrow \nu_\mu) - P(\nu_\mu \rightarrow \nu_e)$$
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

$$\Delta CP \therefore P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$$
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Limits on proton mean life (τ_p)

Exposure: 300 kton ´ year				
4.5 years @ LANNDD	$p \to e^+ \pi^\circ$		$p \to K^+ \bar{\nu}$	
	Efficiency (%)	τ_p (years)	Efficiency (%)	τ_p (years)
No nucl. reinteractions	42	1.5×10^{34}	85	3.1×10^{34}
Nucl. reinteractions (FLUKA)	19	6.8×10^{33}	85	3.1×10^{34}

Exposure: 1000 kton ´ year				
15 years @ LANNDD	$p \to e^+ \pi^\circ$		$p \to K^+ \bar{\nu}$	
	Efficiency (%)	τ_p (years)	Efficiency (%)	τ_p (years)
No nucl. reinteractions	42		85	1.0×10^{35}
Nucl. reinteractions (FLUKA)	19		85	1.0×10^{35}

This talk is a report on the results of a concrete study on a possible answer to the above physics issues.

In the following, preliminary considerations, merit figures and practical physics/technical limits, found in a conceptual design for a next generation, *XL*-mass detector, will be underlined.

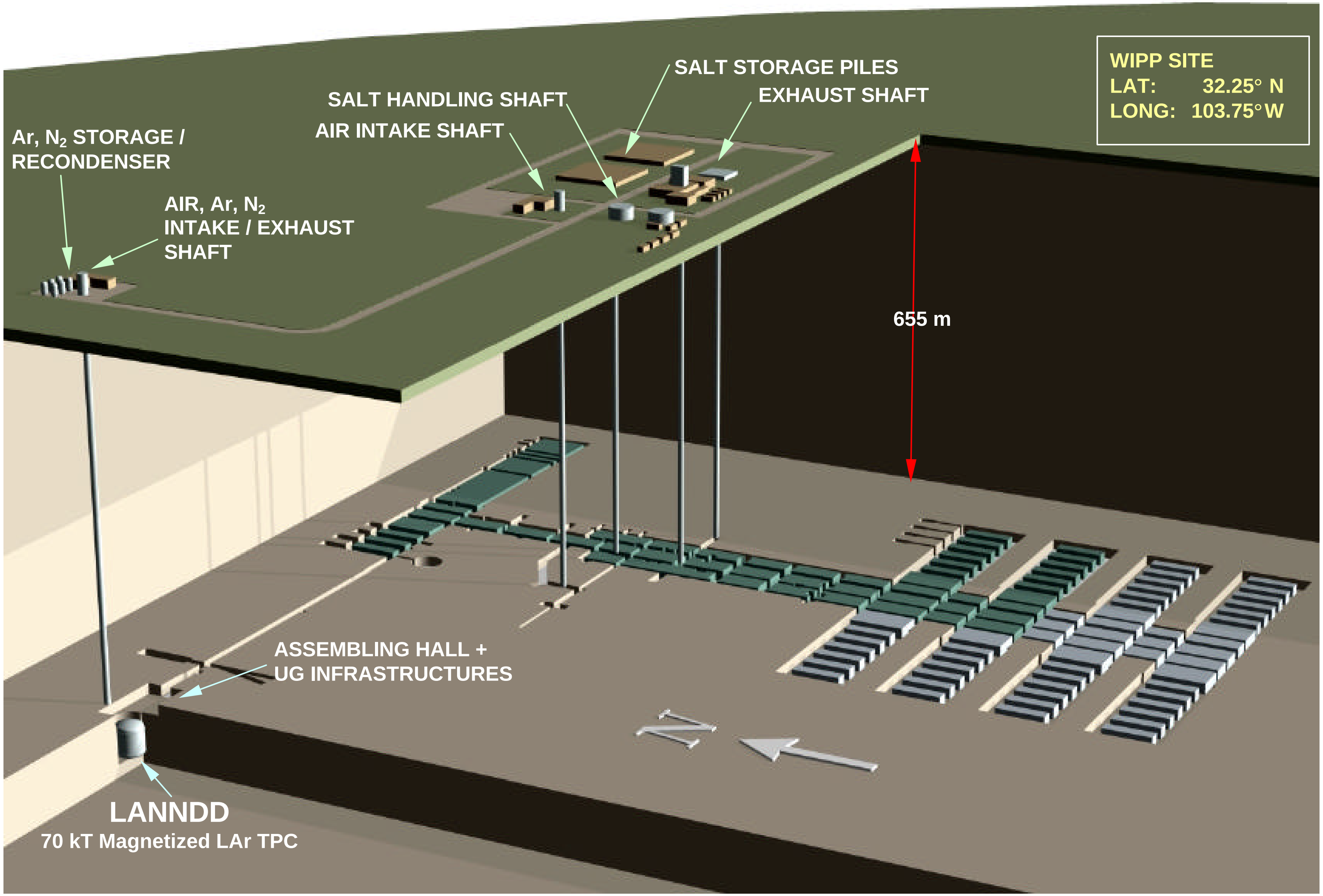
Working conditions

- High space resolution, imaging
- Low energy threshold
- 70 kTon active mass
- Magnetic field for charge sign discrimination for muons (low field)
- Magnetic field for charge discrimination for electrons (high field)
- Underground location

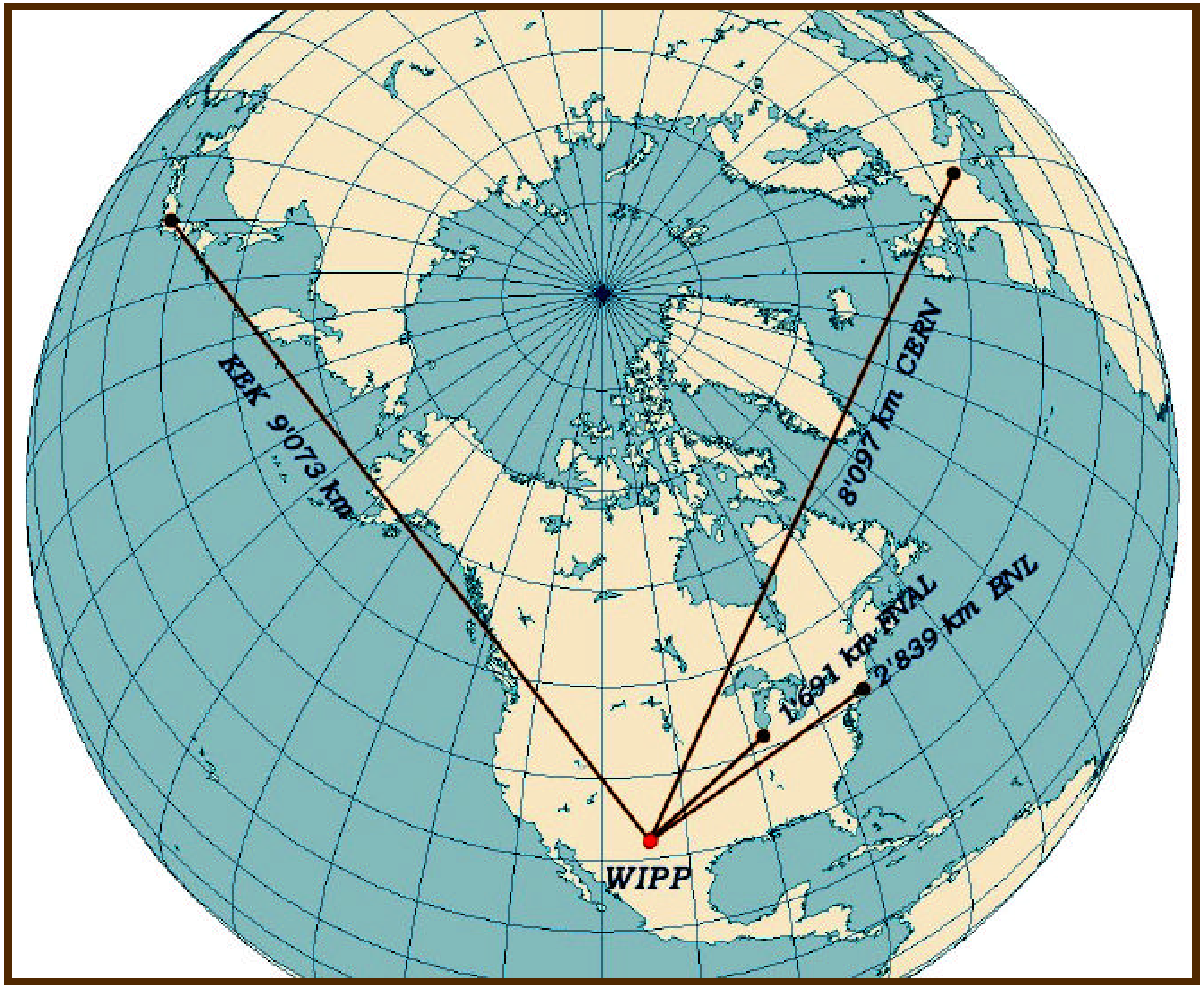
↓

70 kTon Magnetized LAr TPC
at the WIPP site near Carlsbad (NM)

LANNDD at the WIPP site at Carlsbad (NM)



Long baseline ν beams



LBL Beam	Distance	θ_H	θ_V
FNAL	1 691 km	47.9°	7.8°
BNL	2 839 km	62.5°	12.9°
CERN	8 097 km	41.6°	39.5°
KEK	9 073 km	- 44.7°	45.4°

θ_H: angle, in the WIPP site horizontal plane, respect to the NORD

θ_V: angle, at the WIPP site, respect to the horizontal plane

Shape and Orientation

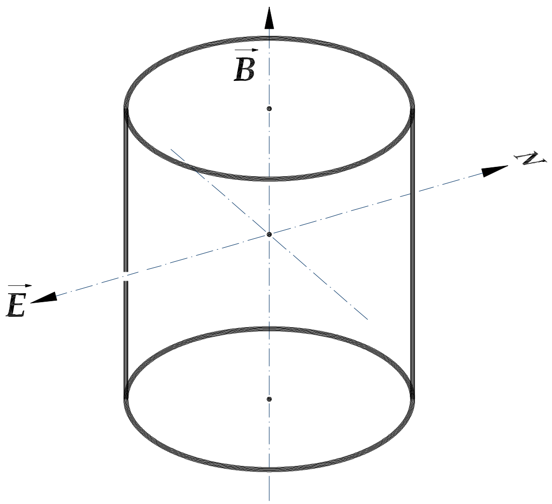
Omni-directionality for atmospheric, solar, cosmic ν's

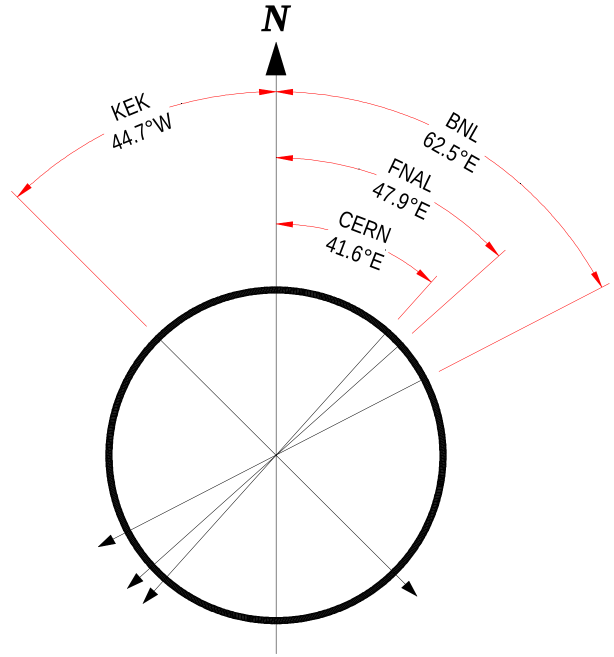
Acceptance for actual and future LBL ν-beams

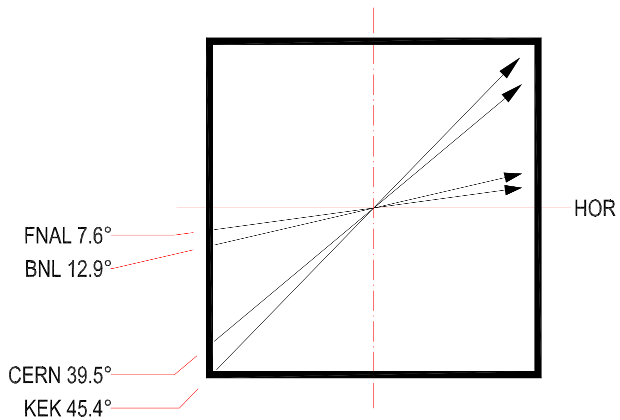
Minimum S/V (surface-to-volume) ratio

- Maximum fiducial volume
- Minimum electronic channel /PMT's number
- Minimum heat input
- Minimum de-gassing /doping
- Minimum magnet power

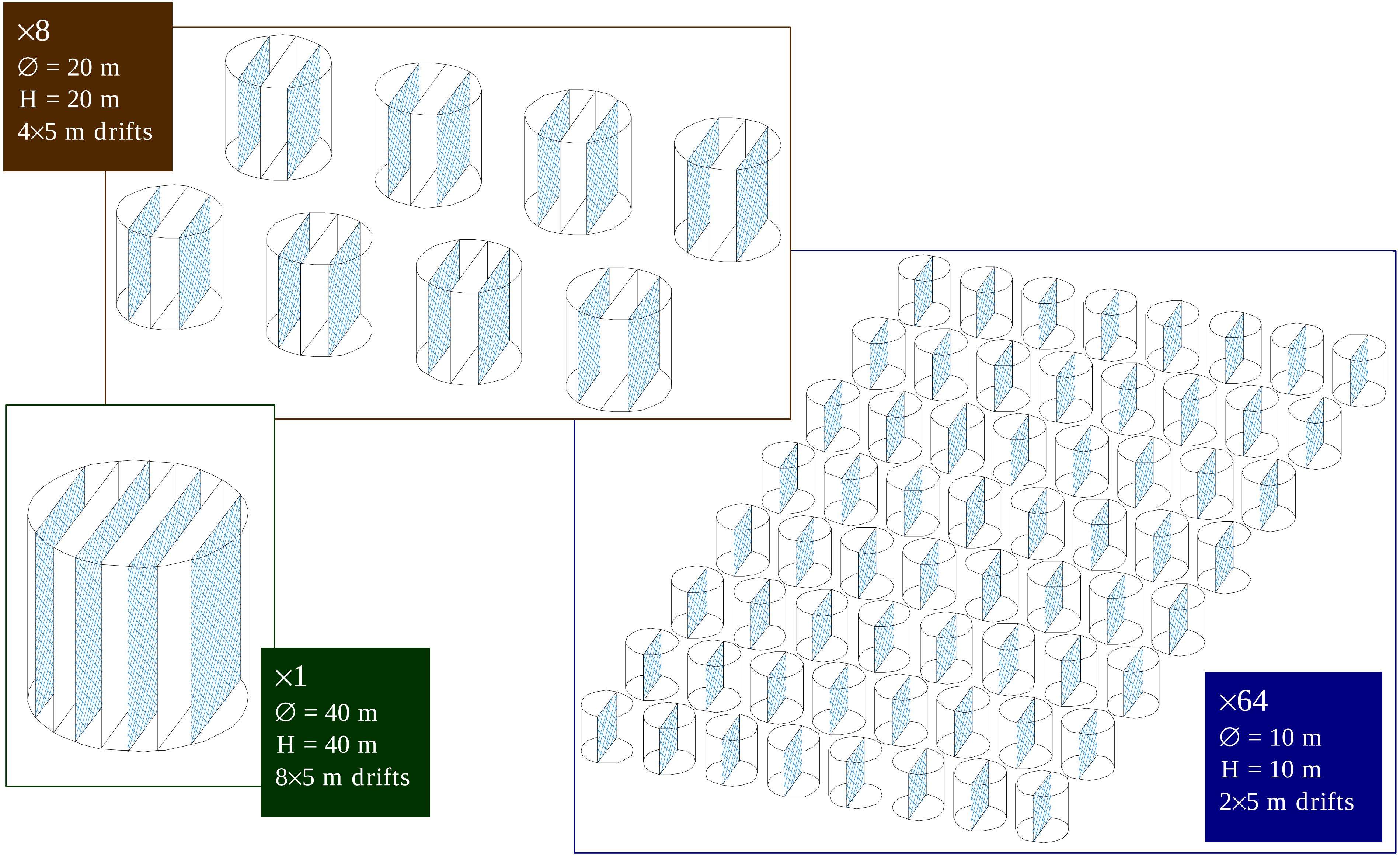
Cylindrical shape with Height = Diameter
(S/V - equivalent to a sphere or to a cube)







Modularity


×8
∅ = 20 m
H = 20 m
4×5 m drifts
×1
∅ = 40 m
H = 40 m
8×5 m drifts
×64
∅ = 10 m
H = 10 m
2×5 m drifts

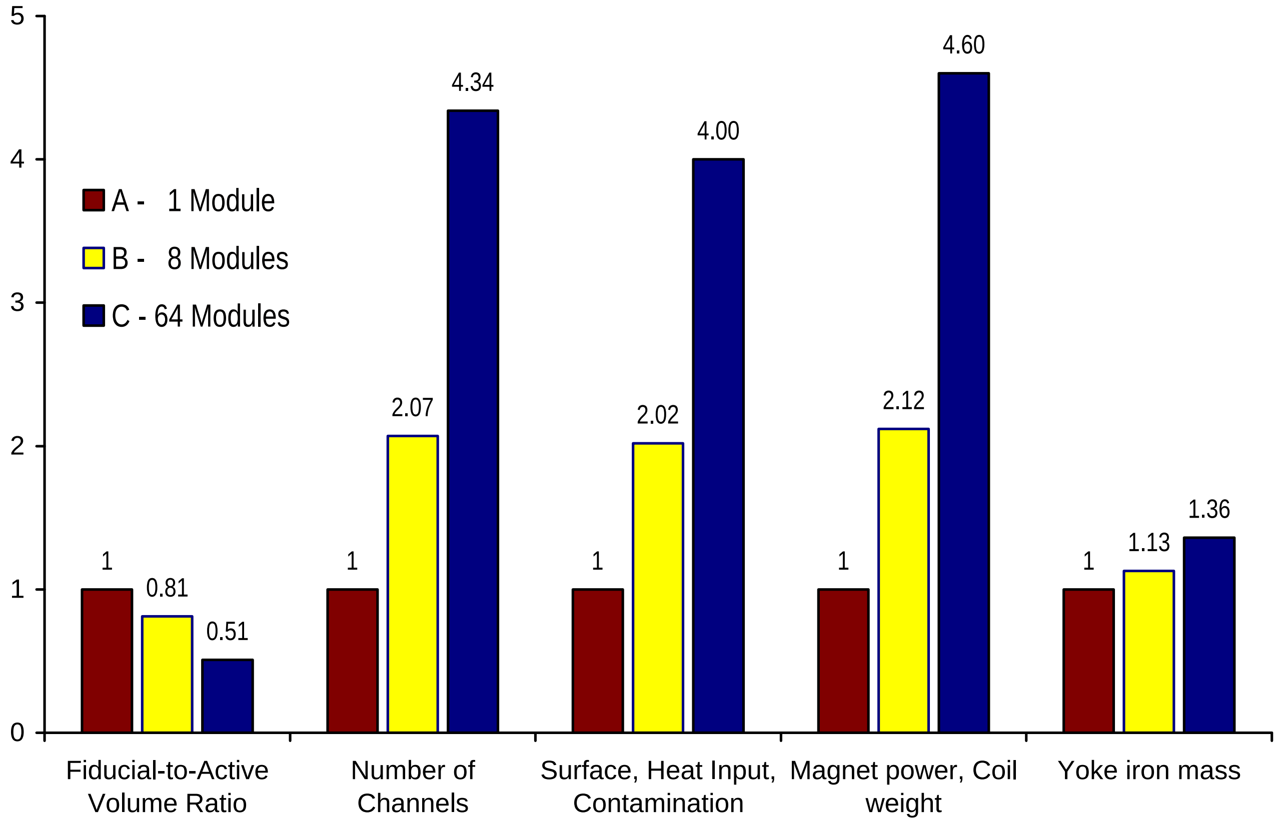
Modularity

Fiducial volume, number of channels (3 mm wire pitch) and heat input (calculated with 1 W / m²) for different detector modularity

		Single module	8 modules	64 modules
Total active volume	[m³]	50×10^3		
Total active mass [1]	[kTon]	69.5		
Active diameter	[m]	40.5	20.4	10.0
Chamber height	[m]	40.5	20.4	10.0
Drift thickness	[m]	5.1	5.1	5.0
Fiducial volume	[m³]	41.4×10^3	33.6×10^3	21.0×10^3
Chamber 1 width	[m]	26.8	17.6	10
Chamber 2 width	[m]	39.2	17.6	-
Chamber 3 width	[m]	39.2	-	-
Chamber 4 width	[m]	26.8	-	-
Number of channels	wires @ 0°, 90°	196×10^3	405×10^3	852×10^3
	wires @ ±45°	277×10^3	573×10^3	1.2×10^6
Total LAr surface	[10^3 m²]	8.4	17.1	33.8
Total LAr volume	[m³]	60×10^3		
Total heat input	[kW]	8.4	17.1	33.8
Magnet power $B=0.2$ T,	[MW]	17	37	79
$B=0.4$ T,	[MW]	35	74	161
$B=1.0$ T,	[MW]	88	189	420
Total coil mass $B=0.2$ T,	[kTon]	16	33	71
$B=0.4$ T,	[kTon]	31	65	141
$B=1.0$ T,	[kTon]	86	181	389
Yoke iron mass $B=0.2$ T,	[kTon]	120	135	163
$B=0.4$ T,	[kTon]	247	281	341
$B=1.0$ T,	[kTon]	677	780	973

[1] Liquid Argon density =1.39 g / cm³ @ p = 1.05 Abs Bar

Modularity



Comparison chart of fiducial volumes, number of channels, heat inputs and magnet parameters for Model A (1 module), B (8 modules) and C (64 modules). Relative values normalized to Model A.

Single module preferable for detection efficiency, construction and running costs

Liquid Argon TPC detection potentialities

- Low energy threshold
- Excellent *dE/dx* resolution
- Momentum, angle, sign and event topology resolution
- Particle identification up to a few GeV

- D.C. operation
- On-line imaging
- Fine grain
  - 3-d pixel $3\times3\times0.64$ mm^3
- Heavy ionisation medium
  - $\rho_{LAr} = 1.4\ g/cm^3$
- Relatively cheap
  - Argon cost
  - TPC geometry
  - N° of channels $\propto$ surface
- Stable
  - Inert fluid
  - Constant temperature operation
  - High thermal inertia ($\delta H_{vap}/\delta m = 227\ MJ/m^3$)
  - Continuously purified (recyclable?)
  - Radiation hard

- Cryogenic liquid
  - $T_{LIQ} = 88°K$ @ $P_{VAP} = 1.05$ Bar
- Long drift time (3÷4 ms)

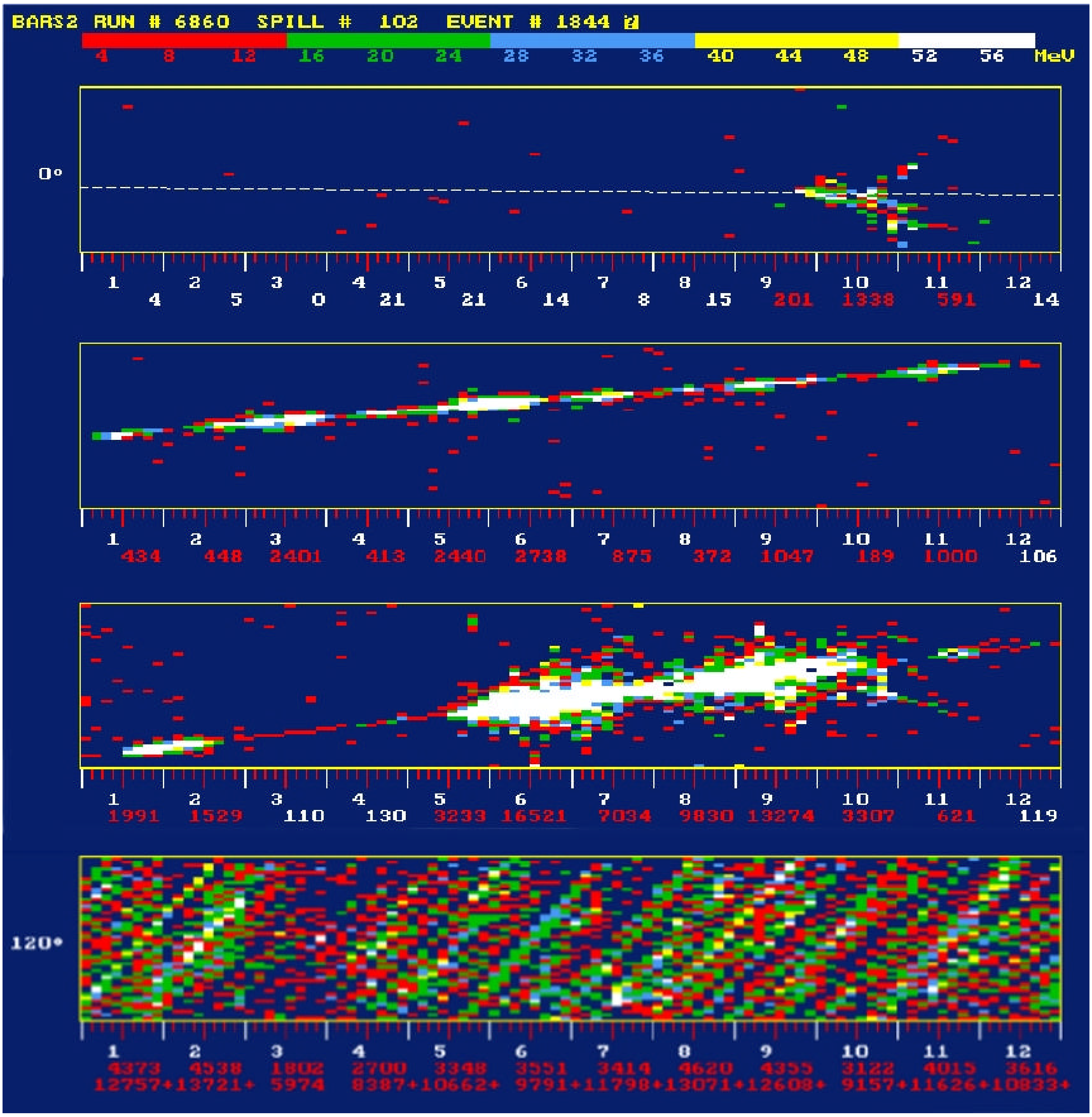
Past experience and results - BARS

Fine grain LAr sampling calorimeter for Tagged Neutrino beams and Cosmic Ray physics

Active volume	2×18m×∅3m
LAr total mass	432.6 tons
LAr active mass	308 tons
Mass of electrode system	118 tons
Mass of plastic scintillator	6.6 tons
Average density	1.6 g/cm^3
Total mass	432.6 tons

Number of cryostats	2
Inner volume of each cryostat	201.8 m^3

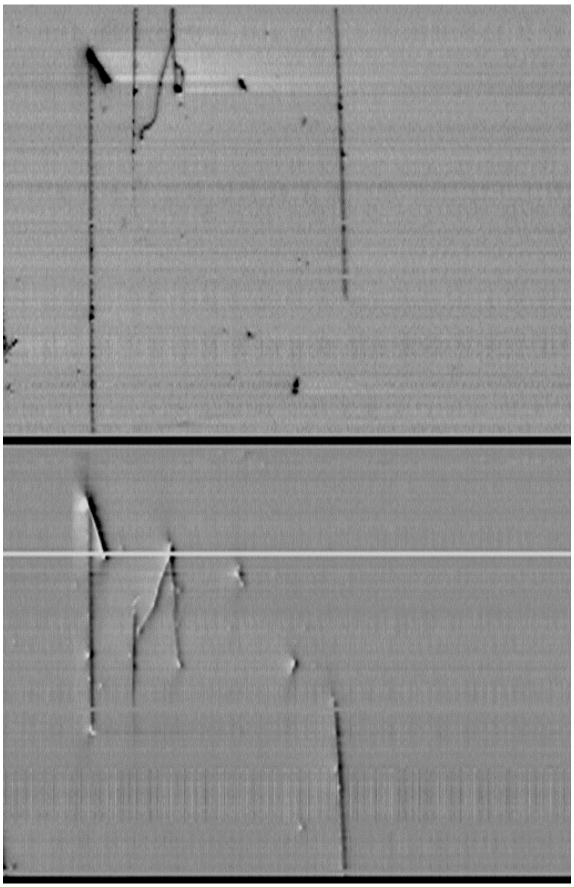
Vacuum insulation with a LN_2 consumption of 2 tons/day
Continuously operating with the same LAr since ≈10 years

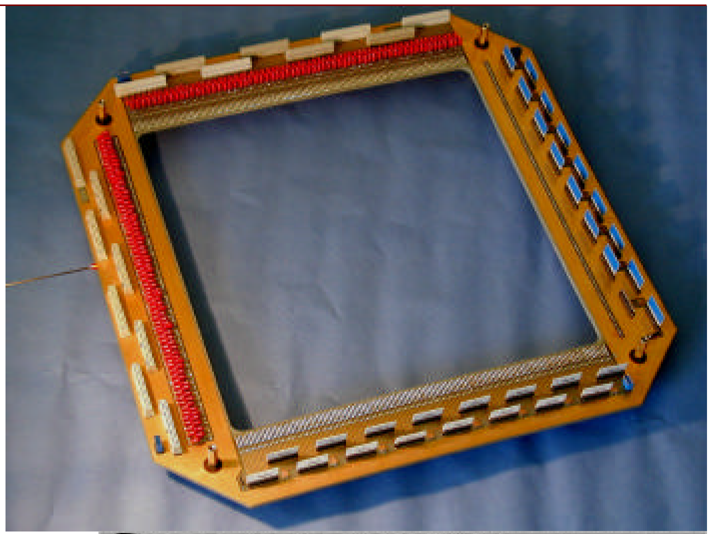


Past experience and results – 50L

LAr TPC

Active volume 50 litre
Read-out planes 2 (0°, 90°)
Drift distance 45 cm



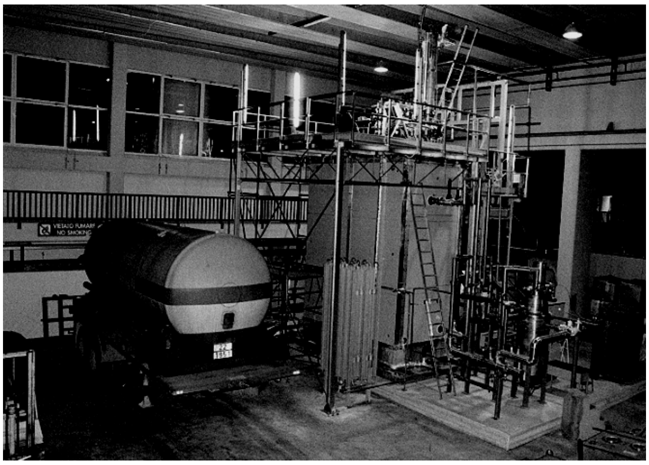


Vertices of ν-interaction events
Fermi-motion effect
Electron direction by δ-rays
dE/dx versus range for soft *K*, π, *p* discrimination
Electron direction in the 5-30 MeV range

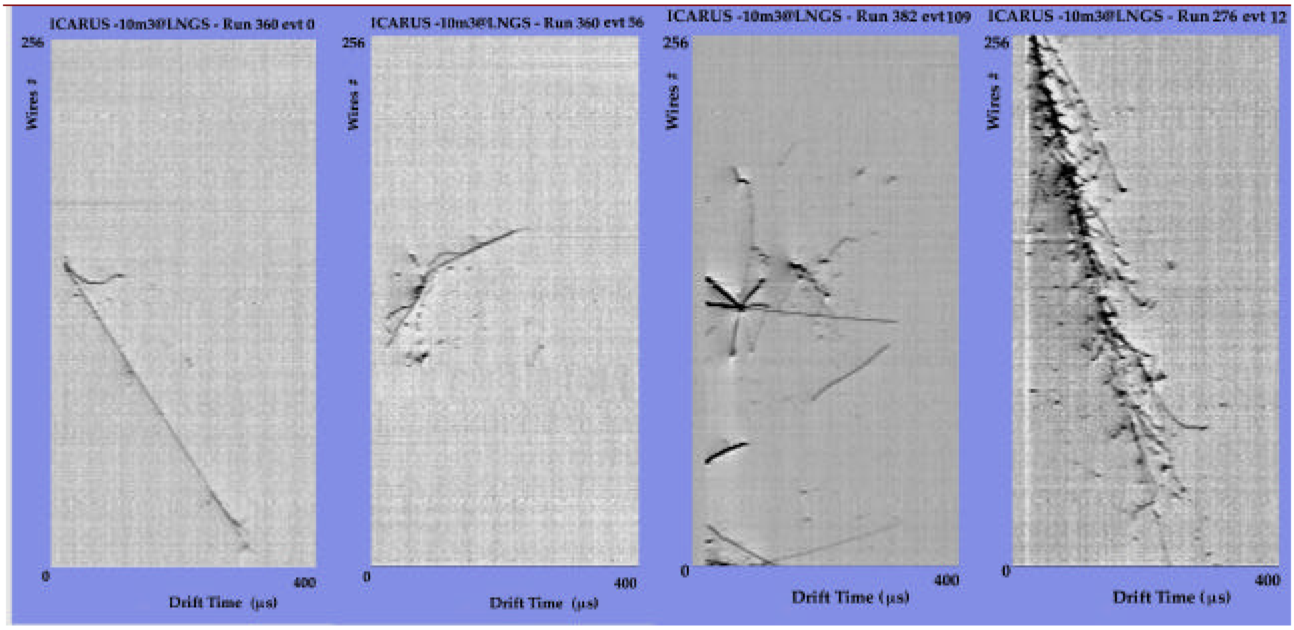
LAr purification by Ar vapour filtering and re-condensation
LAr purity monitoring
Optimisation of the front-end electronics for induction and collection planes (warm and cold electronics)
Signal treatment and event reconstruction
Recording, by PMT's immersed in LAr, of the scintillation light associated to ionisation tracks in the TPC
Wire hanging techniques
1.4 m drift length (special version)

Past experience and results – 10m^3

LAr TPC



Total volume	10 m^3
Active volume	2.3 m^3
Read-out planes	2 (-60°, +60°)
Drift distance	35 cm



Event treatment

External trigger

New generation of purity monitors

Purification in liquid phase

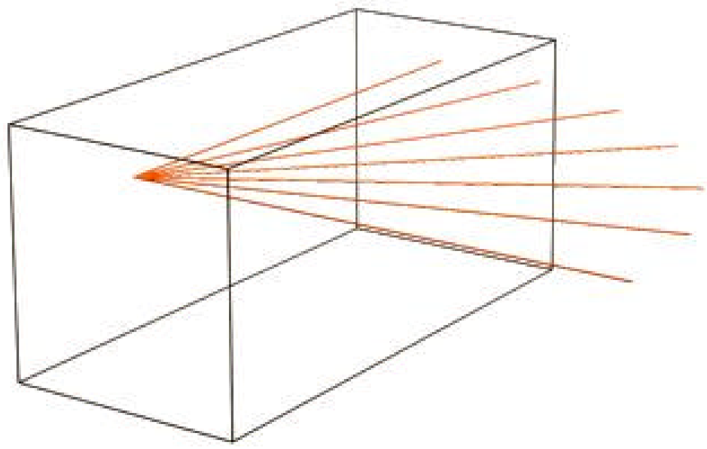
HV feedthrough and degrader

Cryogenic techniques

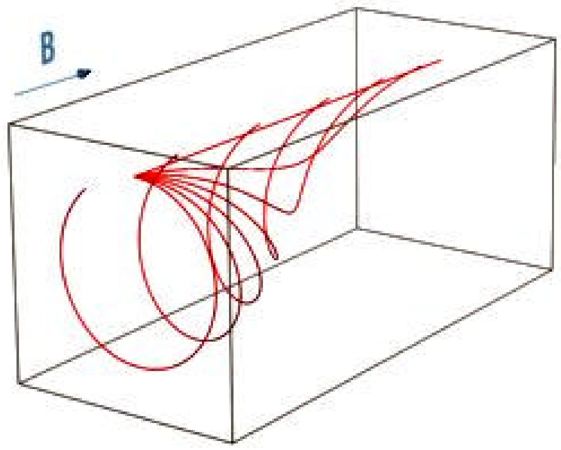
Signal feedthroughs

New requirement: Magnetic field

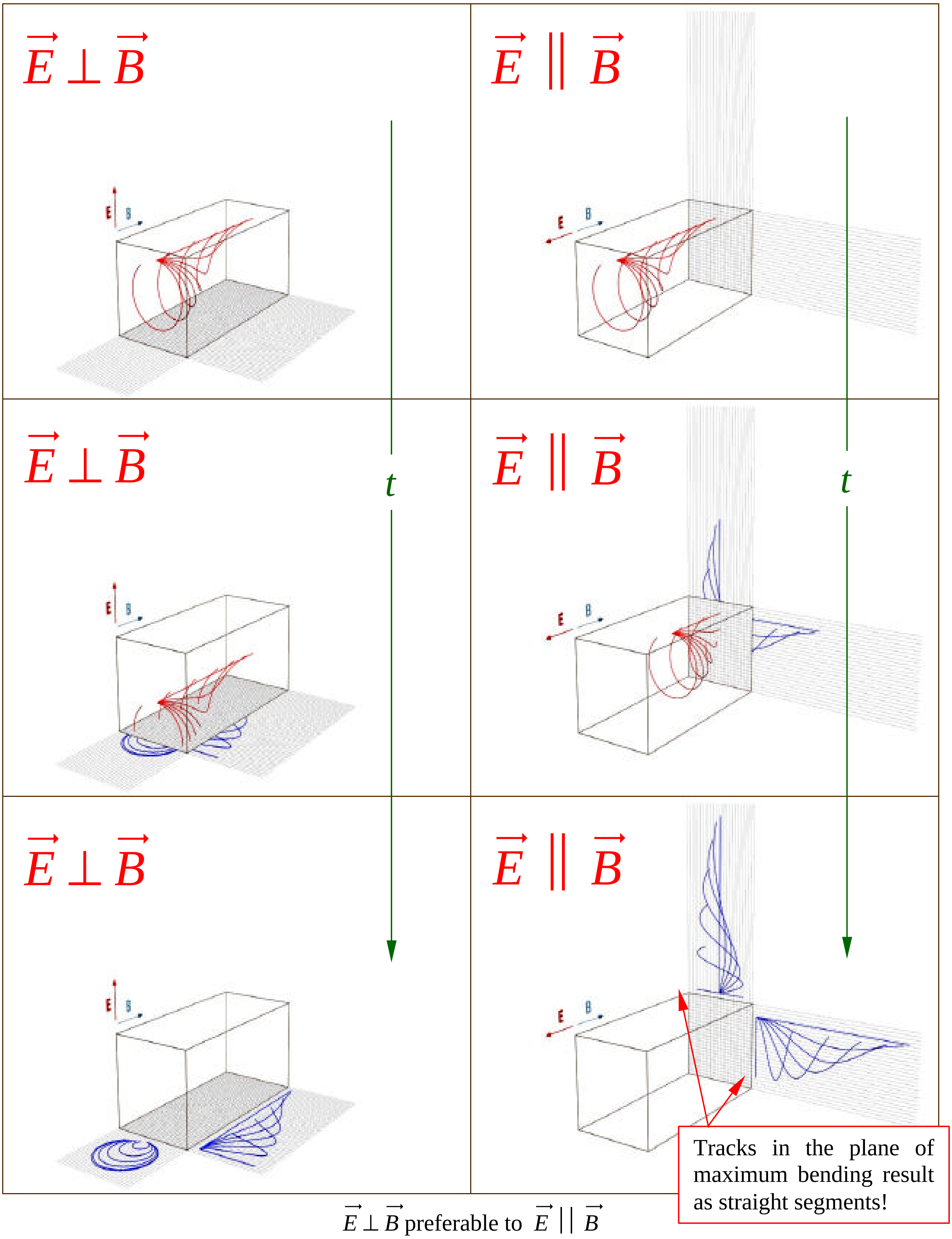
TRACKS



$\vec{B}$



$\vec{E}$ versus $\vec{B}$



$\vec{E} \perp \vec{B}$ preferable to $\vec{E} \,||\, \vec{B}$

Charge sign discrimination in a magnetized LAr TPC

$P_{T\text{-}B}$ kick by magnetic field ***B*** after a path ***t***

$$P_{T\text{-}B} \approx 300\ \mathrm{MeV/c} \cdot t[\mathrm{m}] \cdot B[\mathrm{T}]$$

Multiple scattering **$P_{T\text{-}ms}$** kick after a path ***t***

$$P_{T-ms} = 13.6 \cdot \sqrt{t/X_0} \cdot [1 + 0.038 \cdot ln(t/X_0)]$$

$$P_{T-ms} \approx 36.35\,\mathrm{MeV/c} \cdot \sqrt{t\,[\mathrm{m}]}$$

3-σ sign discrimination against **multiple scattering**

$$P^{+}_{T-B} - P^{-}_{T-B} = 2 \times P_{T-B} \geq 3 \times P_{T-ms}$$

$$B_{\min} \geq \frac{0.18\ \mathrm{T}}{\sqrt{t\,[\mathrm{m}]}}$$

	t	$P_{T\text{-}ms}$ [MeV/c]	$P_{T\text{-}Bmin}$ [MeV/c]	B_{min} [T]
$\mu^{\pm}$	1 m	39	58	0.19
	5 m	92	138	0.09
	10 m	133	199	0.07
$e^{\pm}$	1 X_o	13.6	20.4	0.48
	2 X_o	19.7	29.6	0.35
	3 X_o	24.5	36.8	0.29

Liquid Argon and Detector Parameters

Radiation length .... X_o =14.2 cm

Specific energy loss........................ dE/dx = 2.1 MeV/cm

3D-pixel .... Δ_d = 3.4 mm

*(with a **x-y** wire pitch of 3 mm ´ 3 mm and a sampling interval along the drift of $\Delta_z = v_d \cdot \Delta_t$ = 0.64 mm)*

Space resolution .... σ_d = 1 mm

3-σ sign discrimination against **detector resolution**

Sagitta $s \cong R \cdot \frac{\theta_B^2}{8} = \frac{0.3 \cdot t^2 \cdot B}{8 \cdot P}$

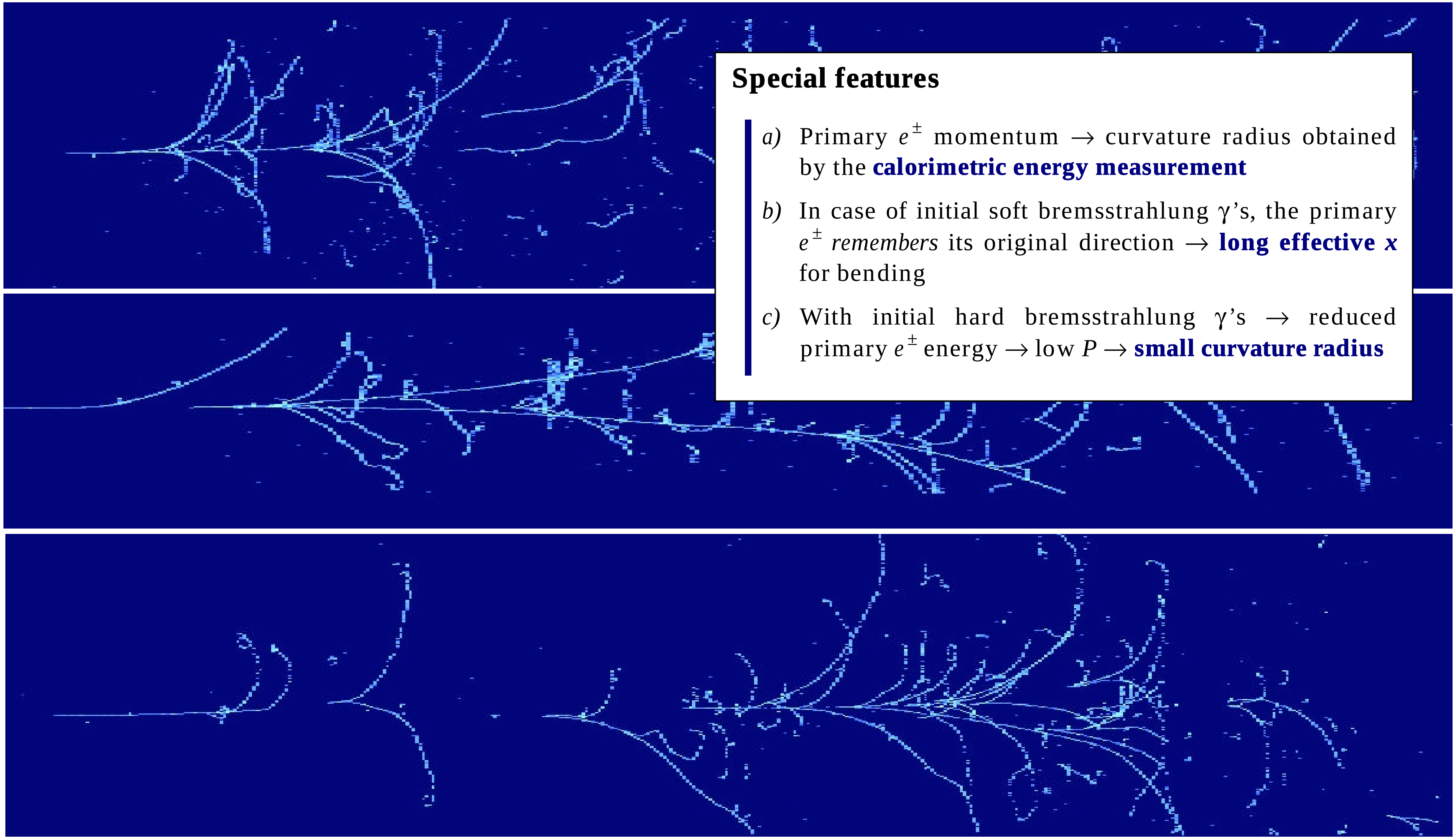
$$s^{+} - s^{-} = 2 \times s \geq 3 \cdot \sigma_d \cdot \sqrt{\frac{\Delta_d}{t}}$$

$$P_{\max} \leq 0.087 \cdot B \cdot \sqrt{\frac{t^5}{\Delta_d^3}}$$

	t	B [T]	s [mm	σ_{res} [mm	P_{max} [GeV/c]
$\mu^{\pm}$	1 m	0.2	-	-	86
	5 m	-	-	-	-
	10 m	-	-	-	-
$e^{\pm}$	1 X_o	0.4	0.23	0.15	1.3
	2 X_o	0.4	0.16	0.11	7.4
	3 X_o	0.4	0.13	0.09	20.3

$e^{\pm}$ sign discrimination

2.5 GeV / c e^{+} simulation @ B = 1 T



Special features

a) Primary $e^{\pm}$ momentum → curvature radius obtained by the **calorimetric energy measurement**

b) In case of initial soft bremsstrahlung γ's, the primary $e^{\pm}$ *remembers* its original direction → **long effective *x*** for bending

c) With initial hard bremsstrahlung γ's → reduced primary $e^{\pm}$ energy → low P → **small curvature radius**

A. Bueno, M. Campanelli, A. Rubbia, *IX International Workshop on "Neutrino Telescopes"*, VENICE, 2001

μ-momentum measurement

Curvature .... $k\,[1/m] = 0.3 \cdot \dfrac{B\,[T]}{p\,[GeV/c]}$

Momentum resolution .... $\dfrac{\delta p}{p} = \dfrac{\delta k}{k} = \dfrac{\sqrt{\delta k_{MS}{}^2 + \delta k_{res}{}^2}}{k}$

Multiple scattering .... $\delta k_{MS} \approx \dfrac{0.016\,(GeV/c)}{t \cdot p} \cdot \sqrt{\dfrac{t}{X_o}}$

Detector resolution .... $\delta k_{res} \approx \dfrac{\sigma}{t} \cdot \sqrt{\dfrac{720}{N+4}}$

Multiple scattering is dominating

$\rightarrow \dfrac{\delta p}{p} \approx \dfrac{\delta k_{MS}}{k_{MS}} \cong \dfrac{14.2\%}{B[\mathrm{T}] \cdot \sqrt{t[\mathrm{m}]}}$ not depending on p

$$\frac{\delta p}{p} \approx 20\%$$

for $B = 0.2\,\mathrm{T}$ and $t = 12.6\,\mathrm{m}$ for any momentum

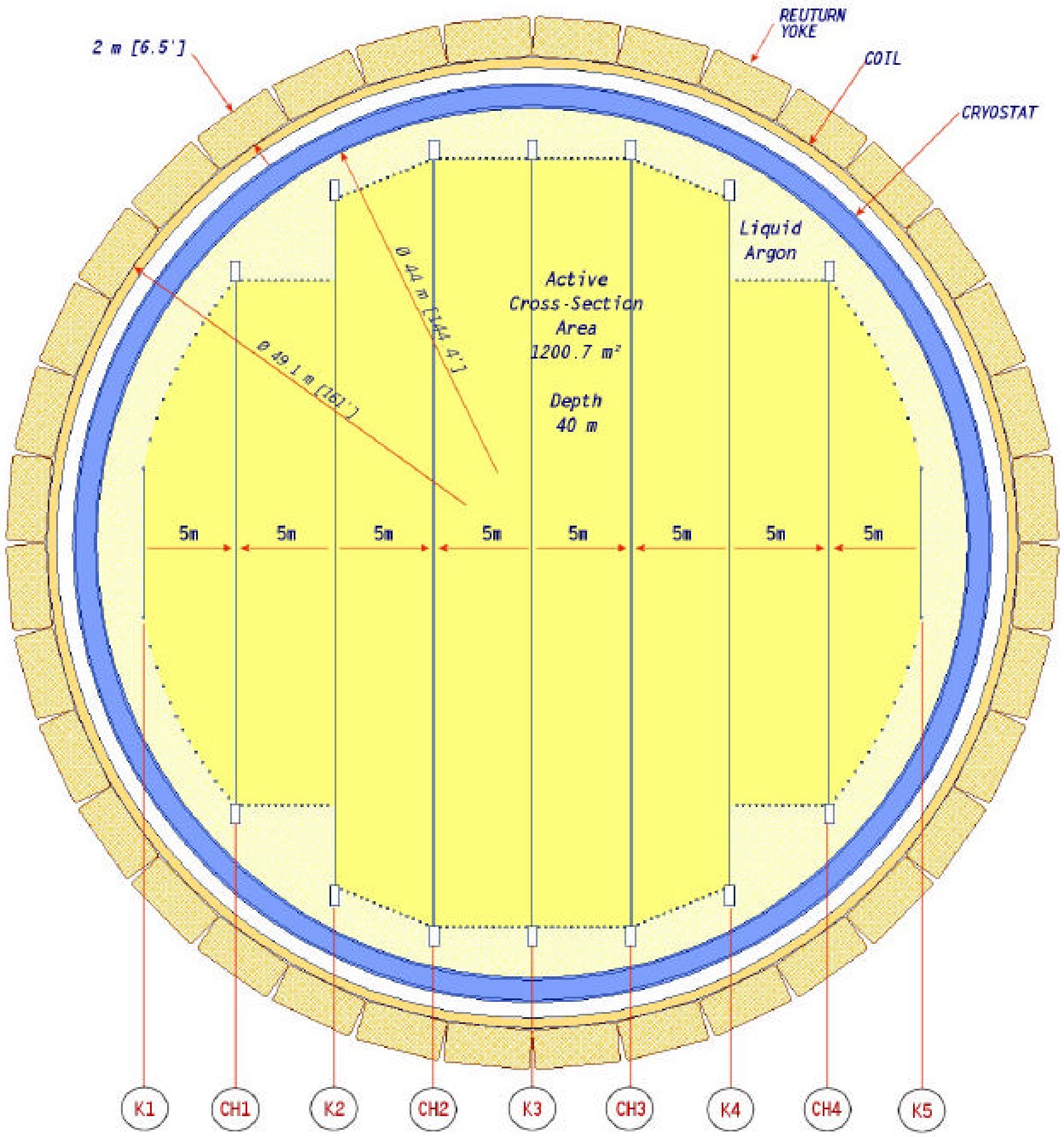
Other estimates: truncate *dE/dx* distribution

Multiple scattering distribution

Detector chamber structure

N° OF WIRE CHAMBERS..4
WIRE CHAMBER ...CH1, CH4..............................W=26.8 m ...H=40 m
CH2, CH3..............................W=39.2 m ...H=40 m
READOUT PLANES / CHAMBER .... [2 at 0°, 2 at 90°] 4
SCREEN-GRID PLANES / CHAMBER..3
TOTAL N° OF WIRES (CHANNELS)...194648

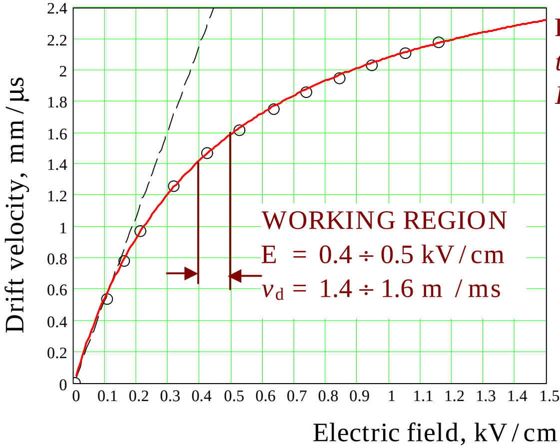
ACTIVE VOLUME ....48000 m^3
ACTIVE MASS ....67 kT
N° OF CATHODE PLANES 5
MAXIMUM DRIFT...5 m
MAXIMUM HIGH VOLTAGE ....250 kV
REQUIRED ELECTRON LIFETIME (PURITY)...................15 ÷ 20 ms



Cross-sectional top view

K1-K5 :...CATHODES
CH1-CH4 : ....WIRE CHABERS
Dotted contour :...... *E*-FIELD ELECTRODES

Drift velocity, diffusion, purity and attenuation

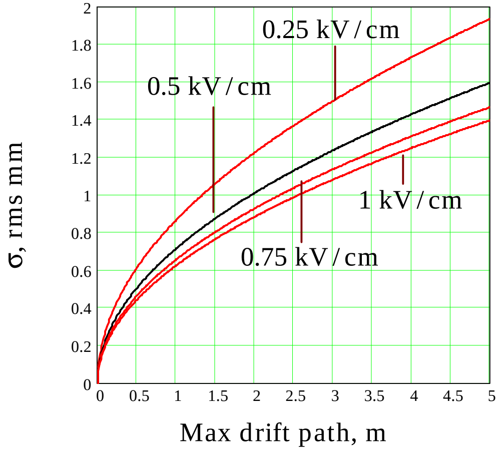


FOR 5 m MAX. DRIFT:

t_{max} = 3.6 ÷ 3.1 ms

HV_{max} = 200 ÷ 250 kV

Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

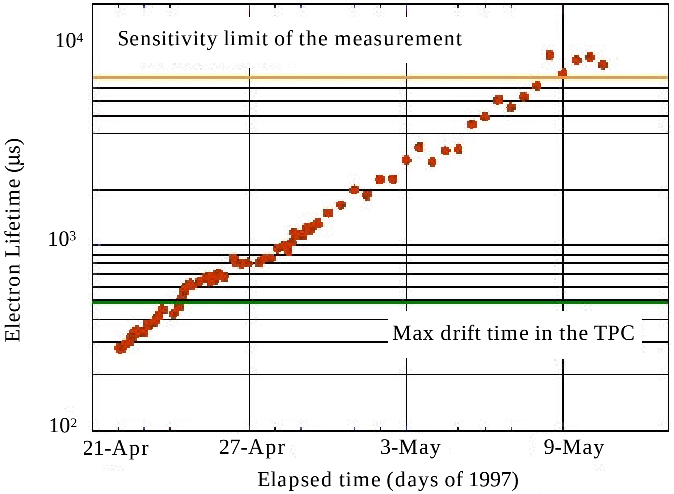
D = 4.06 cm²/s

$$\sigma_D = 0.9\ \text{mm} \cdot \sqrt{T_D[\text{ms}]}$$

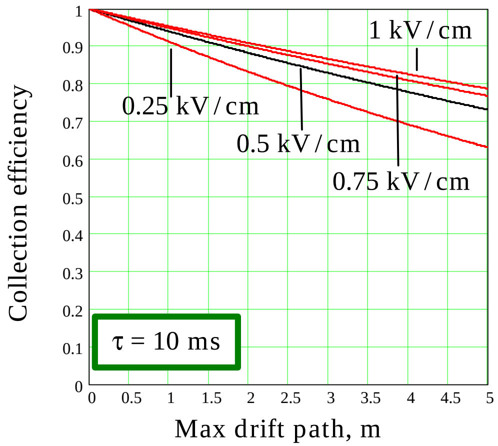
Longitudinal rms diffusion spread at 0.5 kV / cm

Average <σ_D> = 1.1 mm

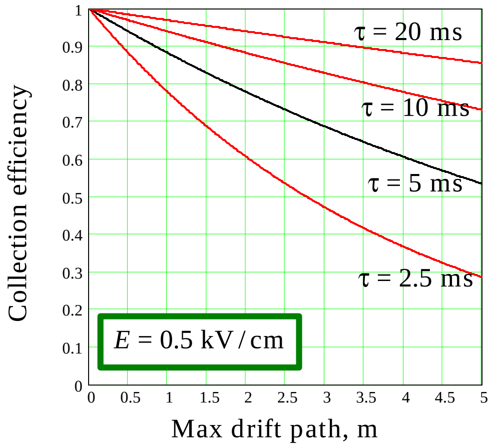
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC



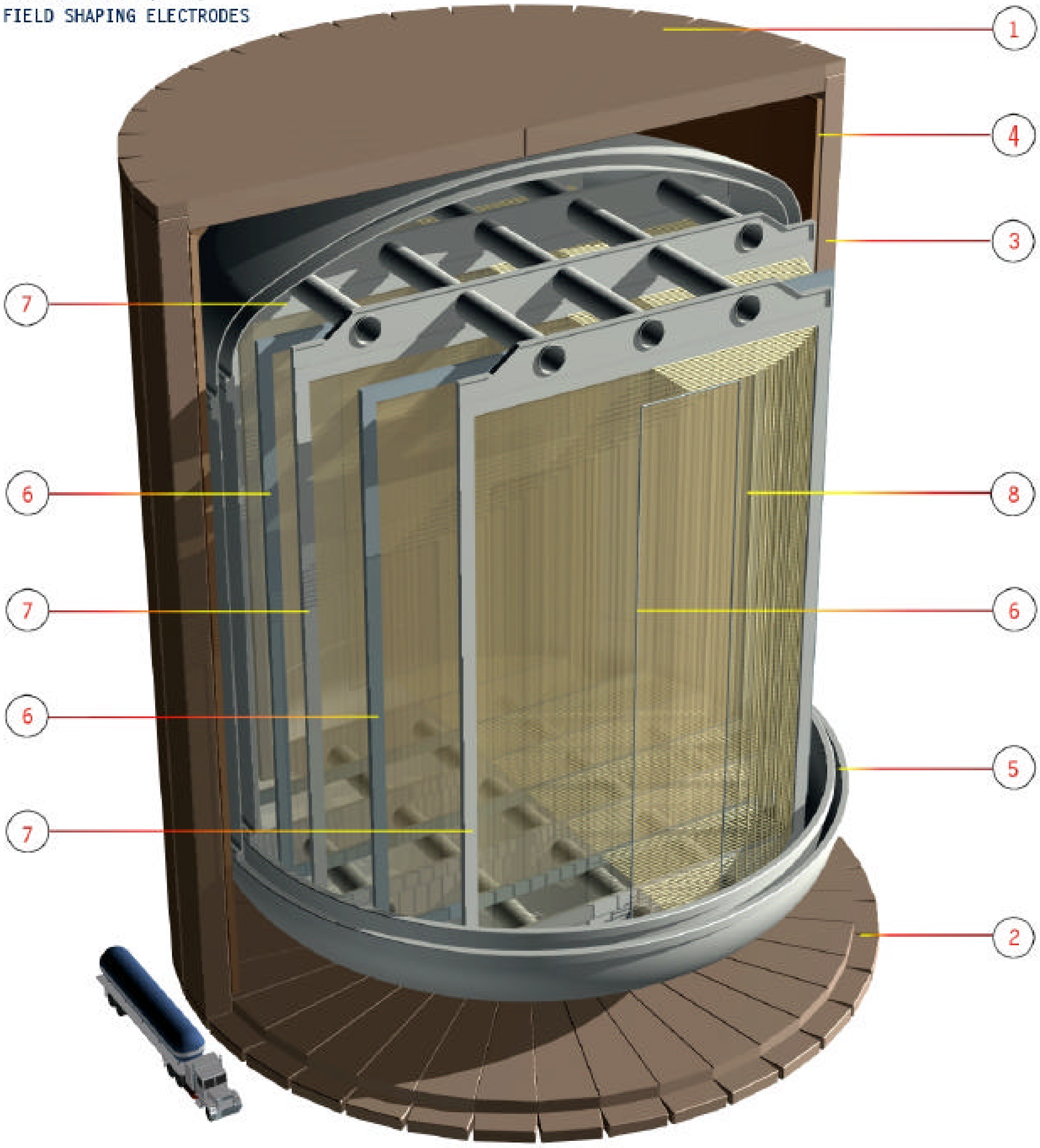
Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



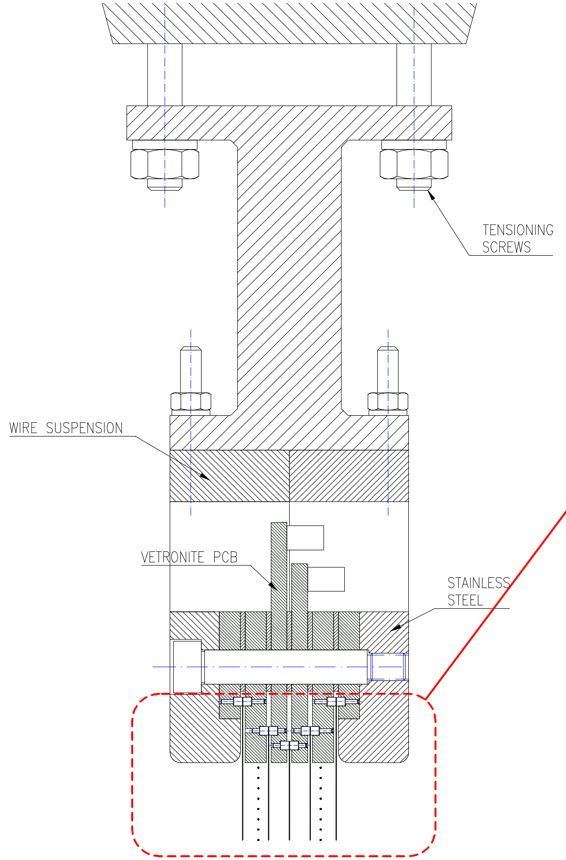
Drifting charge attenuation versus drift path at different electron lifetimes (***E*** = 0.5 kV / cm)

The full detector

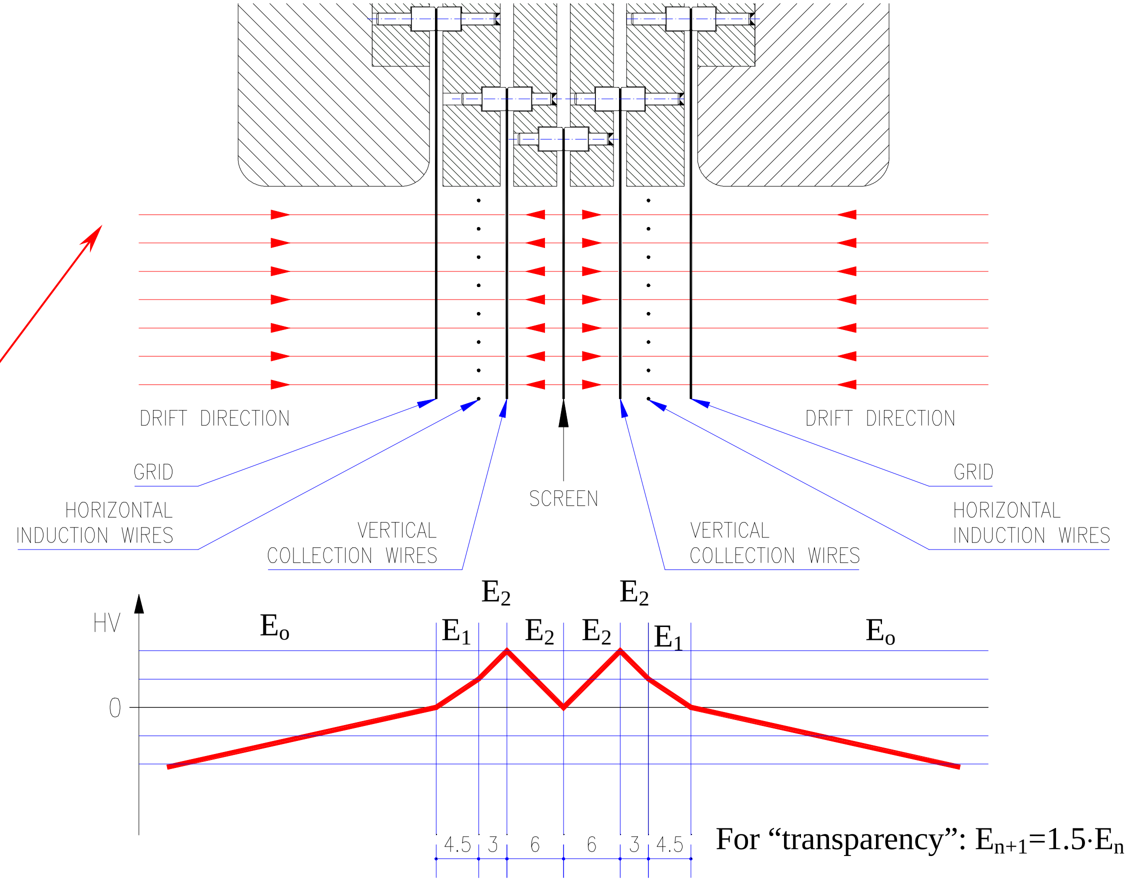
1- TOP END CAP IRON YOKE
2- BOTTOM END CAP IRON YOKE
3- BARREL IRON RETURN YOKE
4- COIL
5- CRYOSTAT
6- CATHODES (N° 5)
7- WIRE CHAMBERS (N° 4)
8- FIELD SHAPING ELECTRODES



Detector details



Wire hanging



7 wire planes:

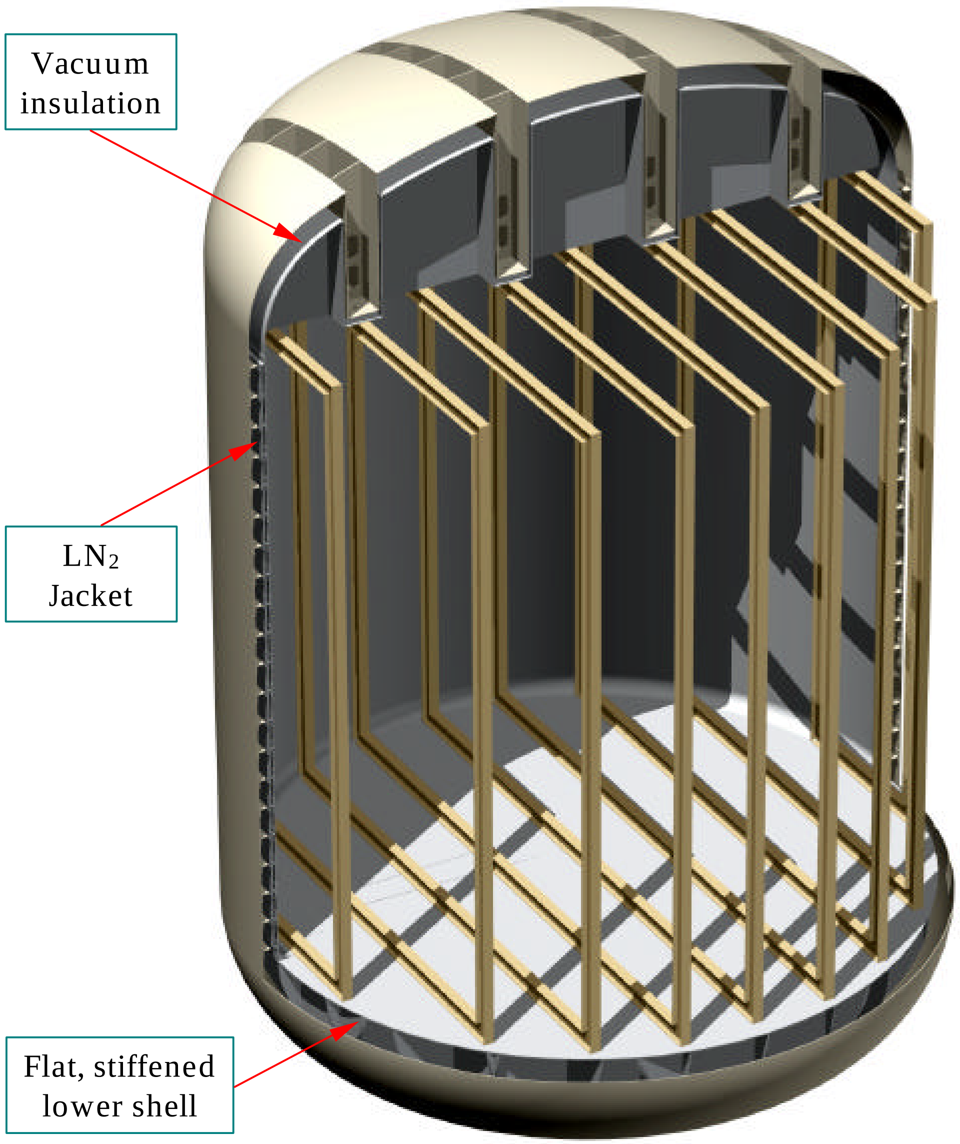
- 2 grid panes + 1 screen plane made by vertical wires referred to ground
- 2 induction planes with horizontal wires biased at +337.5 V
- 2 collection planes with vertical wires biased at +675 V

Stainless steel wires with ∅100 µm at a 3 mm pitch.

Channel maximum capacitance in LAr : 23 pF / m × 40 m + 2 m Cable ≈ 1 nF

ENC ≈ 1600 e^- rms, S / N ≈ 8 for minimum signals

Cryostat



Double wall cryostat, vacuum insulated (40 super-insulation layers $\rightarrow$ 0.5 W / m^2), LN_2 cooled and stabilised.

Heat input by radiation = **5.1 kW** corresponding to a LN_2 consumption of = **2.62 m^3/day.**

Heat input by conduction through cables and mechanical supports ≈ **25 kW** ≡ **6.5 LN_2 m^3/day**.

The magnet

Solenoid

Magnetic flux intensity .... $B = 0.2\ (0.4,\ 1.0)$ T

Ampere turns / m .... $nI = B/\mu_o$ .... $= 318.3$ A / m

Current density in Cu .... $J = 0.8$ A / mm^2

Coil inner diameter .... $D_c = 44$ m

Coil height .... $H_c = 58$ m

Total current .... $I_T = 18.5$ MA

Cu density .... $d = 8.96$ g / cm^3

Cu resistivity at 273 (90)°K .... $\rho = 1.55\ (0.29)$ µΩ·cm

Coil thickness .... $T_c = nI / J$ .... $= 0.2$ m

Power .... $W \approx \frac{\rho \cdot J}{\mu_o} \cdot B \cdot \pi \cdot D_c \cdot H_c = 17\ (37,\ 79)$ MW

Coil mass .... $M \approx \frac{d}{\mu_o \cdot J} \cdot B \cdot \pi \cdot D_c \cdot H_c = 16\ (33,\ 71)$ kT

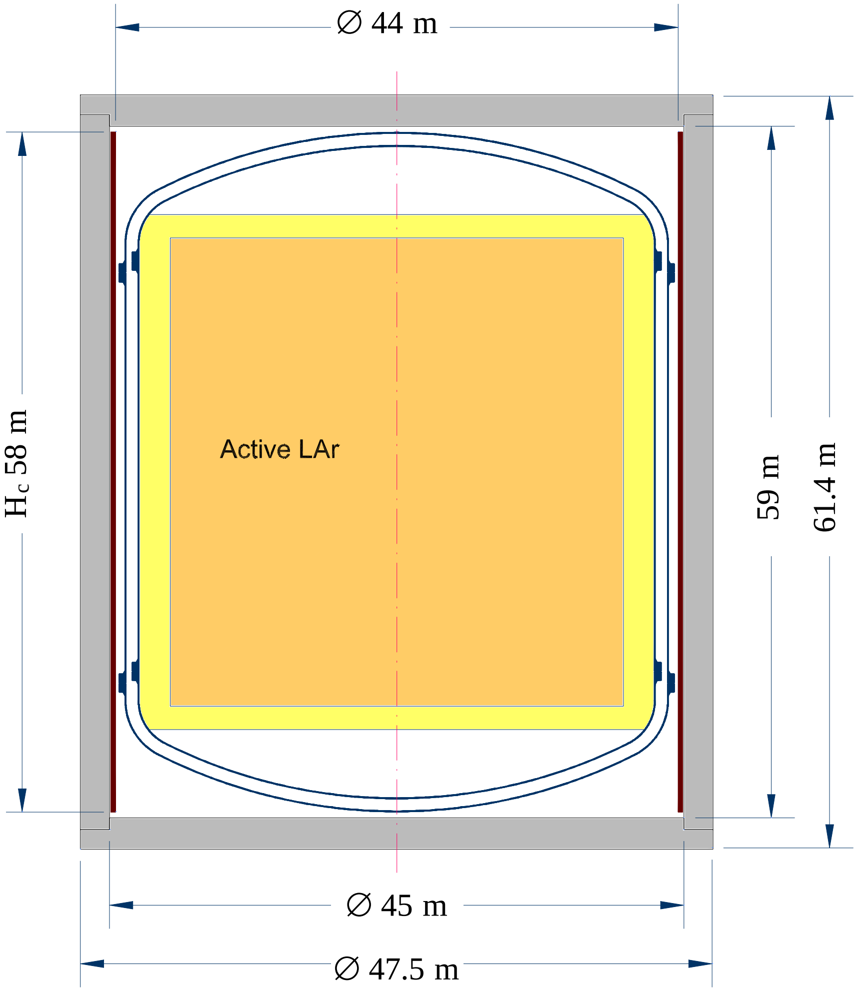
Iron yoke

LAr-to-Iron field ratio .... $\alpha = B / 1.8\,T$ .... $= 0.11\ (0.22,\ 0.55)$

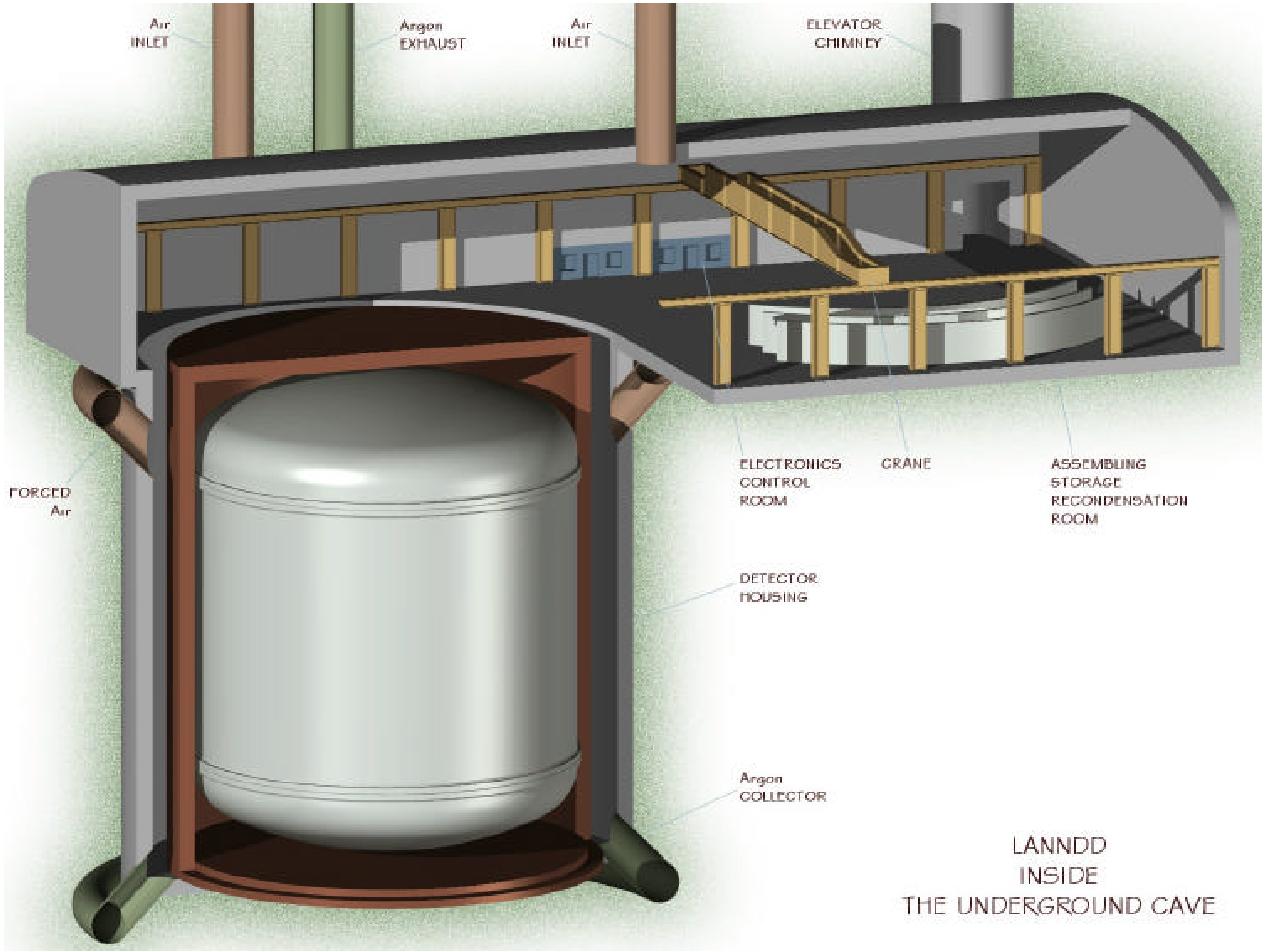
End cap yoke thickness .... $h_{Fe} \approx \alpha \cdot D_c / 4$ .... $= 1.2$ m

Barrel yoke thickness .... $T_{Fe} \approx D_c \cdot (\sqrt{1+\alpha} - 1) / 4 = 1.2$ m

Mass of the return yoke .... $M_{Fe} = 120\ (247,\ 677)$ kT



The underground housing



Preliminary activity

LANNDD PROJECT

- Feasibility study of the project
- Engineering of:
  - Inner detector design
  - Cryostat and cooling
  - Magnet
  - Safety and underground installation
- Commissioning survey
- Geologic survey

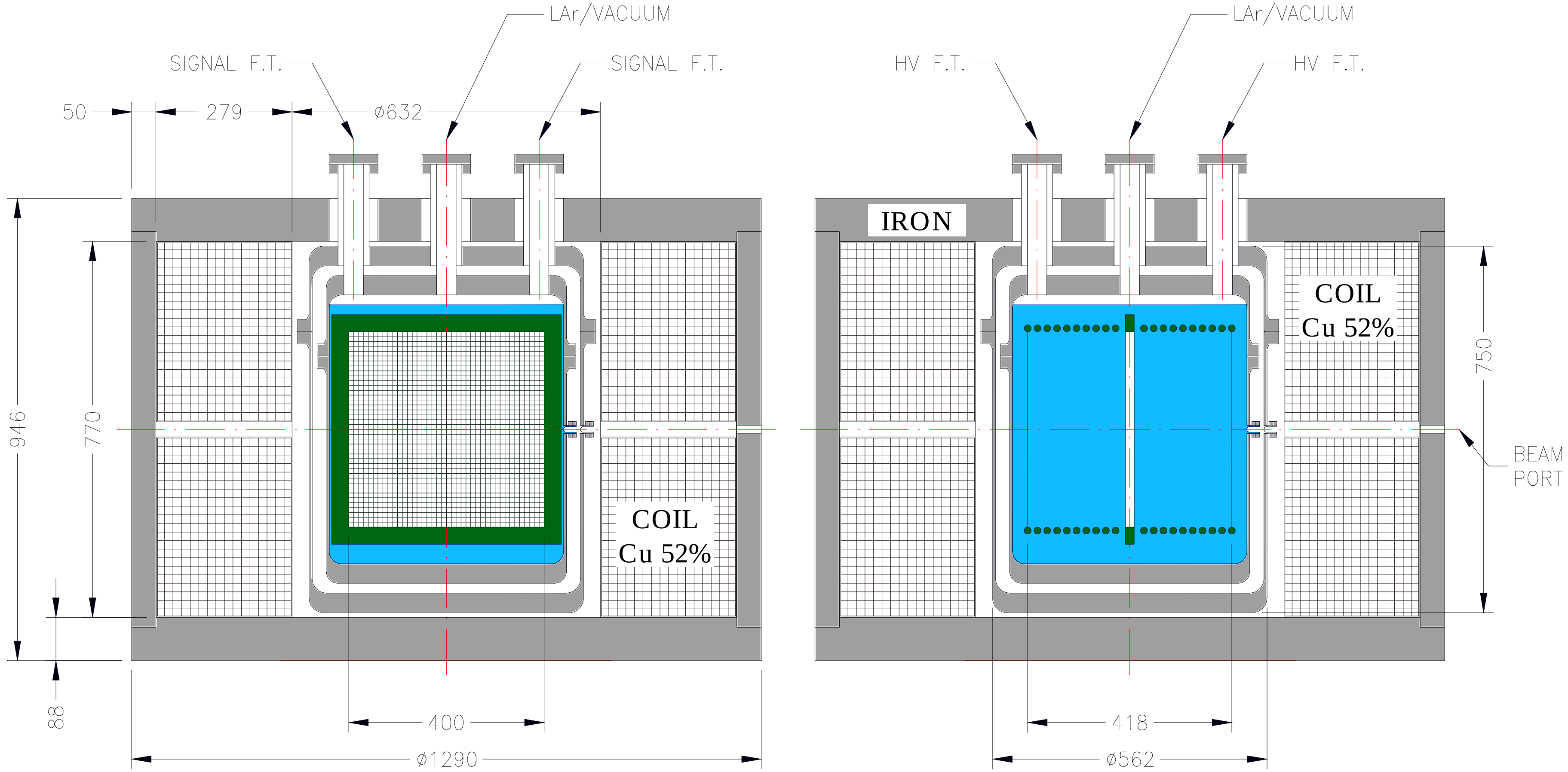
PRELIMINARY R&D Micro-LANNDD

- LAr TPC in magnetic field
- High hydrostatic pressure operation
- Very long drift paths (≥ 5 m)

REDUCED SCALE DETECTOR Mini-LANNDD

- Electron, muon and neutrino events in a magnetized LAr TPC
- Near imaging magnetized detector for ν-factories (and “baby ν-factories”)
- Test of all final technical solutions for LANNDD

µ-LANNDD

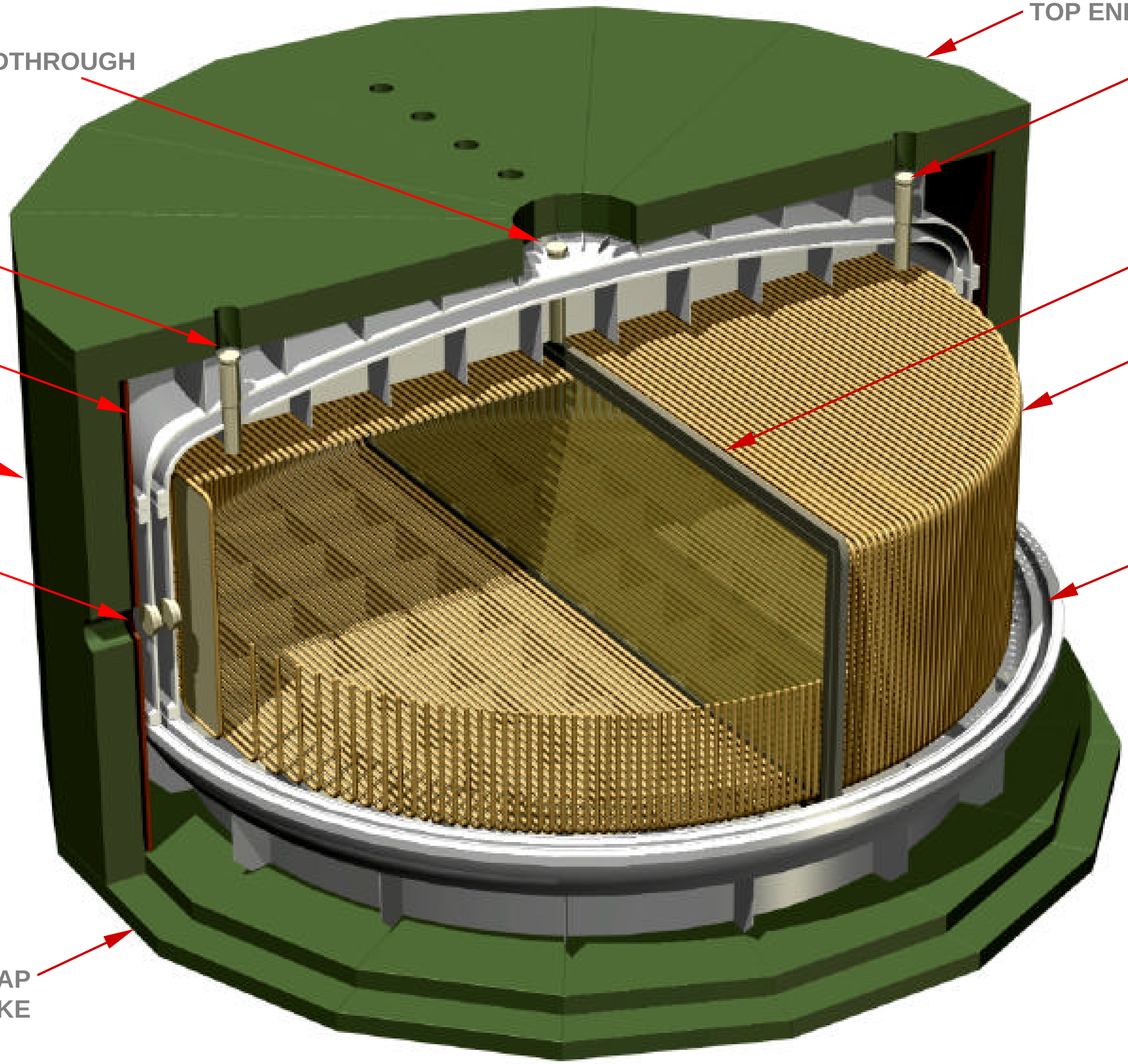


Active volume 50 L	Readout planes 4	Magnetic field 1 T	Power 127 kW
Wire pitch 2.5 mm	Total n of channels 1280	Coil mass 2.4 ton	Iron mass 2.3 ton

The same chamber (without magnetic field) can be instrumented for operating in high hydrostatic pressure conditions.

The long drift test is planned to be made in a dedicated chamber (horizontal axis cylinder, L = 6m, ∅ = 10cm) with HV up to 300 kV.

Mini-LANNDD



M = 440 T
Æ = 10 m
***h* = 4 m**
Drift = 2´5 m
B = 0.7¸1 T

n-event reconstruction in magnetic field

Near detector for a n-factory

Final technical solutions for LANNDD

Conclusions

Difficulties

Underground construction and operation.

Dedicated cryogenic plant required.

High magnetic fields (≈1 T) almost unrealistic for such a size.

Possible alternative

For ν-oscillations with ν-factory beams, we should consider a possible configuration made by a ∅=*H*=40 m detector, with low (≈0.2T) magnetic field, joint to a ∅=*H*=10 m detector, with high (≈1T) magnetic field, at shorter *L* and running at lower beam energy (same *L/E*, same ν-interactions rate, higher charge discrimination for μ and *e*, optimised for matter effects).

This study applies also to the scaled detector of this hypothesis.

Encouraging features

The high active mass, the low energy threshold and the high quality imaging of this detector are a valid response to the proton decay search within a realistic running time.

With such a mass, the configuration with a single module is, by far, too much convenient, from the point of view of detection performances and efficiency, construction and operation costs, compared with multi-module configuration.

A 0.2÷0.4 magnetic field seems affordable for the charge sign discrimination for muons and, with some efforts, for low energy electrons, opening to the study of ν-oscillations and related physics in conjunction with ν-factory beams.

Required

Strong, multi-institutions (international) collaboration.

Funding for preliminary R&D (μ-LANNDD).

Pre-detector (Mini-LANNDD) as near magnetized LAr TPC for ν-factory beams and for the certification of the final detection / technical solutions for LANNDD.

Funding for feasibility study and design engineering.