Neutrino Detector R&D Facilities Workshop

chaired by Brian Rebel (Fermilab)

from Wednesday, 20 January 2016 at **09:00** to Thursday, 21 January 2016 at **18:00** (US/Cent
at **Building 327 (The Big Room)**
Fermi National Accelerator Laboratory Batavia, Illinois

Dual Phase Liquid Argon TPCs

André Rubbia (ETH Zürich)

Fermilab, January 21st 2016

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The LAr TPC: a tool for discoveries

- The **Liquid Argon Time Projection Chamber** is the successful marriage between the “gaseous TPC” and “the liquid argon calorimeter” to obtain a dense and very fine grained 3D tracking device (mm-scale resolution) with local dE/dx information and a homogenous full sampling calorimeter (e.g. $\approx 2\% X_0$ sampling rate for 3mm pitch). It can be operated in trigger-less mode, hence is continuously active.

- After many decades of pioneering R&D, the technology has matured into a **fundamental and necessary technique to address the particle physics challenges of the 21st century.** It has the potential to be the tool to discover new phenomena, such as:
  - **the convincing case for the existence of sterile neutrinos;**
  - **the discovery of CP-violation in the lepton sector;**
  - **the unambiguous observation of nucleon decay;**
  - **the direct detection of Dark Matter WIMPs-induced recoils or of the “neutrino floor”;**
  - **the possible observation of unpredicted rare events.**

- We aim at the best possible of all detectors…

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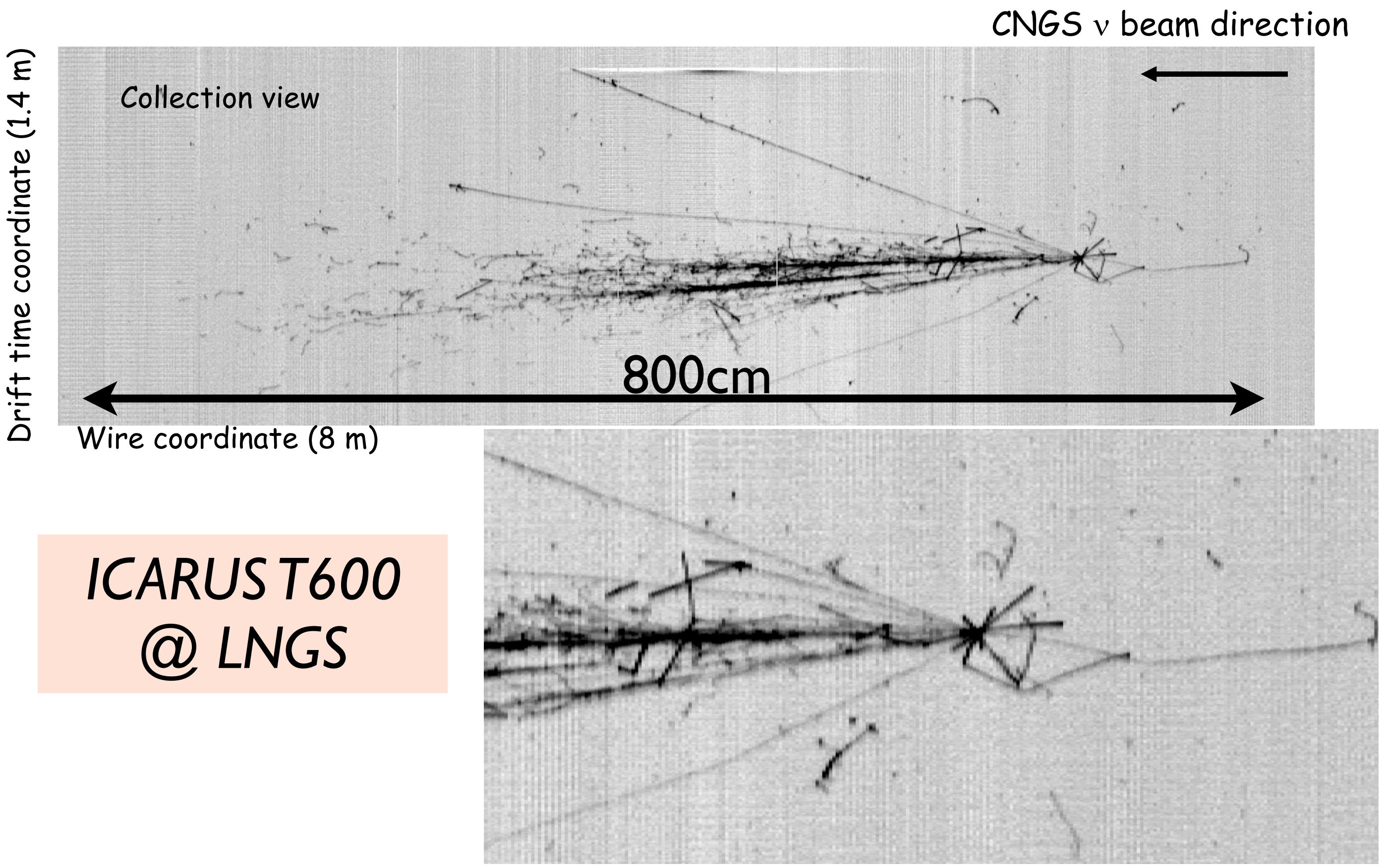
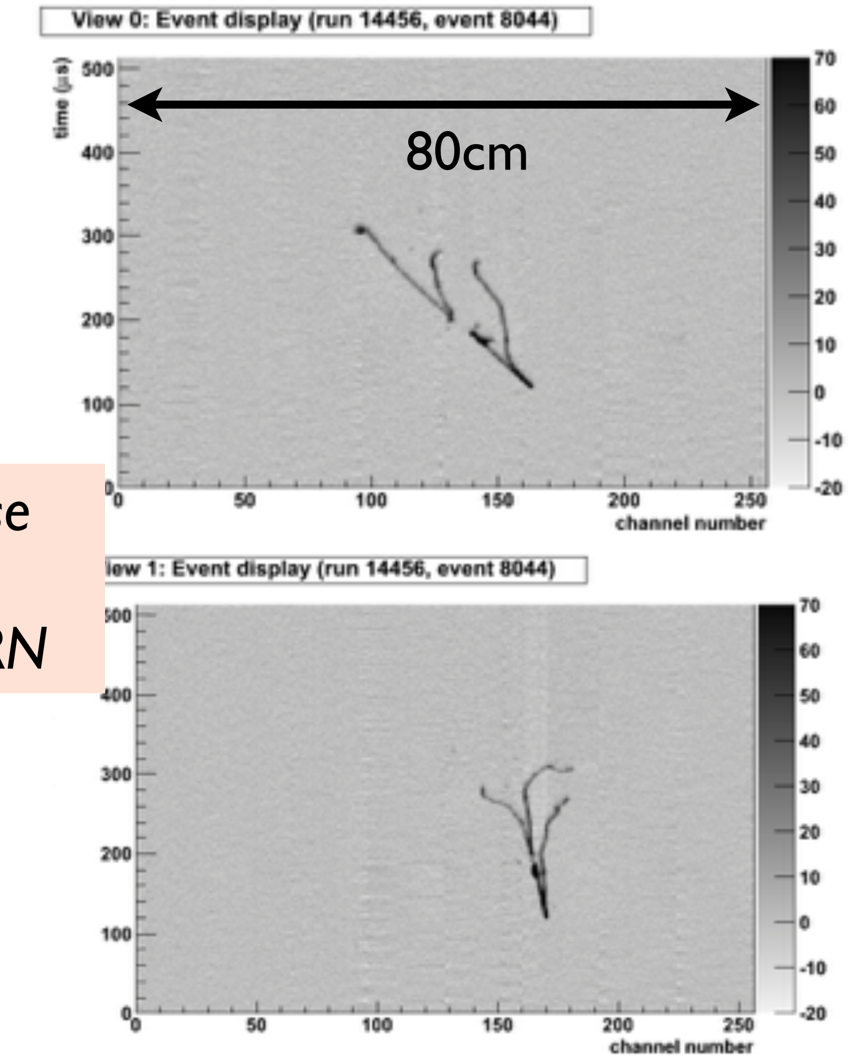
Any one of these would be a major discovery !!!!

- ★ We aim at the best possible of all detectors…

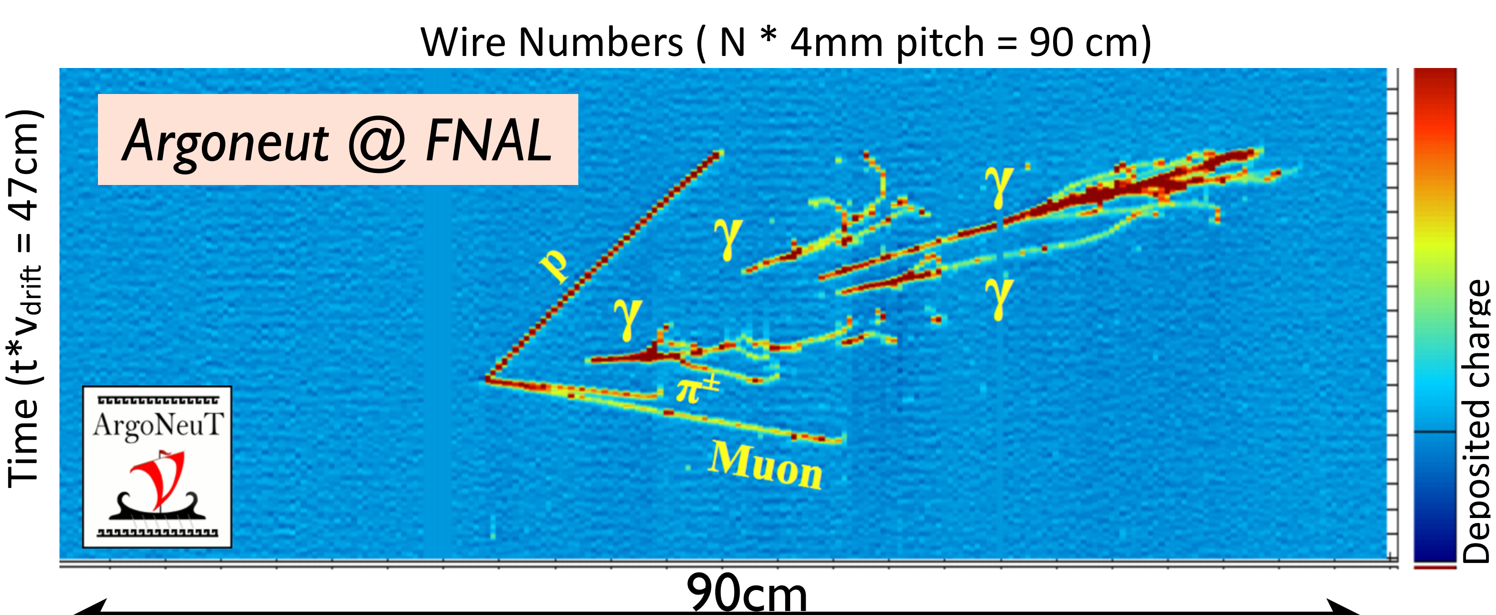
The "electronic bubble chamber"



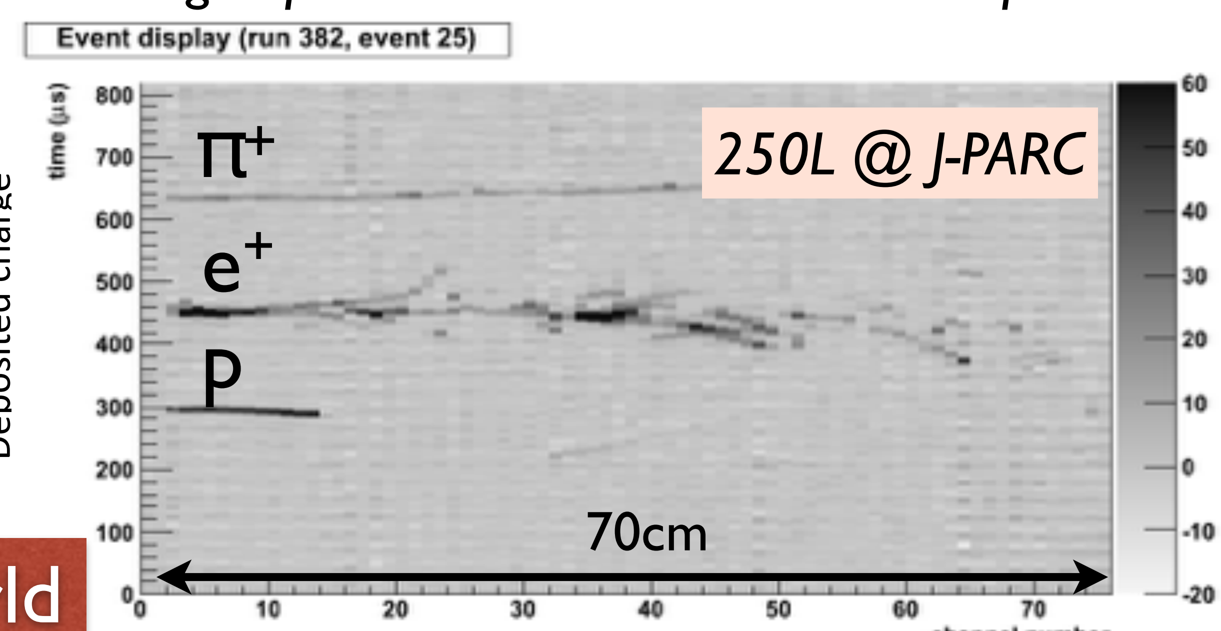
ICARUS T600 @ LNGS



Dual phase 250L @ ETHZ/CERN



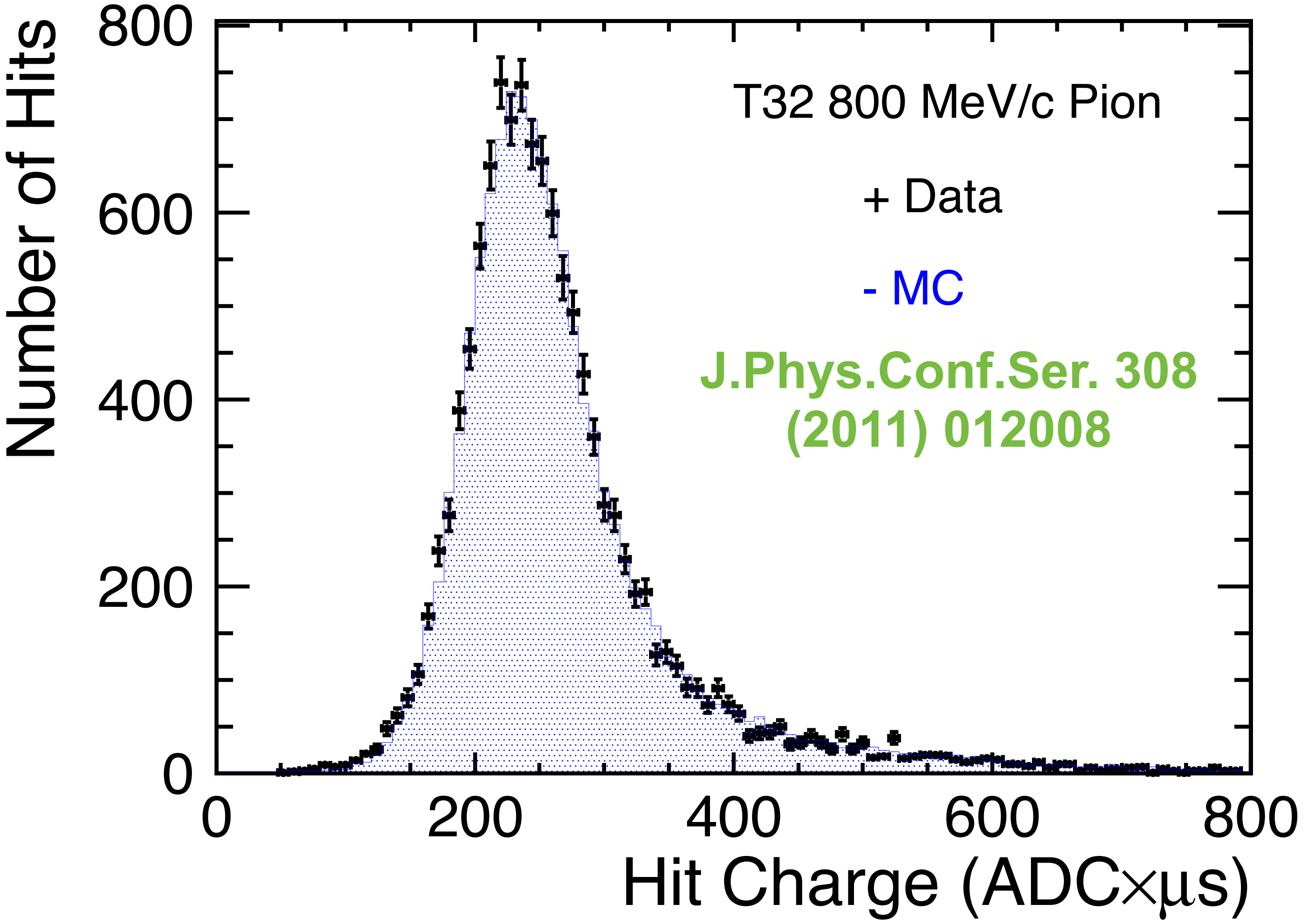
Charged particle beam ≈800 MeV/c exposure



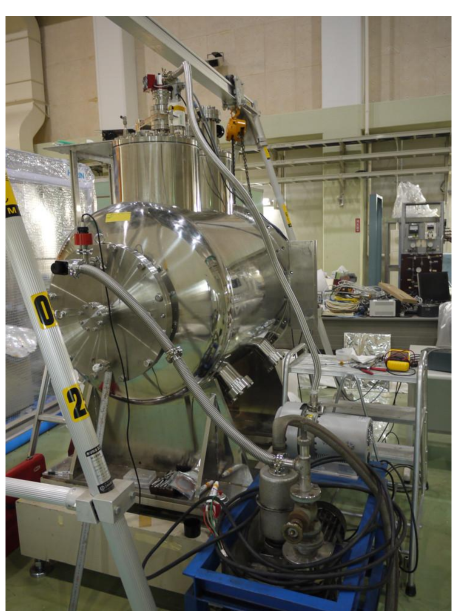
Basic features reproducible around the world

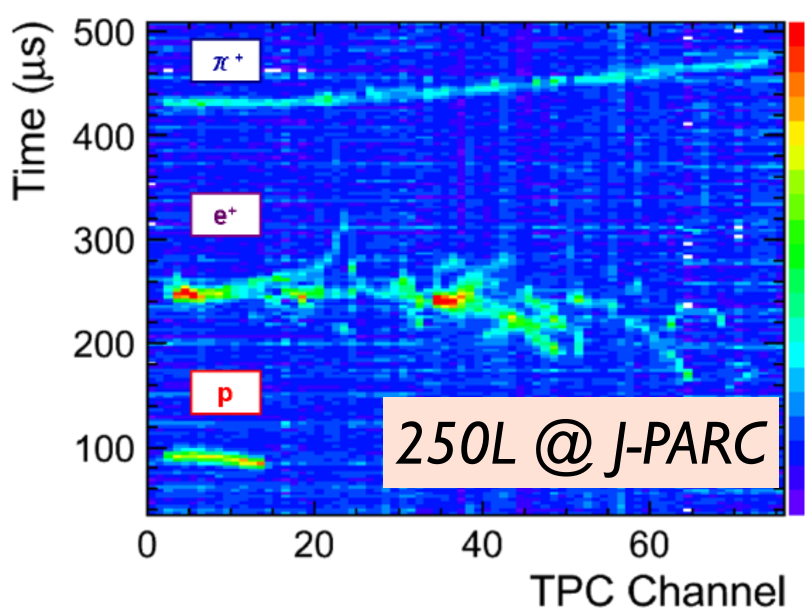
Tracking performance

JPARC T32 exposed to K1.1BR tagged beam



J-PARC T32 chamber (ETHZ-KEK-Iwate-Waseda)





Charge recombination

Data well described by:

Birks Law

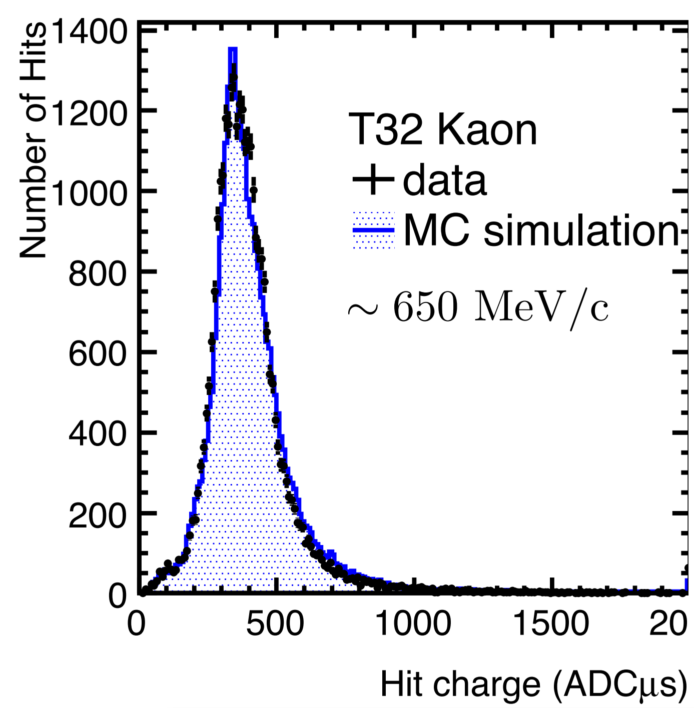
$$Q = A \frac{Q_0}{1+(k/\varepsilon)\times(dE/dx)\times(1/\rho)}$$

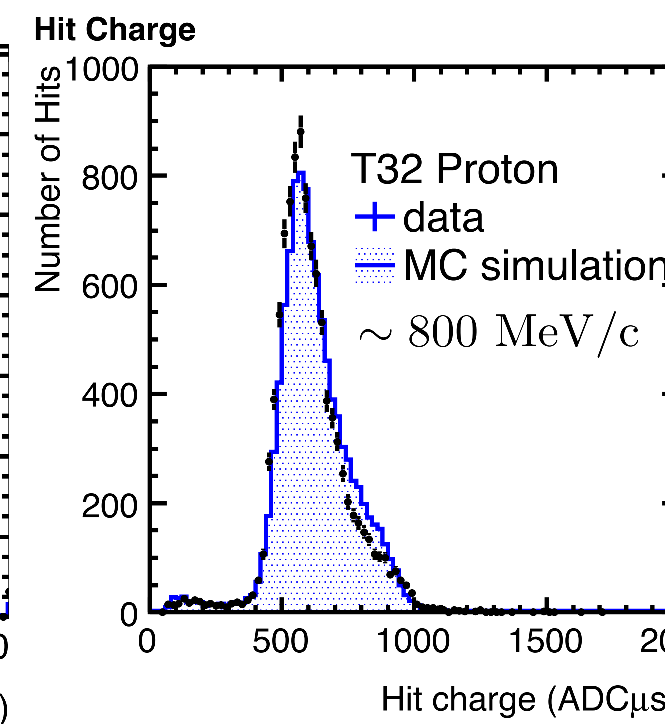
Q: Observable charge; Q_0: Raw charge

$$A = 0.8$$

$$k = 0.0486\ \mathrm{kV/cm}\,\frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$$

NIM A 523, 275 (2004)



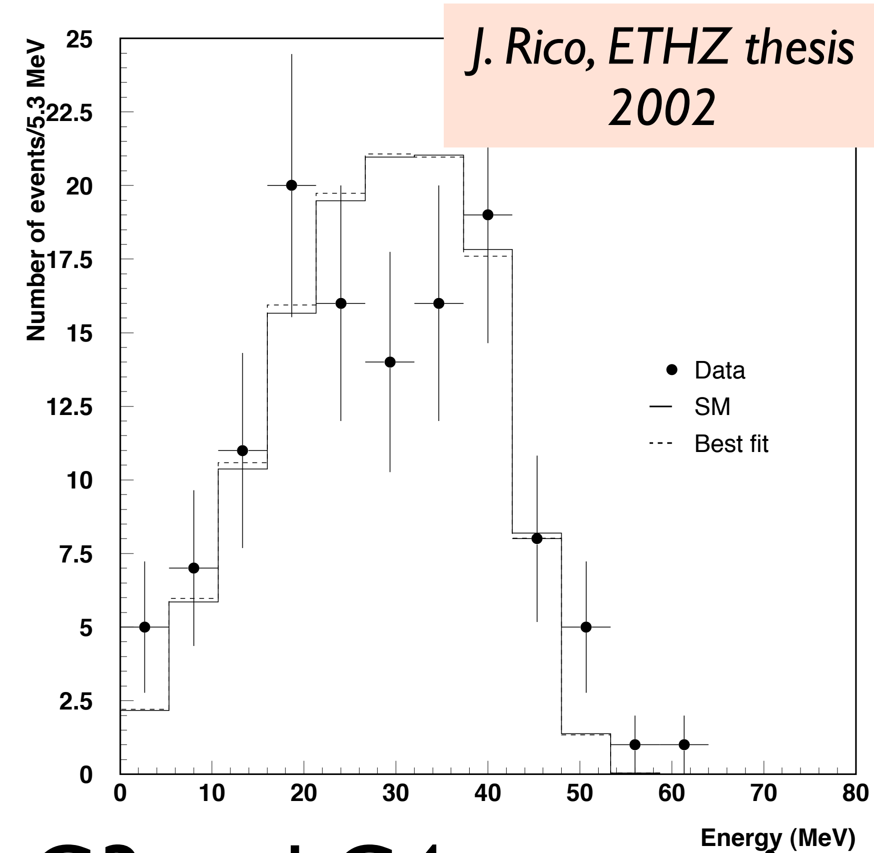


Good understanding of tracking

Calorimetric performance

Michel electrons form stopping muon decay sample

$$\frac{\sigma_e}{E} \simeq \frac{11\%}{\sqrt{E(\mathrm{MeV})}} \oplus 4\%$$



Eur. Phys. J. C33, 233 (2004)

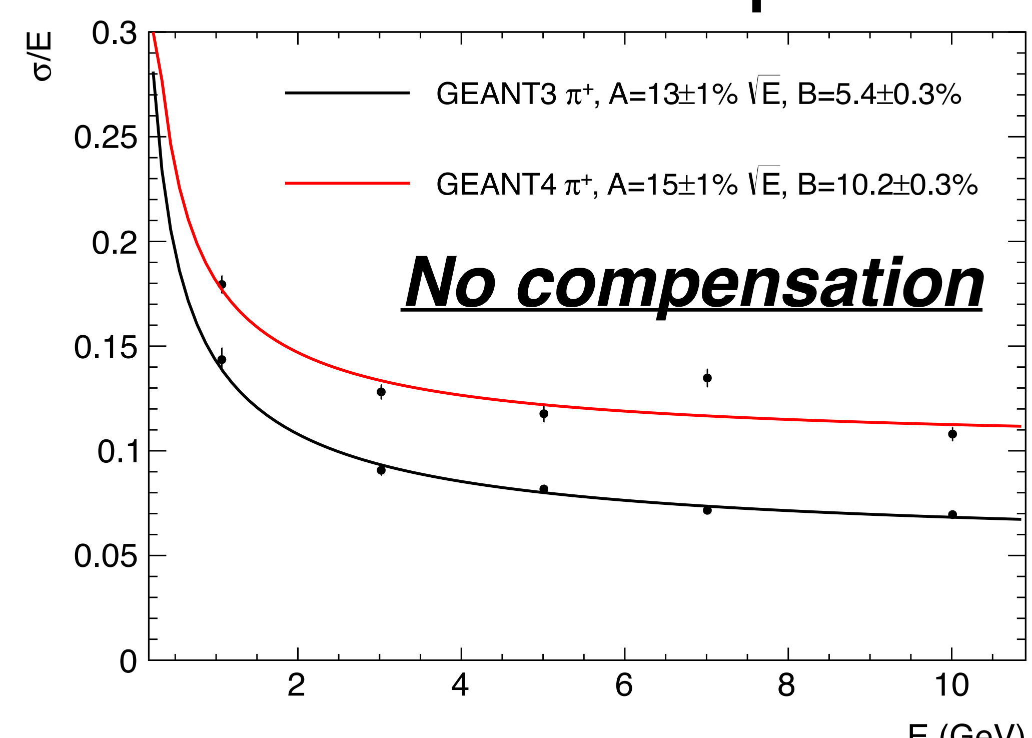
MC simulations at higher energies:

$$\frac{\sigma^{MC}_{em}}{E} \simeq \frac{3\%}{\sqrt{E}} \oplus 1\%$$

$$\frac{\sigma^{MC}_{had}}{E} \simeq \frac{15\%}{\sqrt{E}} \oplus 10\%$$

↑ needs to be confirmed by experimental data

G3 and G4 comparison

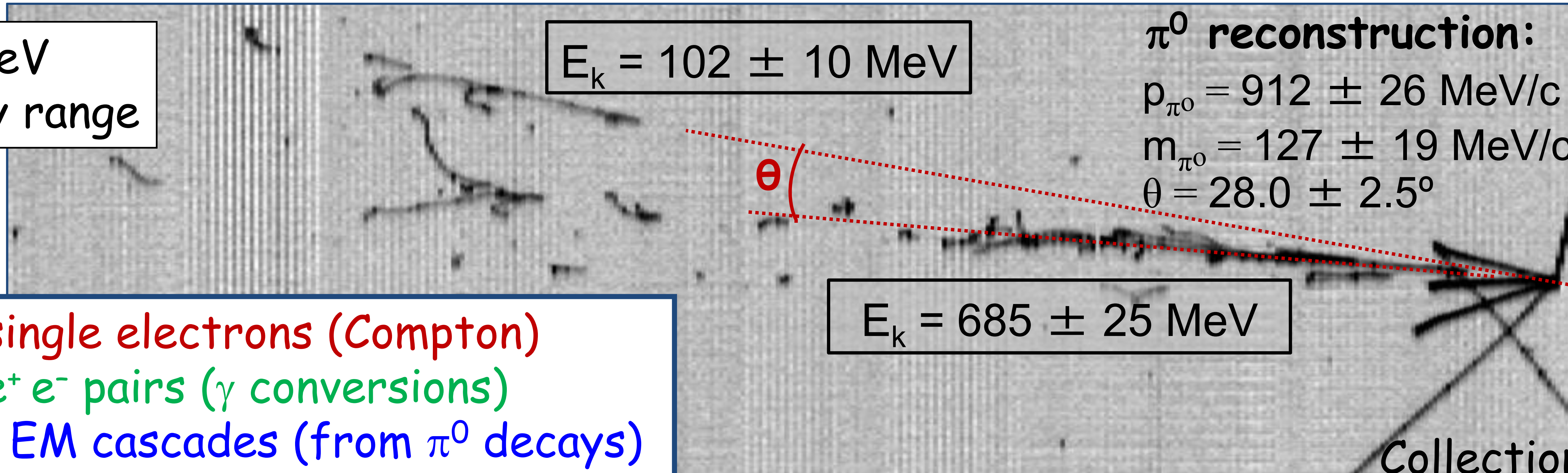


Calorimetry with LAr TPC is less well known

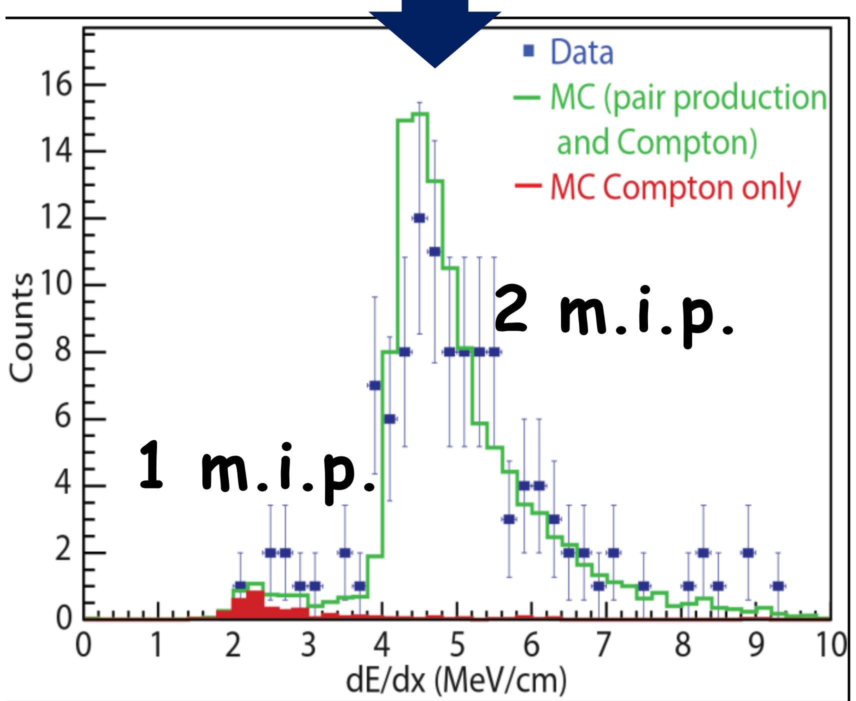
e/gamma separation

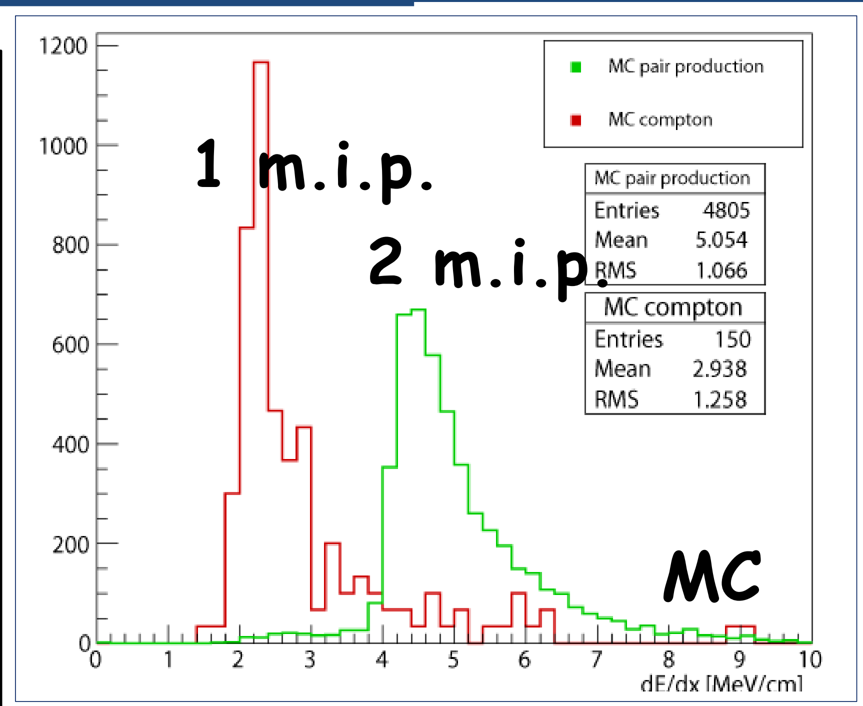
ICARUS T600 @ LNGS

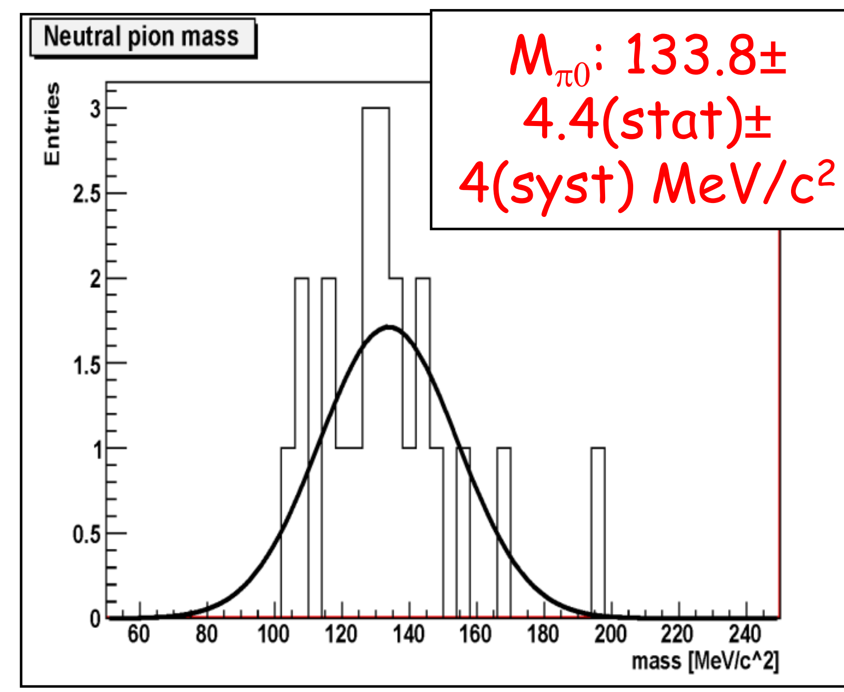
Sub-GeV Energy range



- MC: single electrons (Compton)
- MC: $e^+ e^-$ pairs (γ conversions)
- data: EM cascades (from π^0 decays)







LAr unique features allow e/γ separation and π^0 reconstruction

Performance is promising - showers reconstruction still challenging

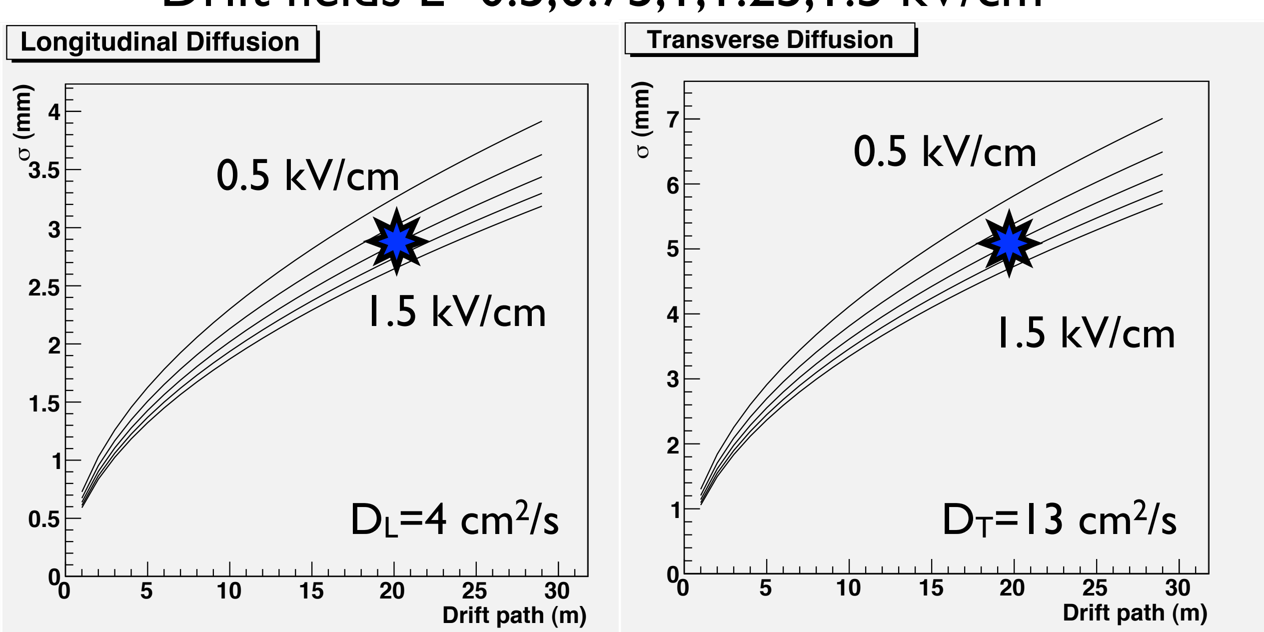
Liquid Argon properties

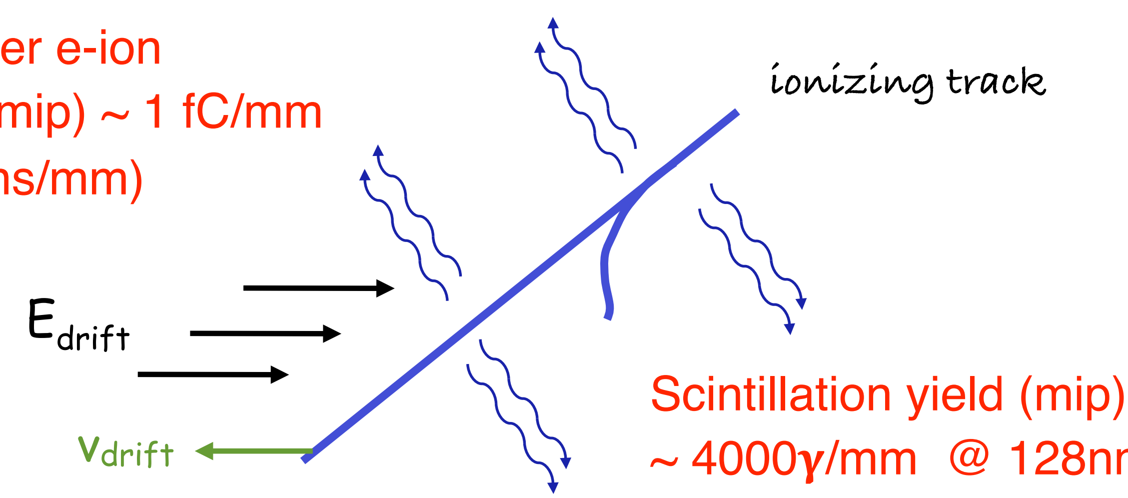
Property	Liquid Argon
Density (g/cm3)	1.4
Radiation length (cm)	14
Interaction length (cm)	83.6
dE/dx mip (MeV/cm)	2.1
We (eV) @ E=∞	23.6
Wγ (eV) @ E=0	20
Refractive index (visible)	1.24
Cerenkov angle	36°
Cerenkov $d^2N/dEdx$ (β=1)	≈ 130 eV^{-1} cm^{-1}
Muon Cerenkov threshold	140 MeV/c
Boiling point @ 1 bar	87 K

Noble liquid

Liquid Argon:
+ High density, cheap medium
+ Quasi free electrons from ionizing tracks are drifted by E_{drift}.
+ Electron drift velocity ≈ 2mm/μs @ 1 kV/cm
+ Ion mobility << electrons & badly measured (10^{-2}-10^{-4} cm^2/Vs)
+ Electron cloud diffusion is small ($\sigma \approx \sqrt{2Dx/v_{drift}}$ ≈ mm after several meters of drift)
+ High scintillation yield (@ 128 nm) can be used for T_0, trigger, ...

Drift fields E=0.5,0.75,1,1.25,1.5 kV/cm





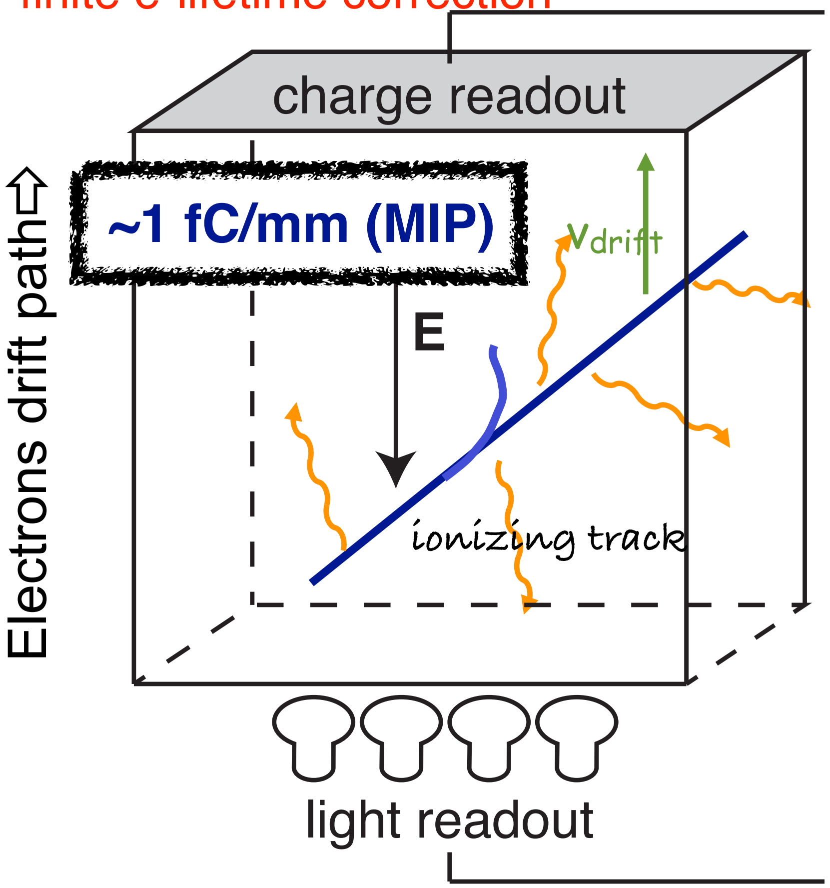
(Electron-ion recombination ≈ 30% for m.i.p. @ 1 kV/cm)

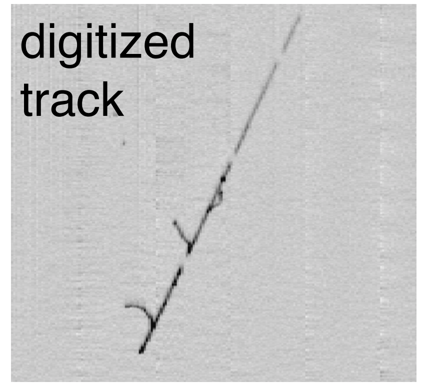
The ionisation signals provide the most valuable information of the event. For a 3mm pitch, collect ≈18000 electrons for m.i.p, so ≈1000 ENC noise gives S/N ≈ 20.

Principle of the LAr TPC

Basic technique established

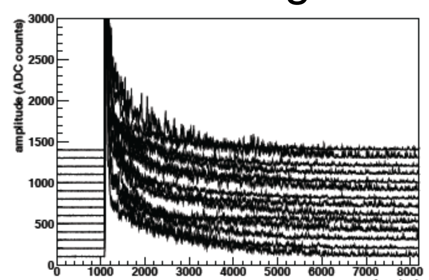
Charge yield after e-ion recombination (mip) ~ 1 fC/mm (~ 6000 electrons/mm) before finite e-lifetime correction





Scintillation yield (mip) ~ 4000γ/mm @ 128nm

scintillation light



Technical challenges:

– Long drift requires ultra high purity
  * free of electro-negative molecules (O_2, H_2O, ...)
    Goal << 100 ppt O_2 equivalent !!
  * Drift field implies high voltage on the cathode

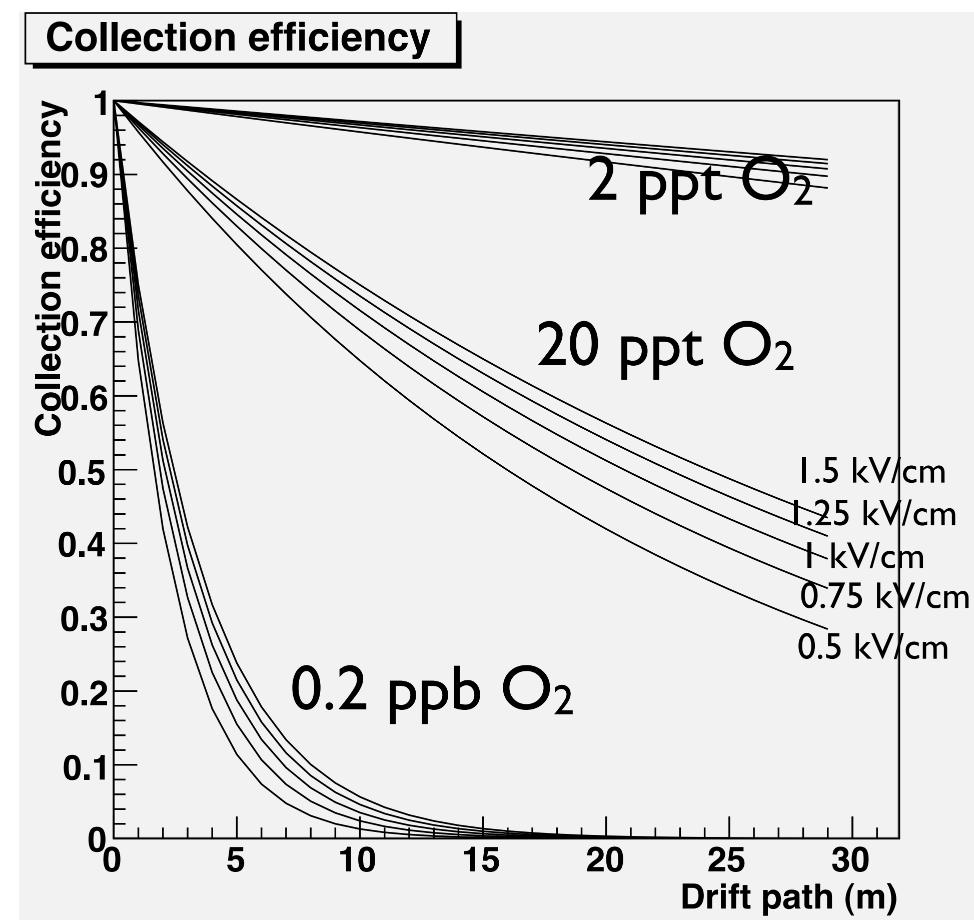
– Large readout chambers at cryogenic T

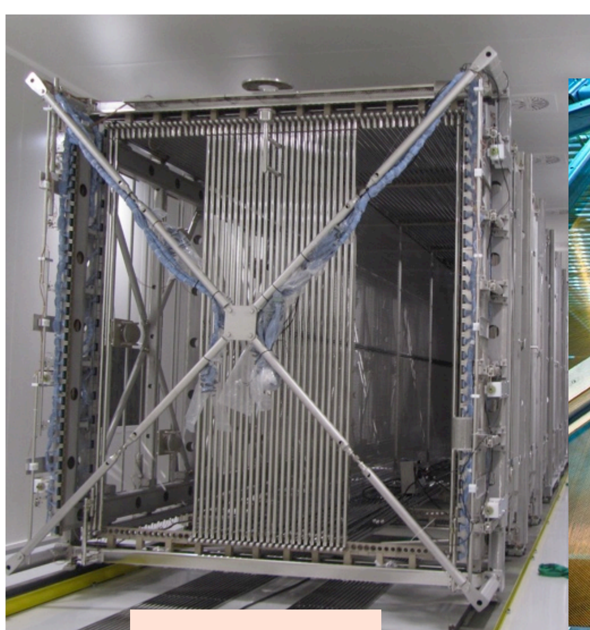
– No charge amplification in single phase: fC-level charge sensitive preamplifiers

– Large #readout channels

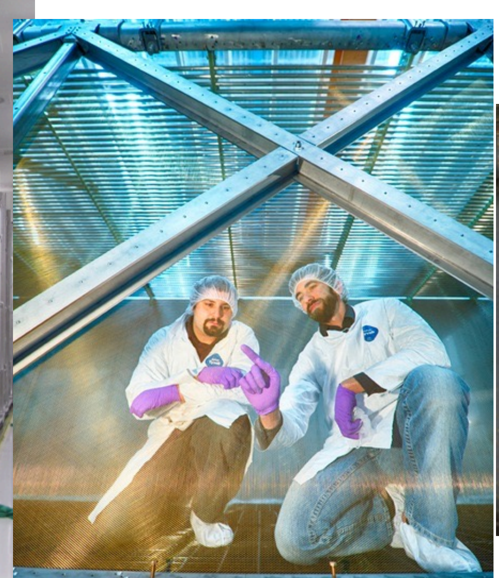
– Large cryogenic systems

Charge attenuation because of attachment to impurities

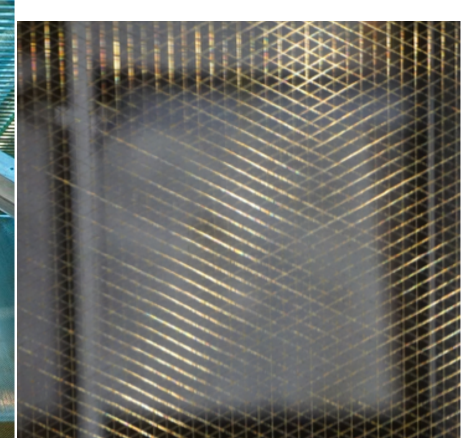




ICARUS

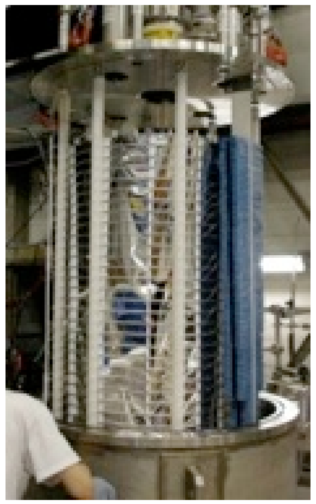


MicroBoone



3mm wire pitch

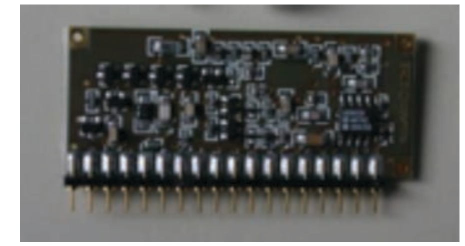
The path towards very large detectors



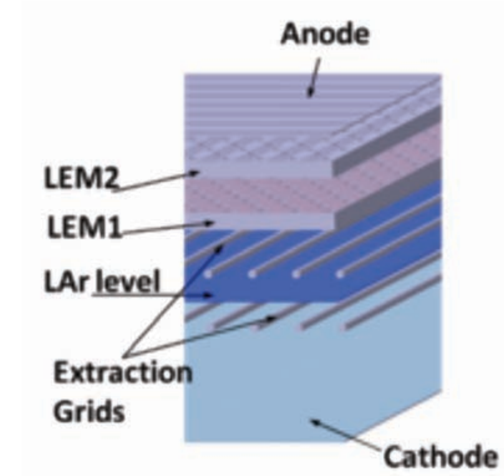
High Voltage systems

Long Drift

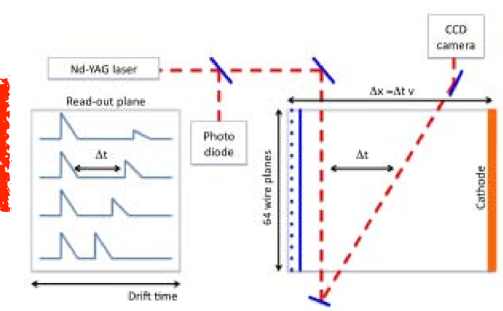
Diffusion



Readout devices and electronics

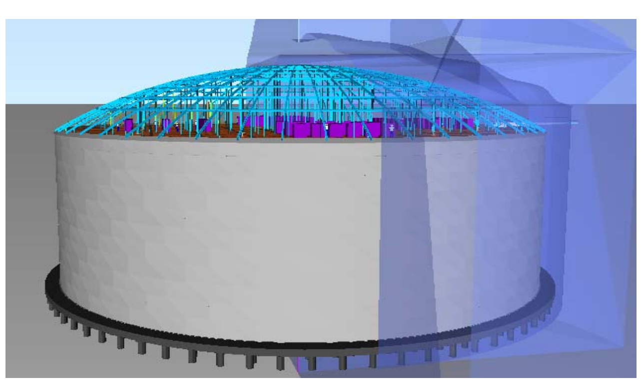


Argon purity

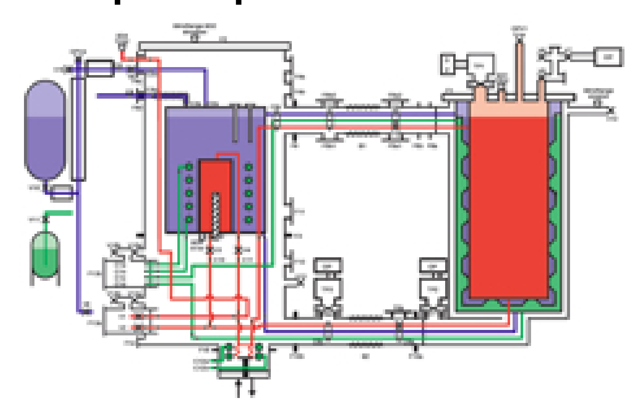


LAr vessel

Detector engineering, safety, underground construction



Argon purification, cryogenic pumps



Focusing on charge readout

Milestones towards dual phase TPC

2003: The concept

- AR, Experiments for CP-violation: A giant liquid argon scintillation, Cherenkov and Charge imaging experiment? hep-ph/0402110.

2008-2011: Proof of principle with 10x10 cm^2 double phase 3 liter LAr LEM-TPC prototype:

- A. Badertscher *et al.*, "Operation of a Double Phase pure argon Large Electron Multiplier Time Projection Chamber: comparison single and double phase" NIM A617 (2010) p188-192
- A. Badertscher *et al.*, "First operation of a double phase LAr Large Electron Multiplier Time Projection Chamber with a two- dimensional projective readout anode" NIM A641 (2011) p. 48-57

2011: First successful operation of a 40x80 cm^2 ton-scale device

- First operation and drift field performance of a large area double phase LAr Electron Multiplier Time Projection Chamber with an immersed Greinacher high-voltage multiplier JINST 7 (2012) P08026
- First operation and performance of a 200 lt double phase LAr LEM-TPC with a 40x76 cm^2 readout, JINST 8 (2013) P04012

2012-2013: further R&D towards final, simplified charge readout:

- First results presented at TPC Symposium in Paris
- Long-term operation of a double phase LAr LEM Time Projection Chamber with a simplified anode and extraction-grid design C Cantini et al 2014 JINST 9 P03017
- **Creation of WA105 project at CERN Neutrino Platform**

Milestones towards dual phase TPC

2014: further optimisation of the anode & LEM geometries

- Performance study of the effective gain of the double phase liquid Argon LEM Time Projection Chamber C Cantini et al JINST 10 (2015) 03, P03017
- Large-scale neutrino detector demonstrators for phased performance assessment in view of a long-baseline oscillation experiment, L. Agostino *et al*.. CERN-SPSC-2014-013, SPSC-TDR-004
- **Approval of WA105 6x6x6m3 proposal by CERN**

2015: design and development of 3x1x1m3 and 6x6x6m3 detectors

- Progress report on LBNO-DEMO/WA105 (2015) CERN-SPSC-2015-013 ; SPSC-SR-158
- Short Status Update on LBNO-DEMO/WA105 (2015), CERN-SPSC-2015-027 ; SPSC-SR-166
- **WA105 activities becomes part of DUNE prototyping effort known as ProtoDUNE-DP**

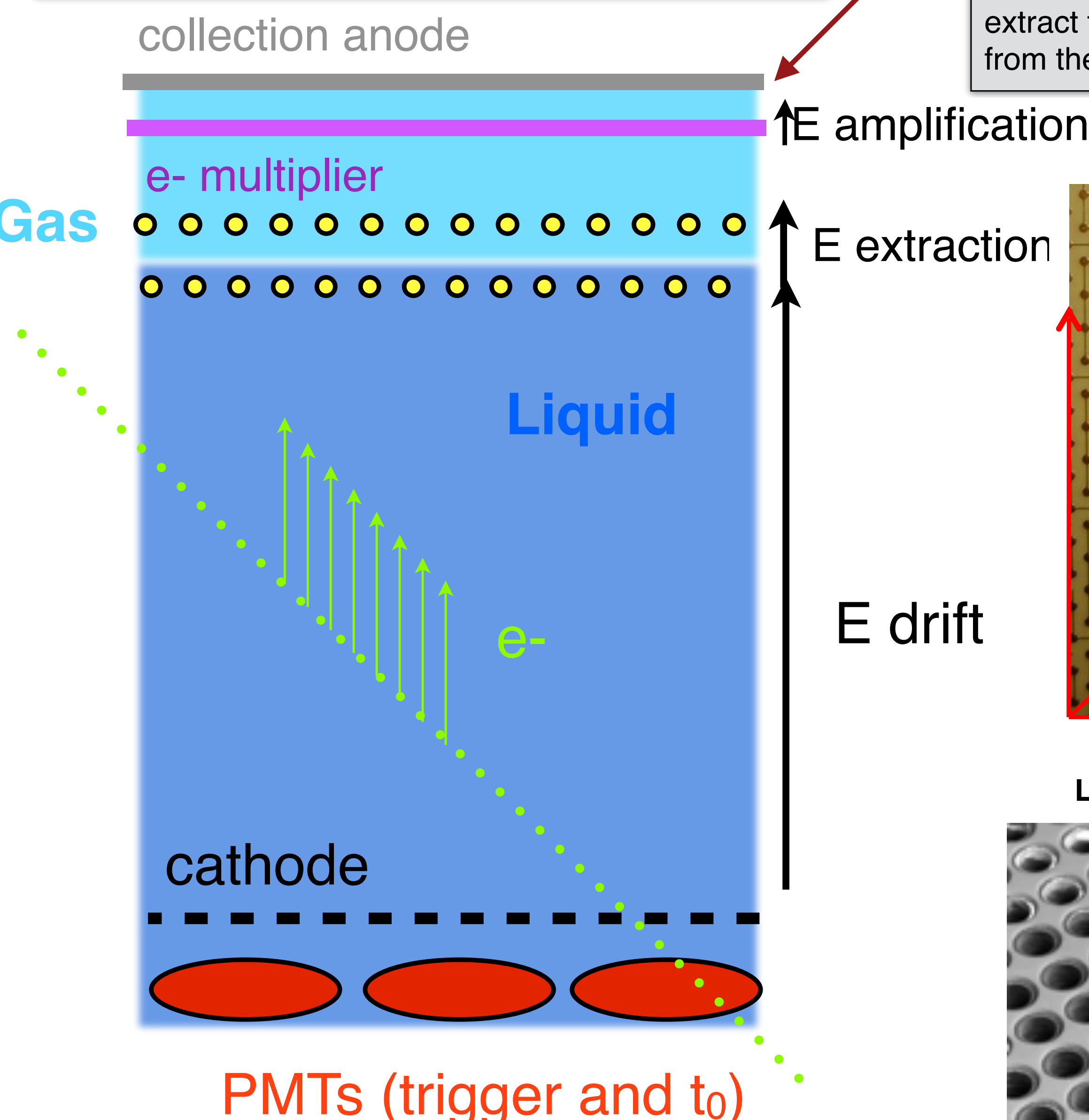
2016 ?: first operation of 3x1x1m3 (10-ton scale) detector

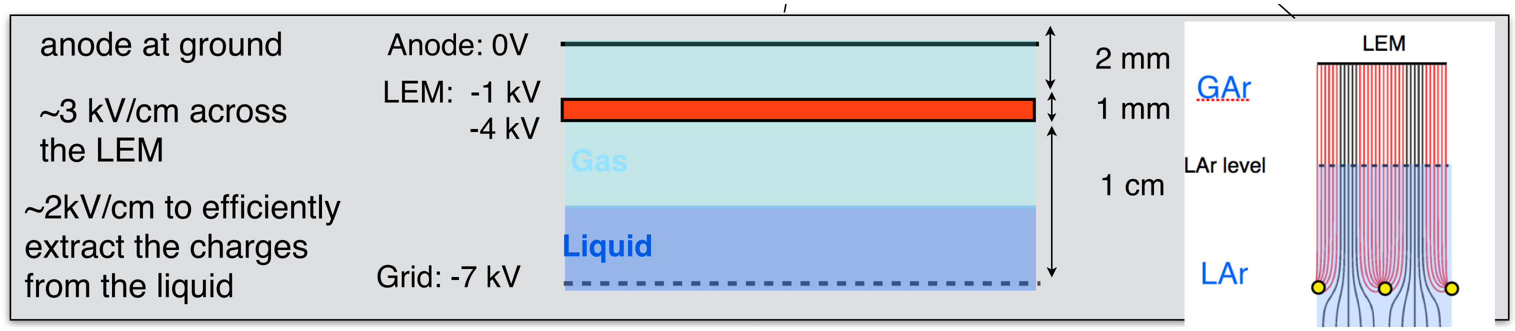
- Short Status Update on the WA105 experiment (2016) at the Neutrino Platform CERN-SPSC-2016-009 ; SPSC-SR-179. - 2016

2018 ?: first operation of 6x6x6m3 (300-ton scale) detector

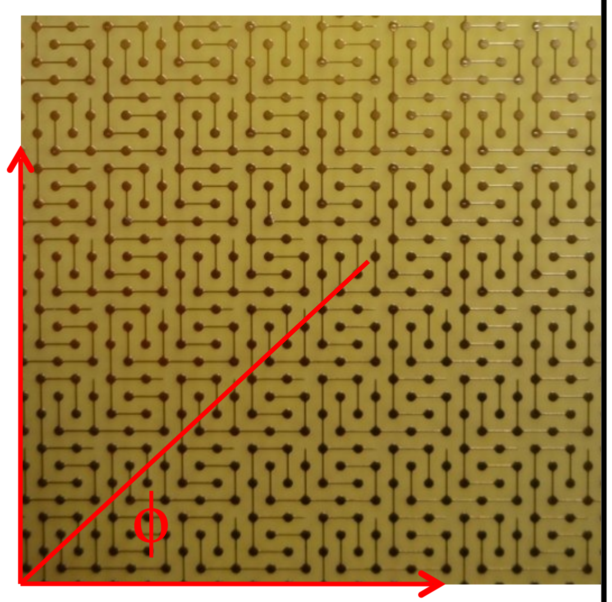
Dual phase LAr TPC

Basic technique OK – R&D towards large scale

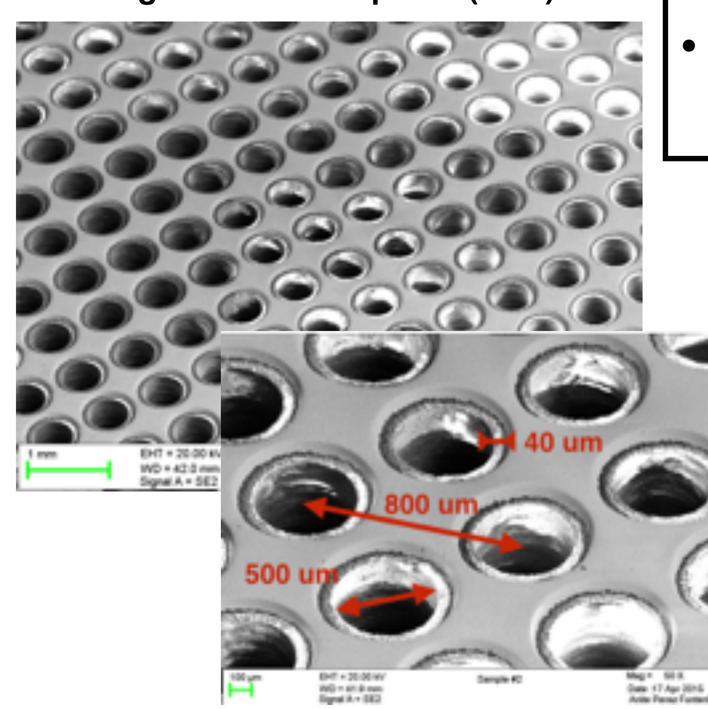




Anode

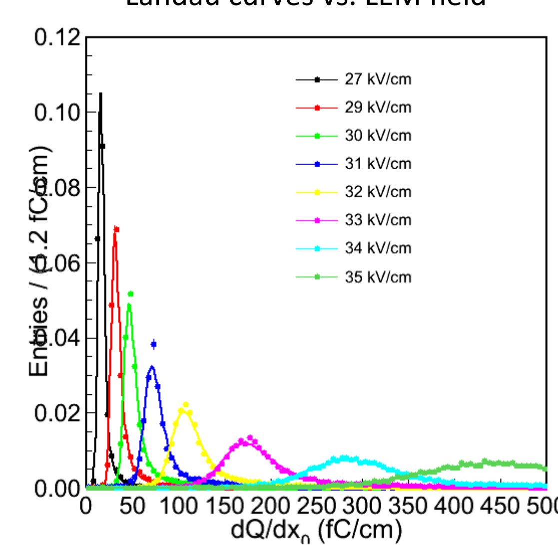


Large Electron Amplifier (LEM)



- Fine readout pitch (3mm or less?)
- Robust S/N ratio with tuneable gain
- Low detection energy threshold
- Only charge collection (no induction planes) → pattern reconstruction with two views, save on r/o channels
- Cope with electron diffusion & charge attachment so longer drift paths
- Insensitive to microphonic noise
- Gain demonstrated up to 180 → S/N≈10 for 15 keV of energy
- Optimal gain for neutrino physics operation ≈ 10 - 20

Landau curves vs. LEM field



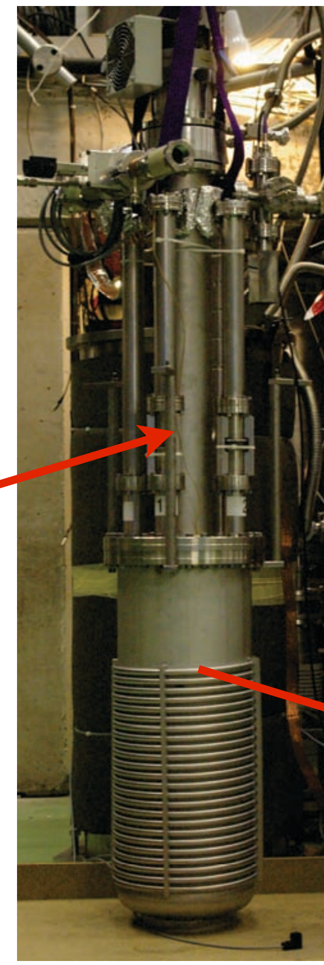
For MIPs:
- 10 fC/cm — ~10 k e^- for each strip (3 mm pitch,2 views) — SNR of 10 (noise of 1000 e^-)
- SNR of 100 — gain of 20 is needed

A. Badertscher et al. NIM A641 (2011) 48-57

Charge readout R&D: the 3L double phase argon LEM-TPC @CERN

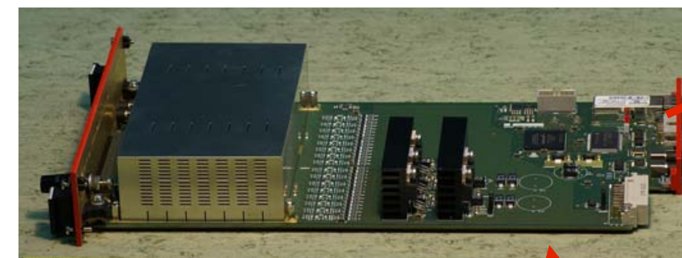
- 3L size LAr-TPC is used to test new readout techniques in order to improve the signal to noise ratio
- Successful tests done with two different gas multipliers: LEM (coupled with 2D anode) and MicroMeGas

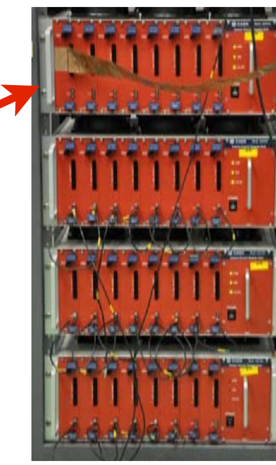
Setup located at CERN



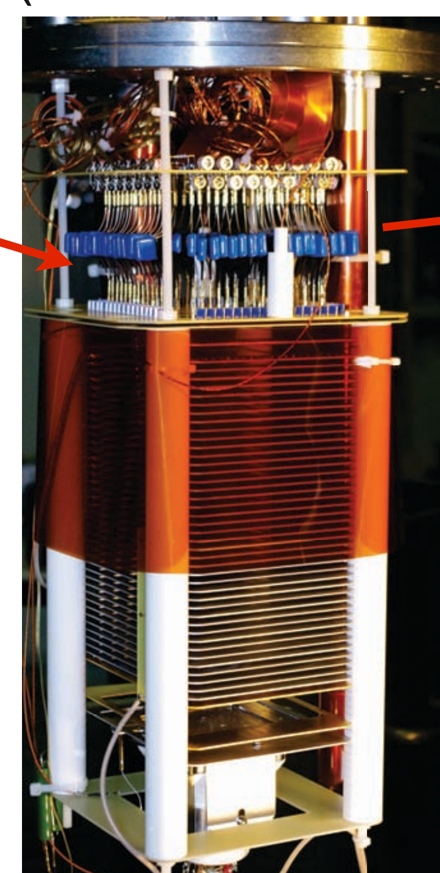
UHV vessel (kept cold with open LAr bath)

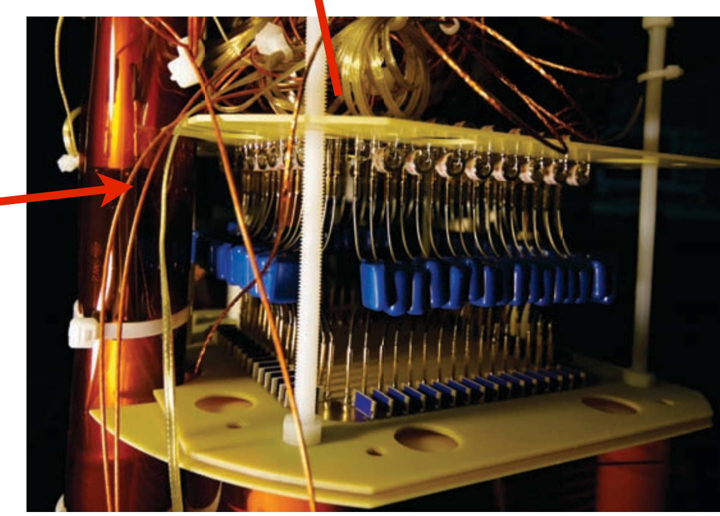
CAEN DAQ system





TPC (10x10x20 cm^3)

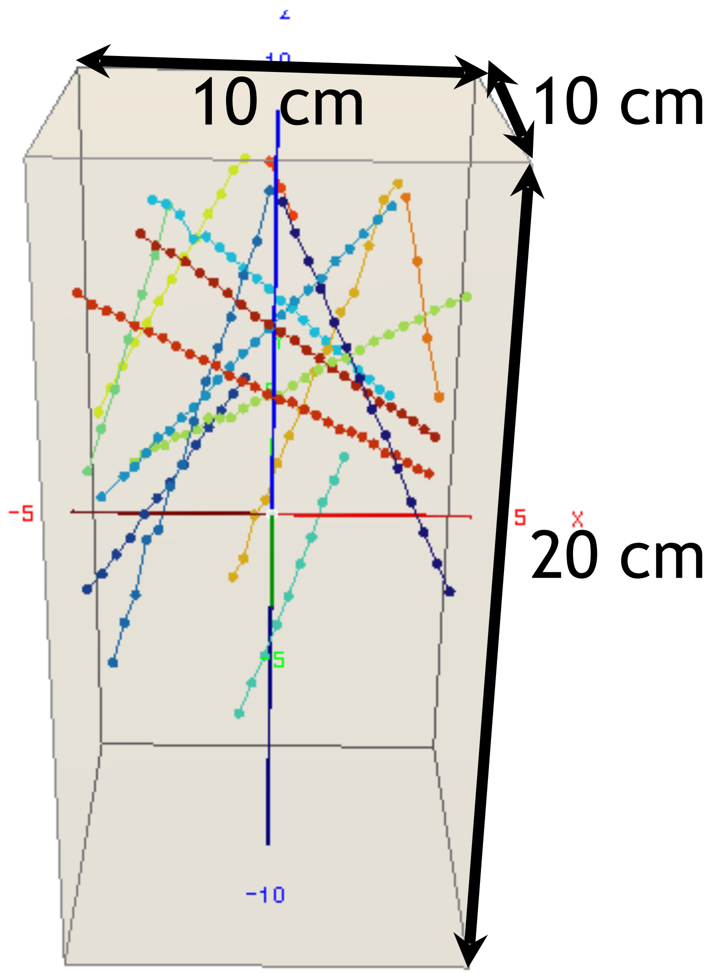


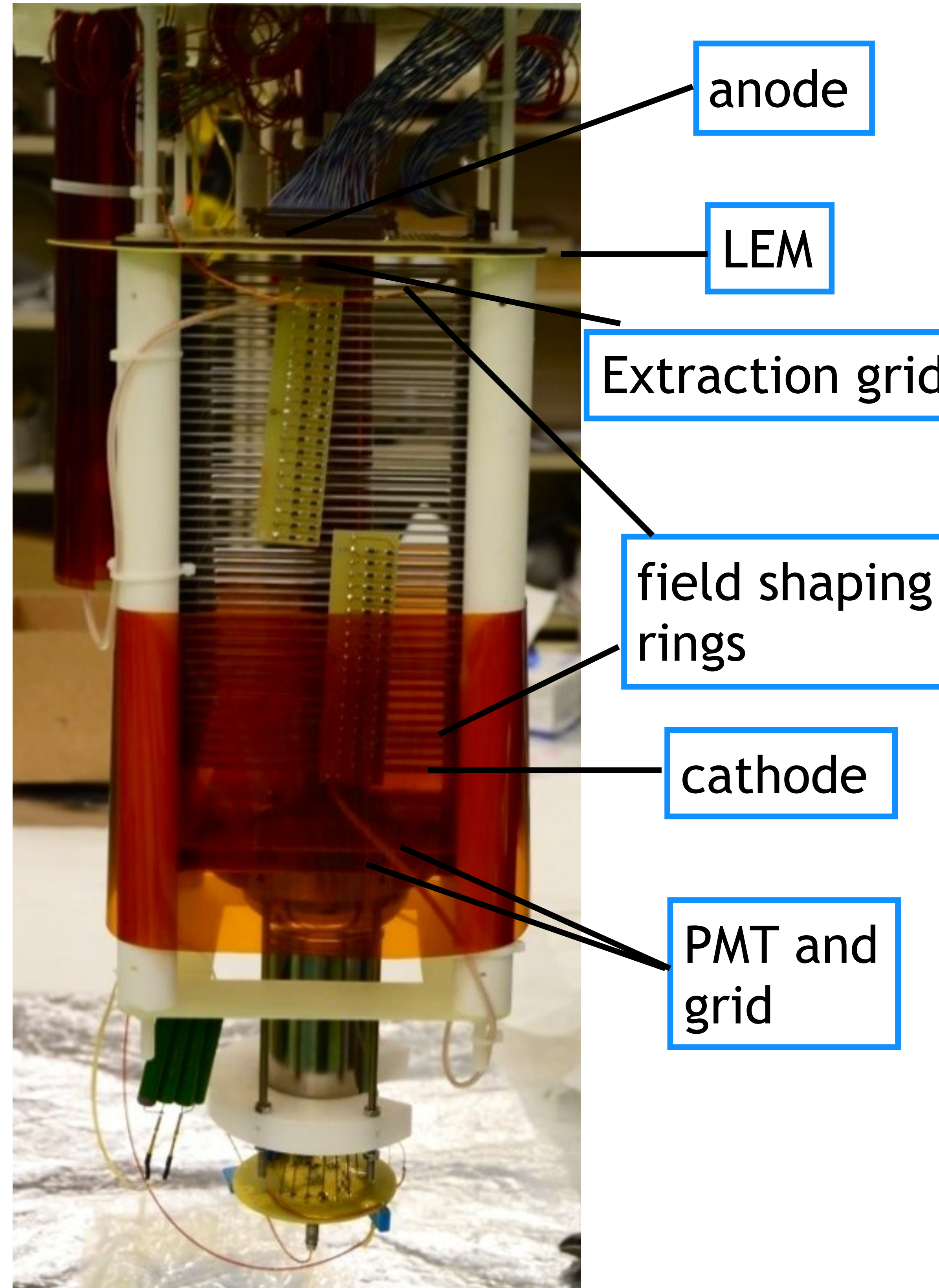


Charge Readout system (in gas phase above pure LAr)

Dual phase "3L" setup (since 2008)

NIM A617 (2010) p188-192





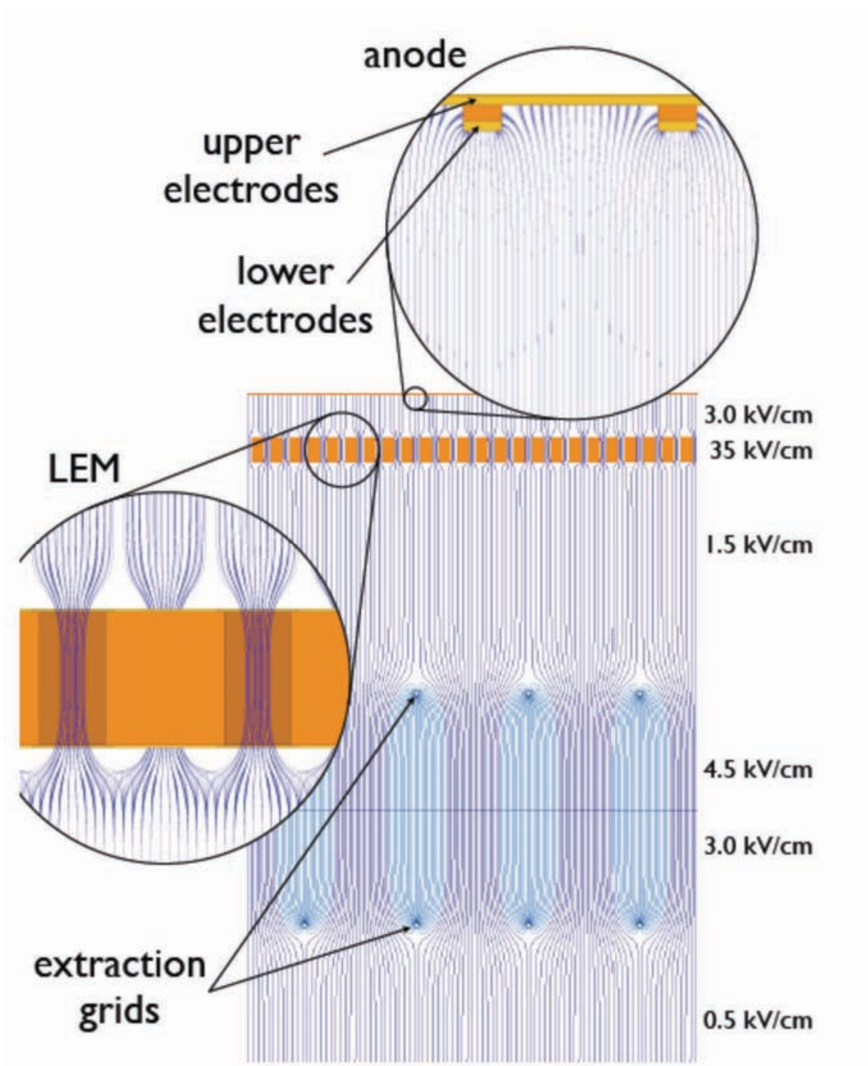
Recent developments:

- **Low noise (capacitance) 2D anode**.
- LEM with **uniform** and **long term stable** gain and discharge resistance.
- **Simplified** readout electronics system.

Double phase charge readout principle: LEM and projective 2D anode

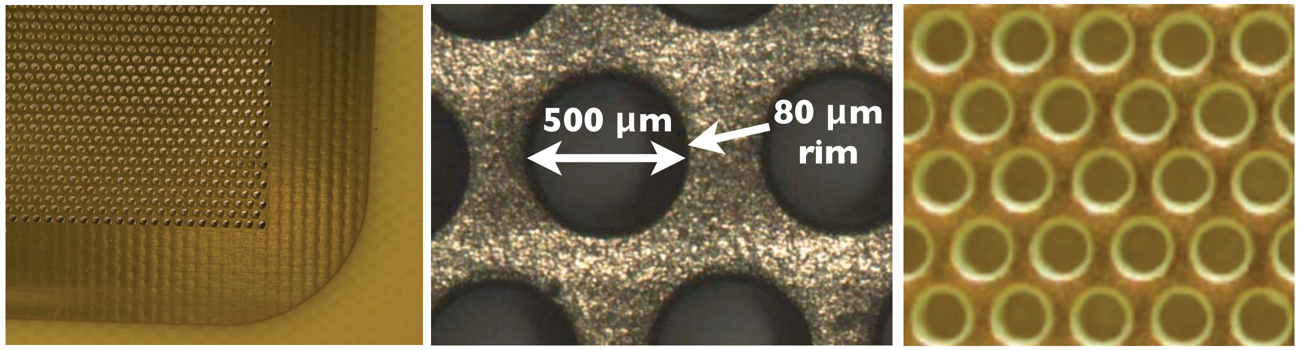
Readout principle
1. ionization electrons are **drifted** to the liquid-gas interphase
2. if the E-field is high enough (≈ 3 kV/cm) they can efficiently be **extracted** to the gas phase
3. in the holes of the LEM the E-field is high enough to trigger an electron avalanche
4. the **multiplied** charge is collected on a 2D readout

Electric fields



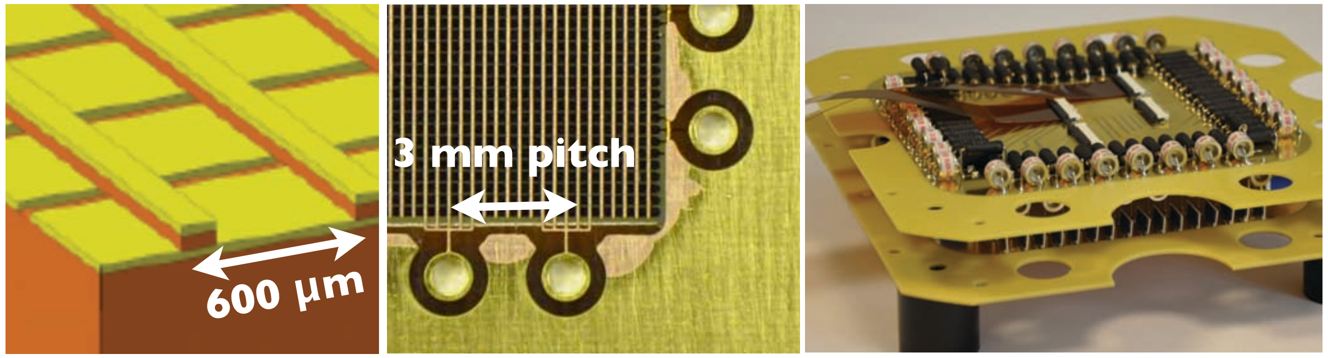
LEM (THGEM): Large electron multiplier

•Macroscopic Gas hole multiplier
•more robust than GEMS (cryogenics, discharges)
•manufactured with std. PCB techniques
•Large area coverable (1 m^2 size modules)



Projective 2D anode readout

•Charge is equally collected on two sets of strips (views)
•induced signals have the same shape for both views
•readout independent of multiplication

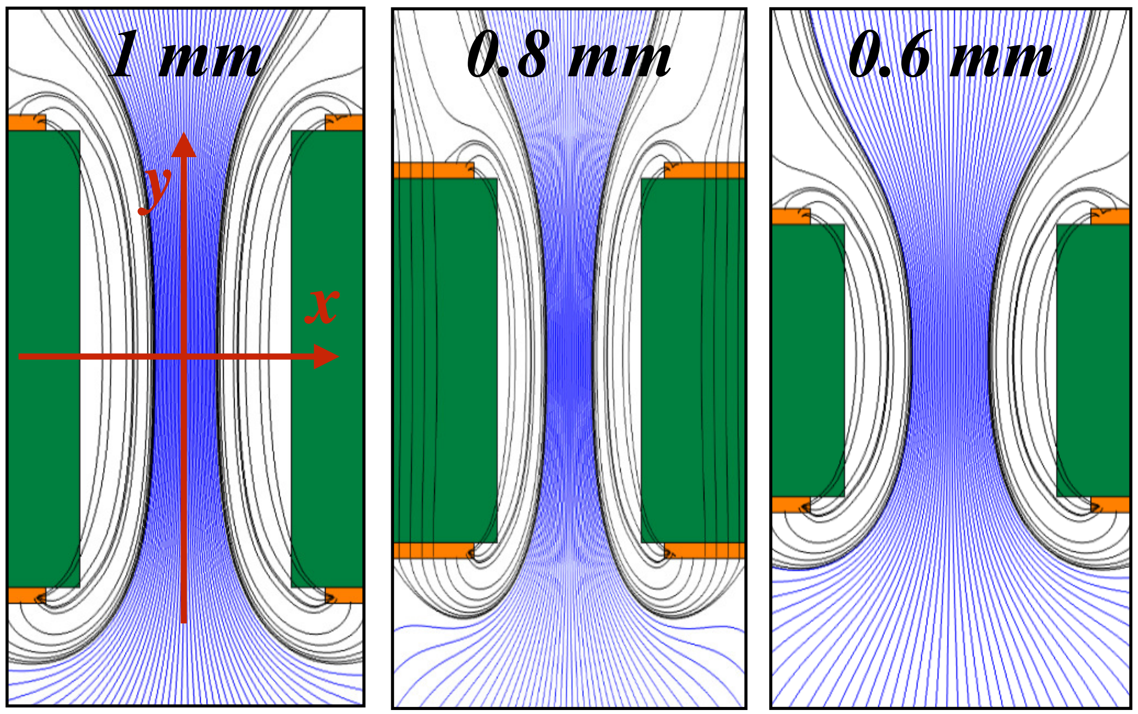


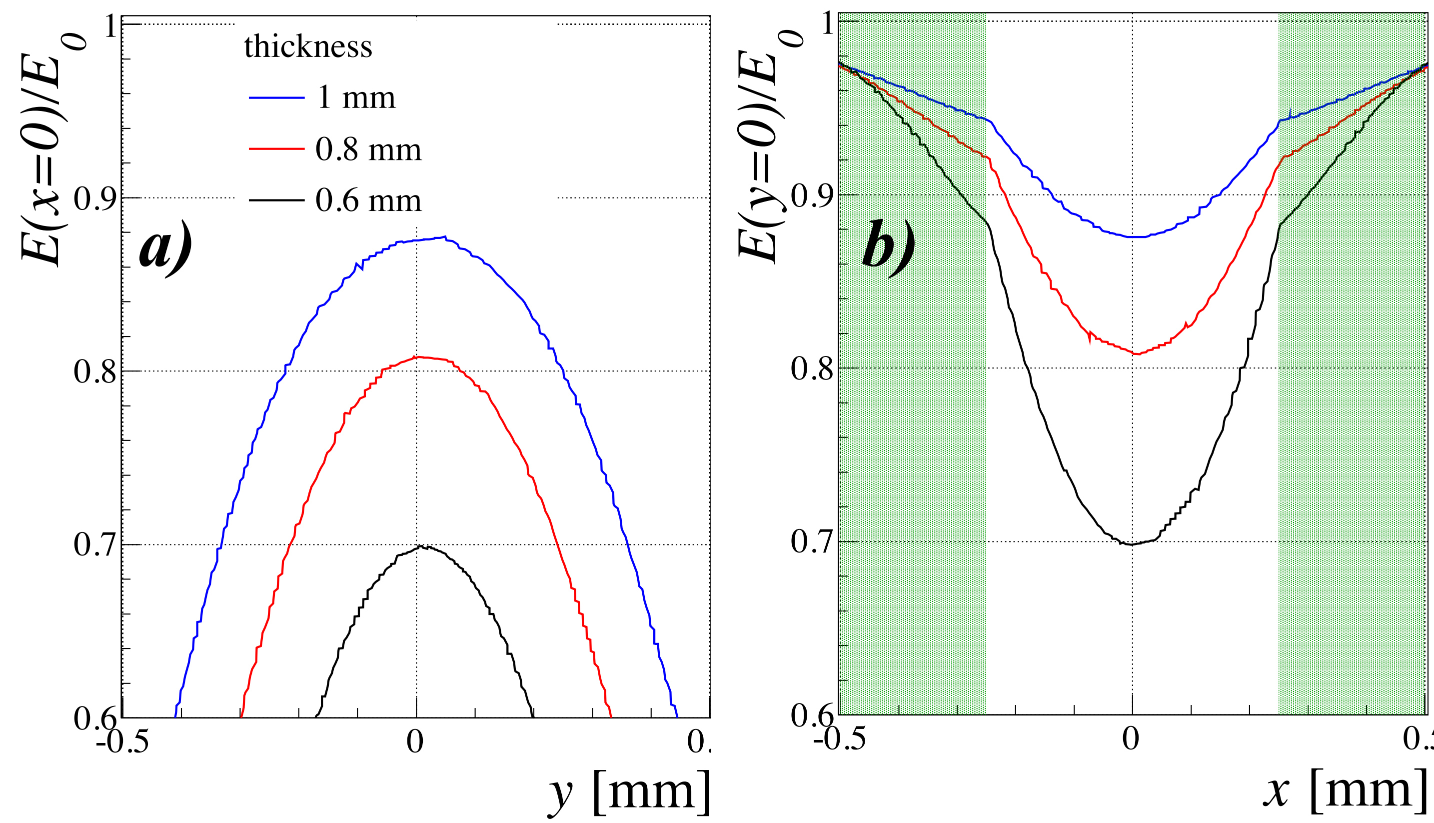
LEM and 2D anode produced by CERN TS/DEM group

ref: A. Badertscher, et al., NIM A 641 (2011) 48-57

Effective gain of the LEM

JINST 10 (2015) 03, P03017





Effective gain:

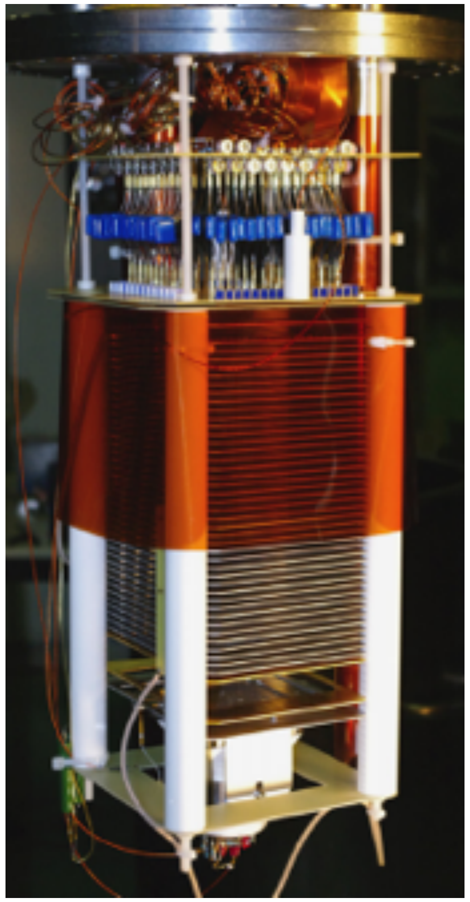
Transparency — Charging up ("time dep")

$$G_{\mathrm{eff}}(E,\rho,t) \equiv \mathscr{T}\, e^{\alpha(\rho,E)x} \times \mathscr{C}(t)$$

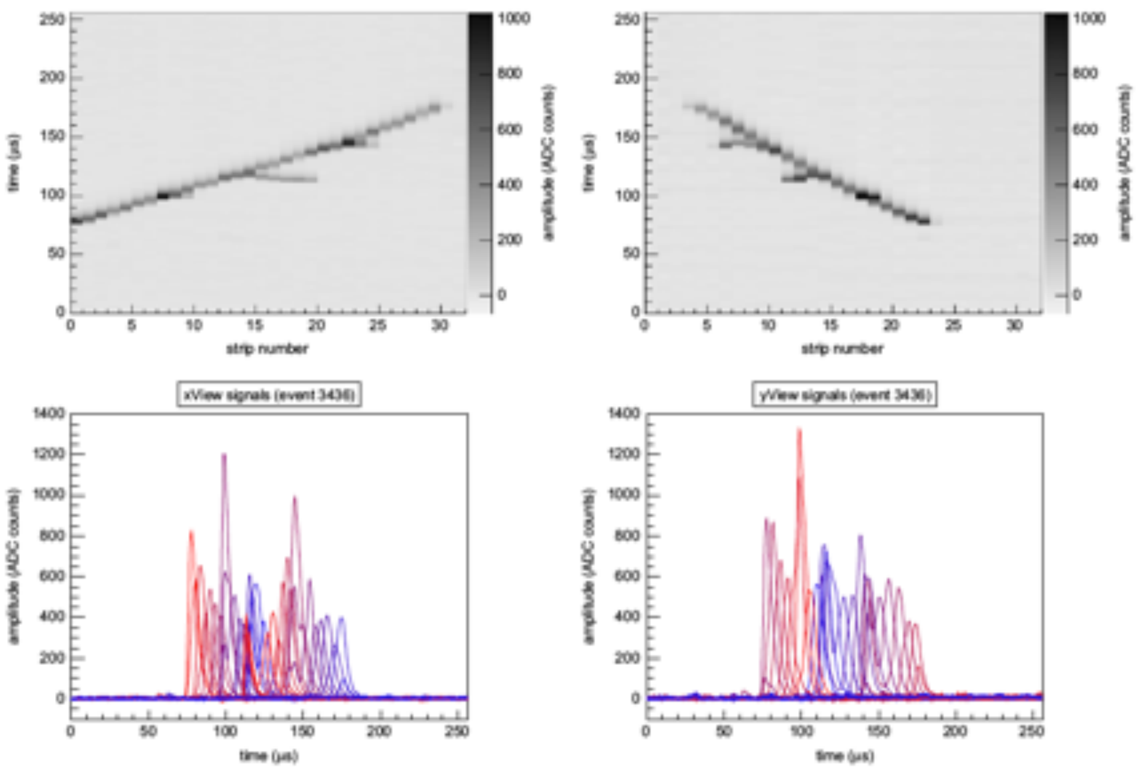
Townsend coefficient: $\alpha(\rho,E) = A\rho e^{-B\rho/E}$

MAGBOLTZ T=87K, p=0.980bar $A\varrho = (7339 \pm 90)\ \mathrm{cm}^{-1}$ and $B\varrho = (183 \pm 1.0)\ \mathrm{kV/cm}$

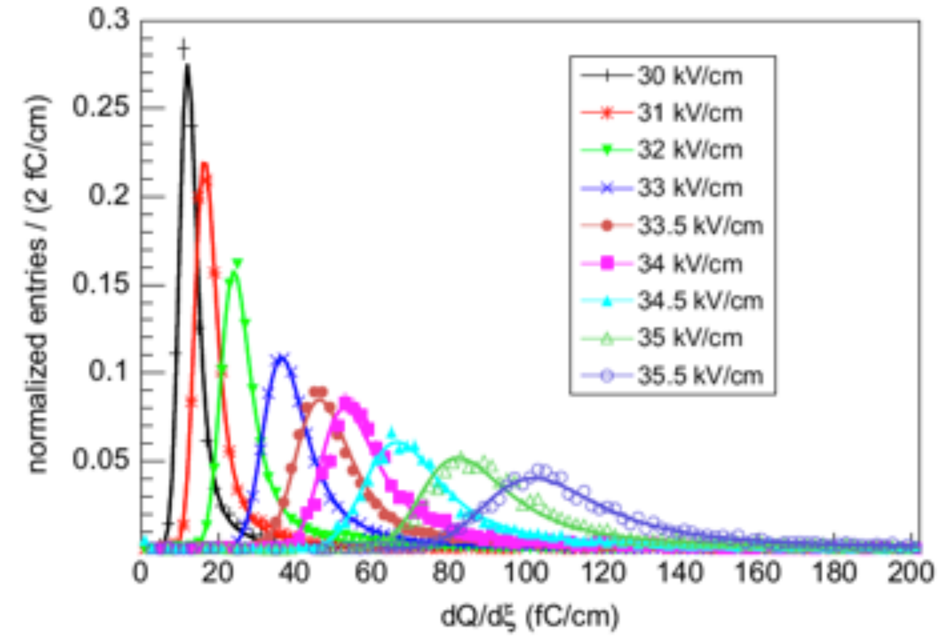
Proof of principle on 10x10cm2



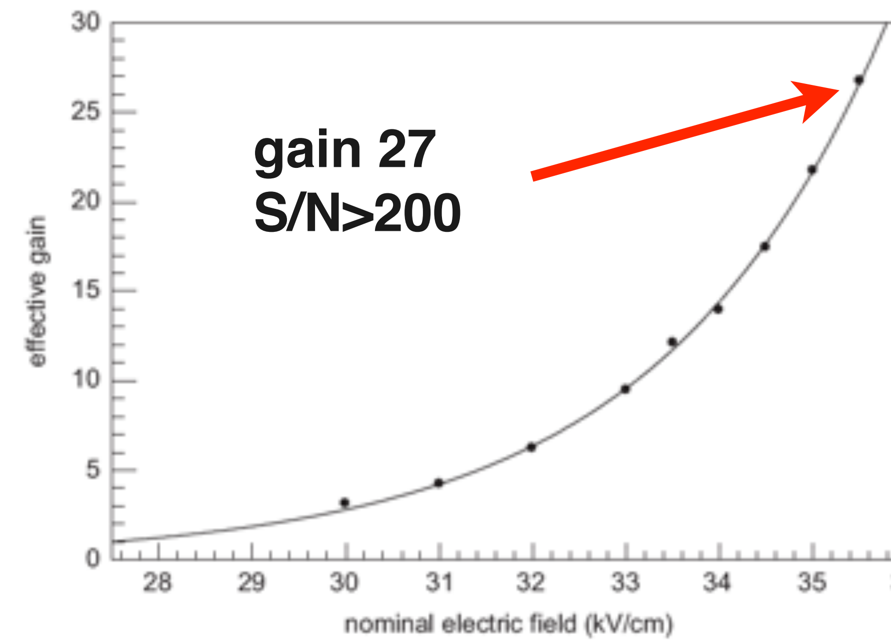
typical cosmic muon event



dQ/dx distribution with different gains



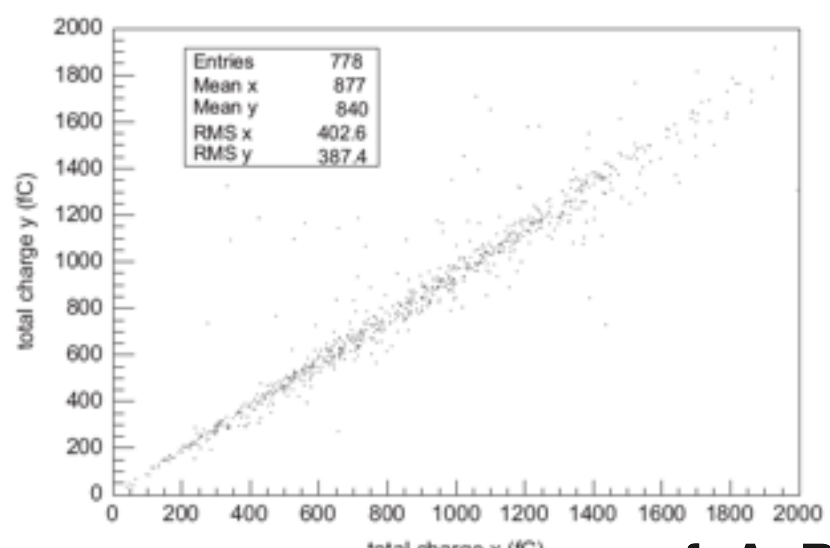
gain curve



➡ dQ/dx data from MIPs have been used to characterize the detector:

charge sharing test of the 2D anode

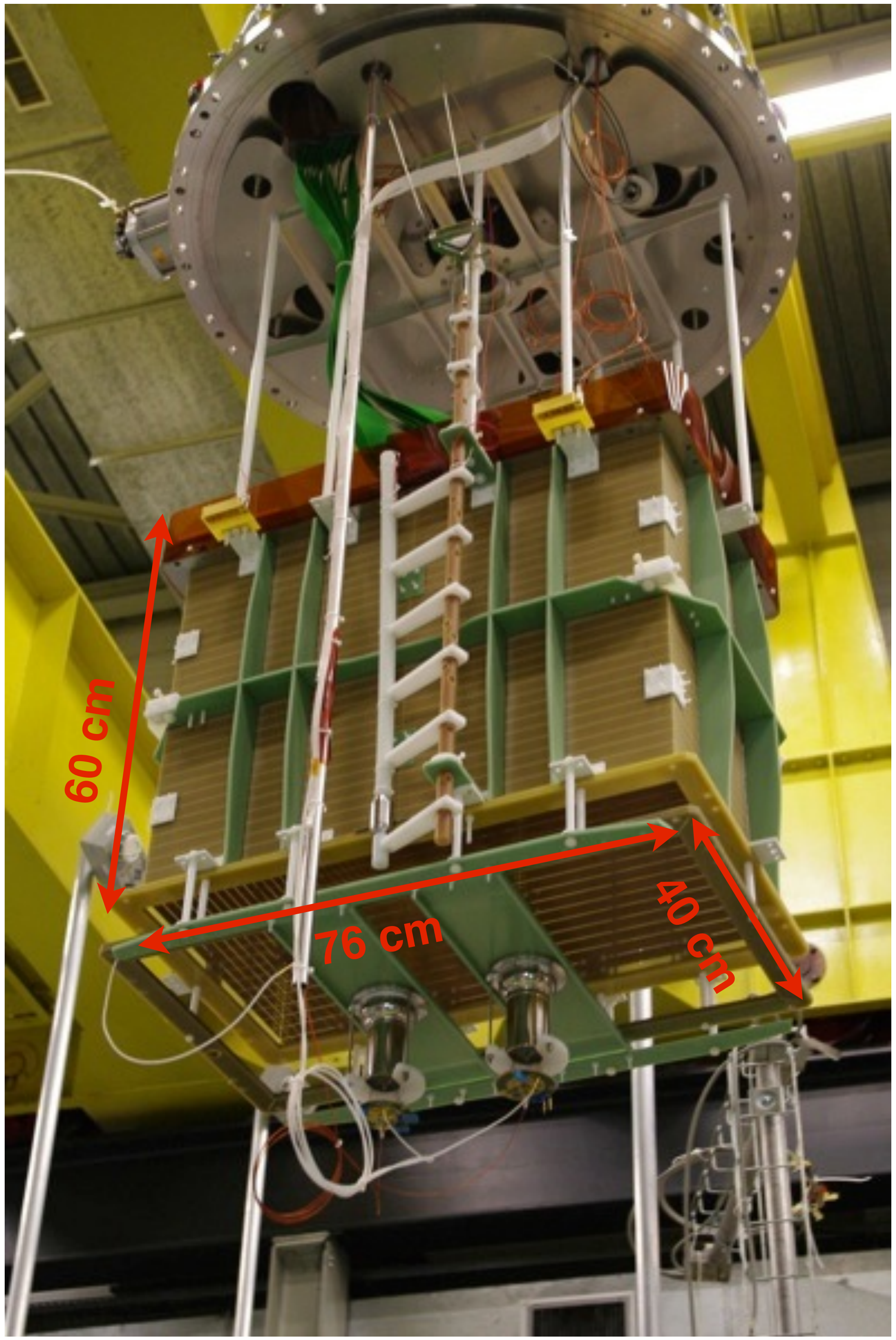
- signal shape of x and y view identical
- charge sharing verified: (x-y)/<x+y> better than 5%
- design parameters verified



ref: A. Badertscher, et al., NIM A 641 (2011) 48-57

Dual-phase 250L prototype (2011)

detector fully assembled



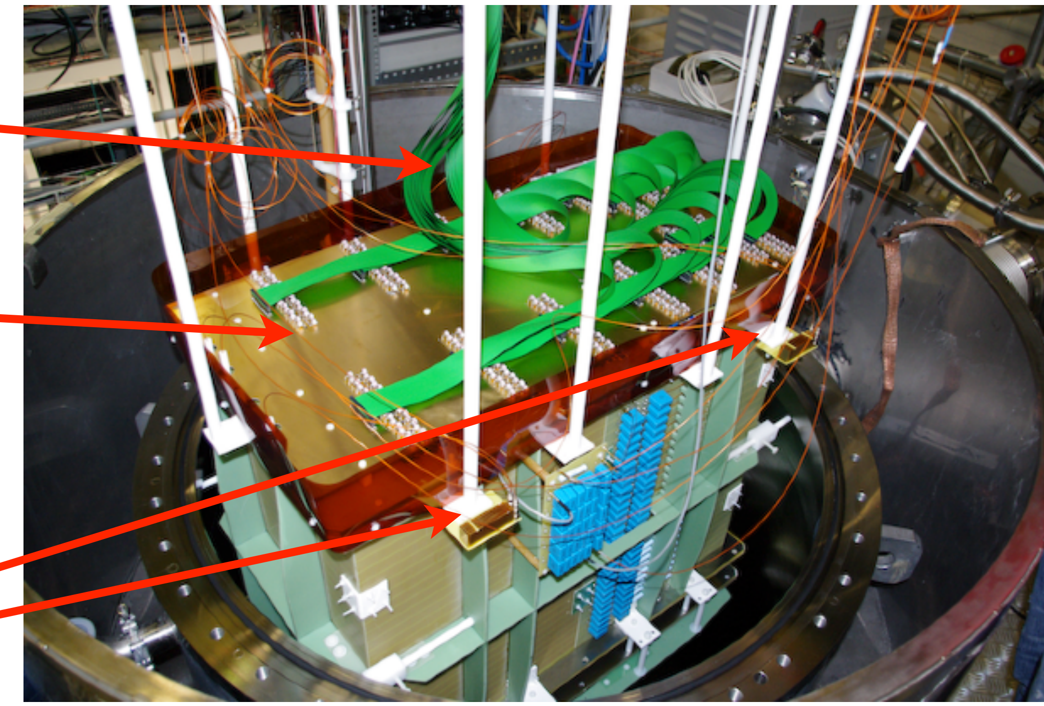
A. Badertscher et al. JINST 8 (2013)P04012,

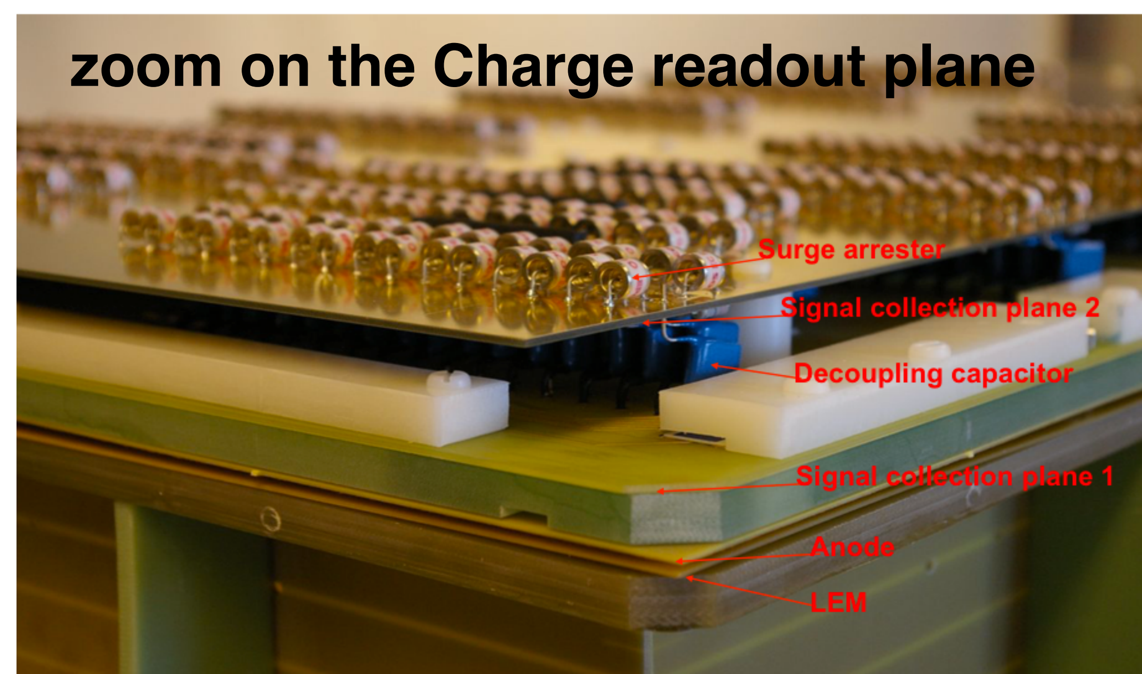
going into the ArDM cryostat

16 signal cables

charge readout plane

4 capacitive level meters

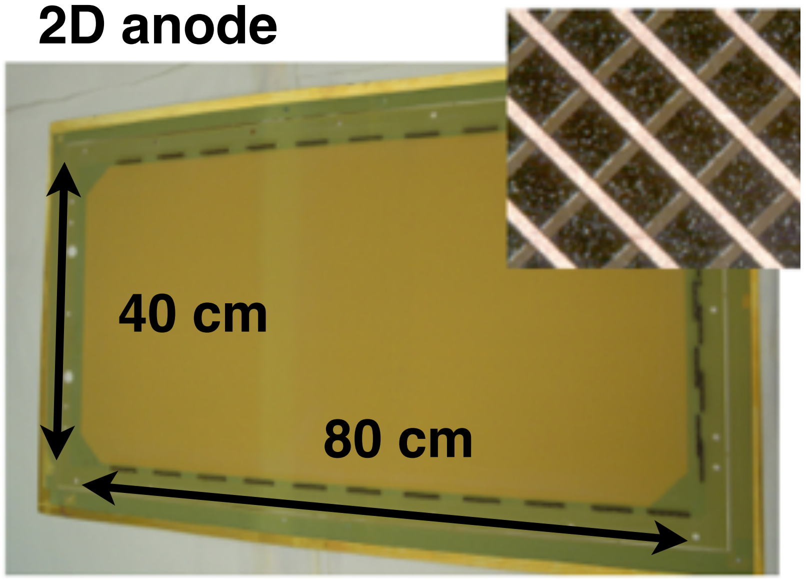




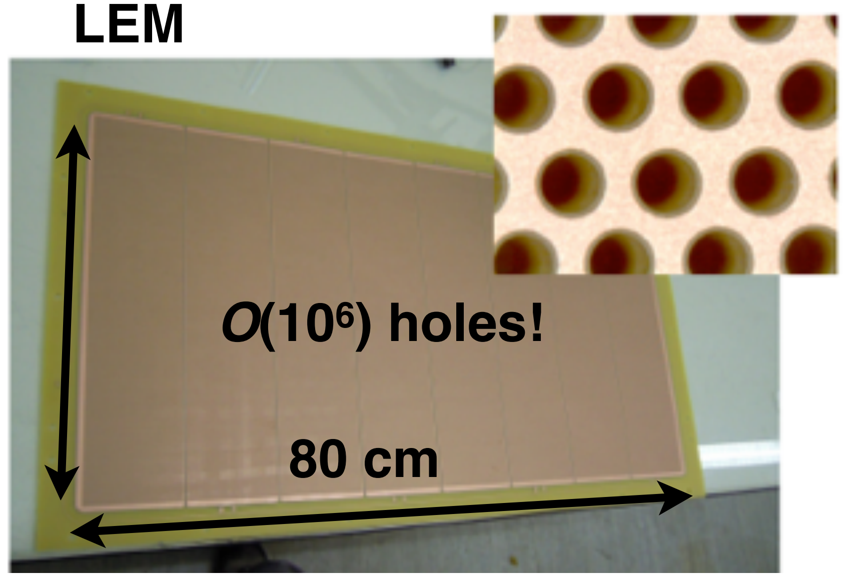
The first production of a 40x80 cm² charge readout sandwich !

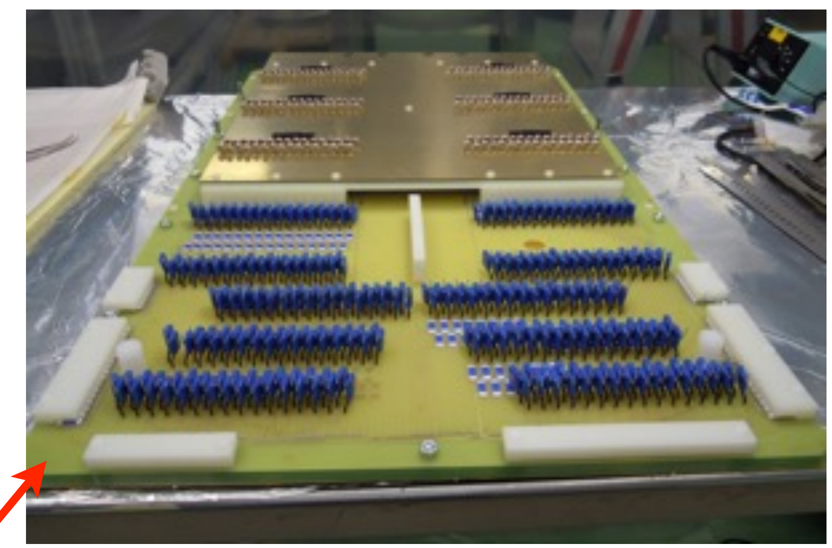
‣After successful test of LEM and 2D anode in the 3L setup we designed and produced a 40x80 cm² charge readout for a new 250L LAr LEM-TPC (production and assembling finished by summer 2011)
‣The ArDM cryostat @CERN was used for a first test of the new charge readout system

2D anode



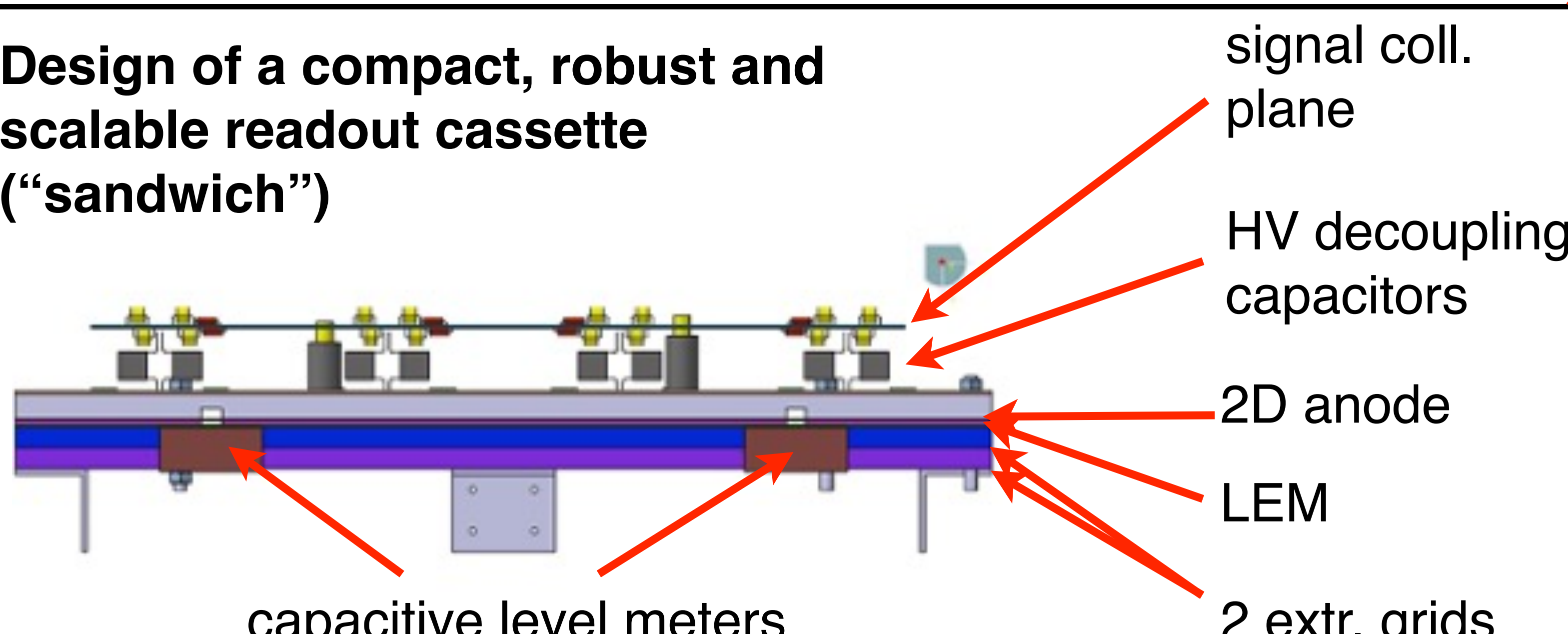
LEM

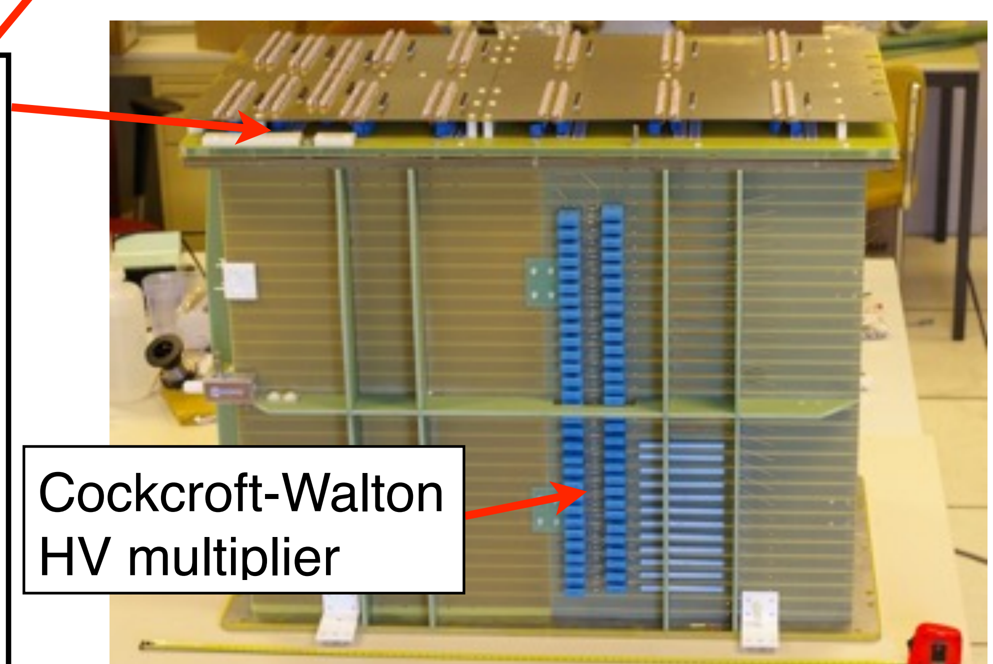




- Manufacturer: CERN TS/DEM group and ELTOS company (Italy)
- Largest LEM/THGEM and 2D readout ever produced!!!

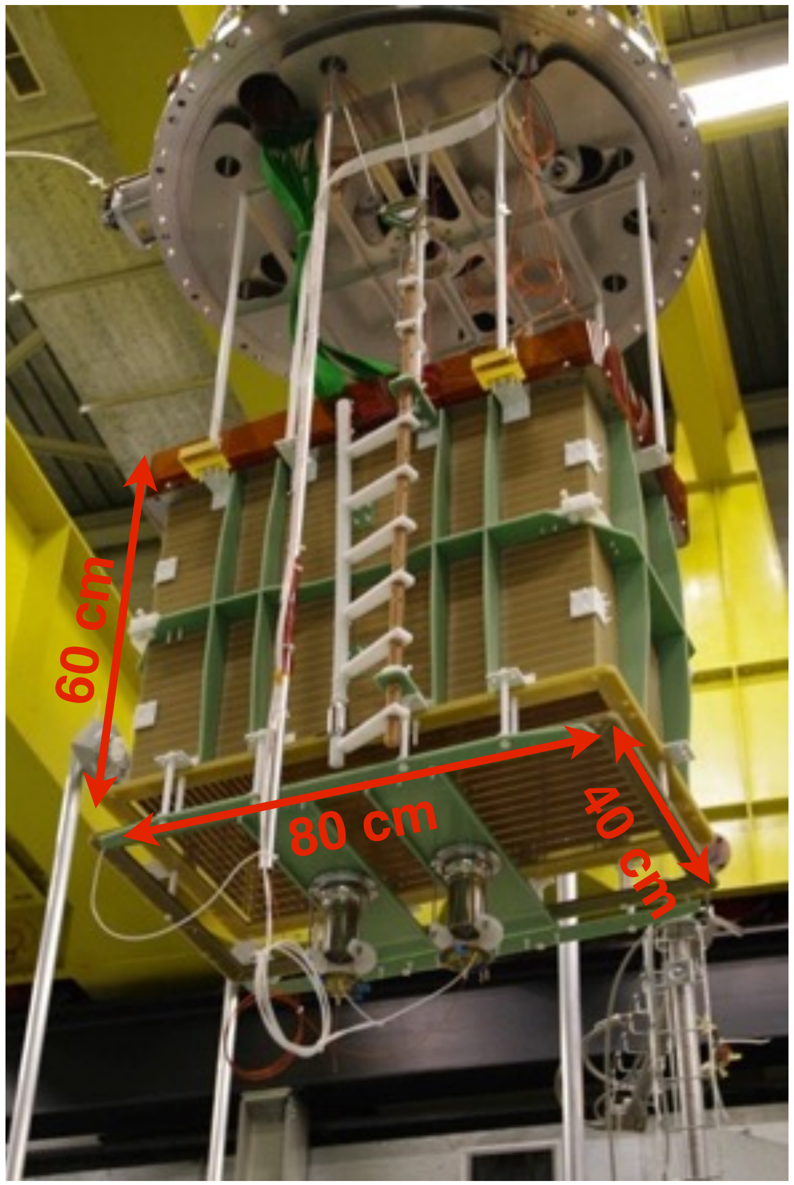
Design of a compact, robust and scalable readout cassette ("sandwich")



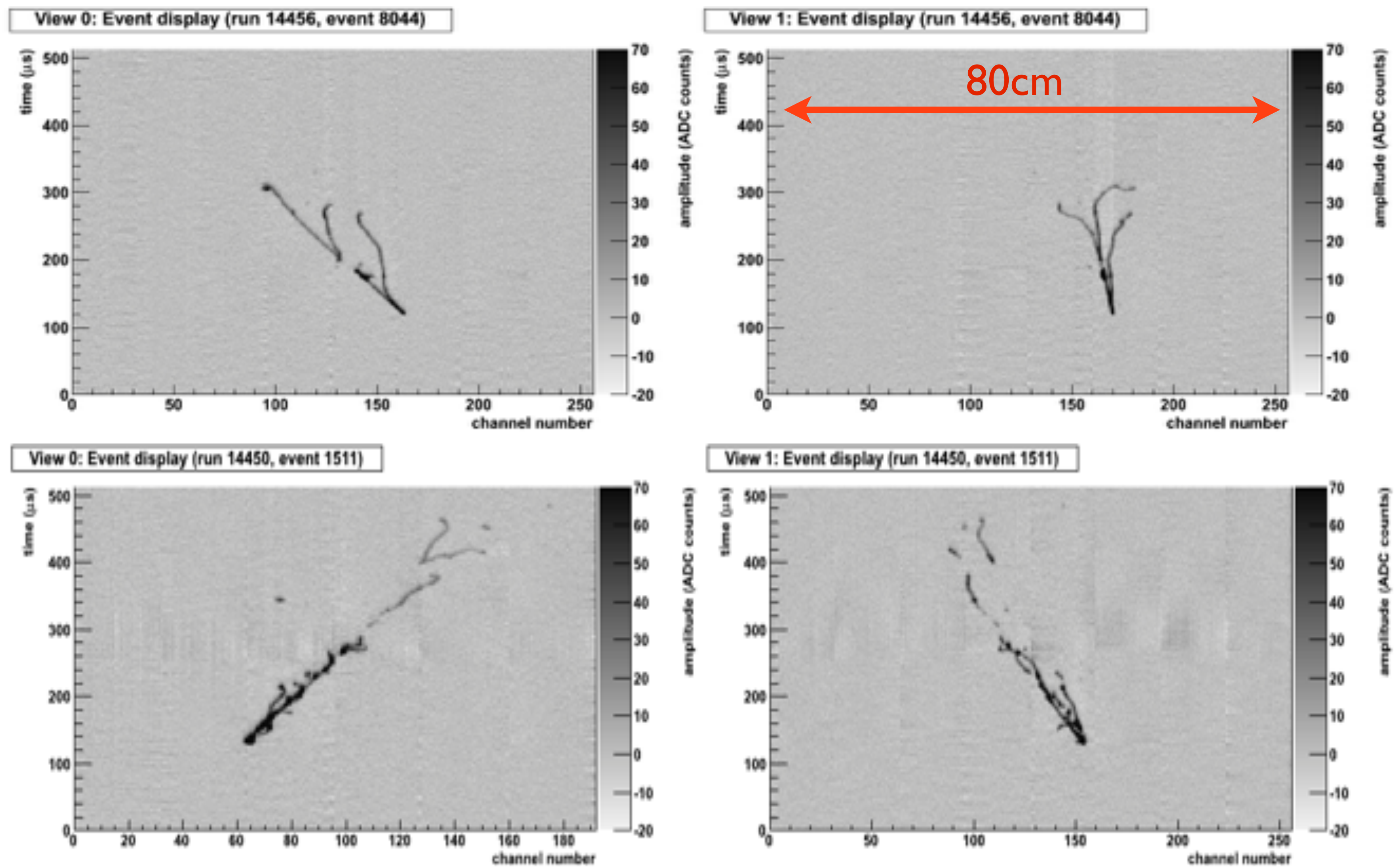


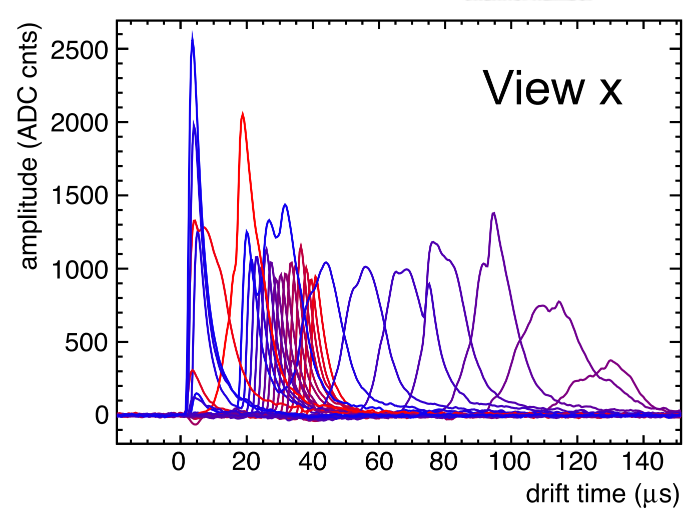
CR events in dual-phase 250L

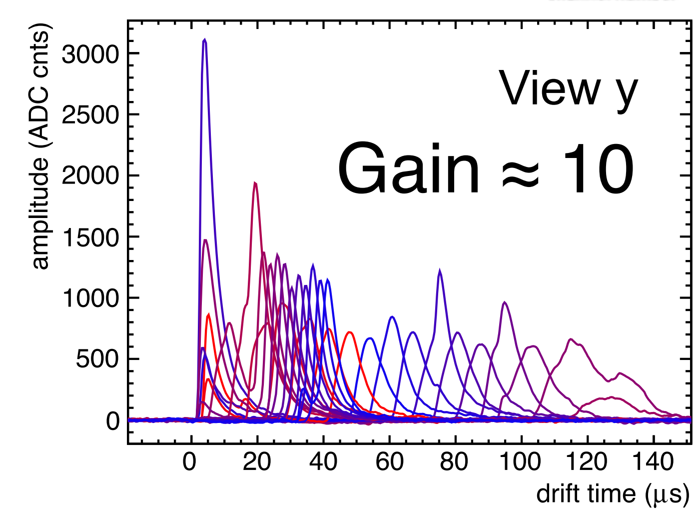
Dual phase demonstrated with a detector of the size of ArgoNEUT/LArIAT



Dual phase 250L chamber @ ETHZ/CERN in 2012

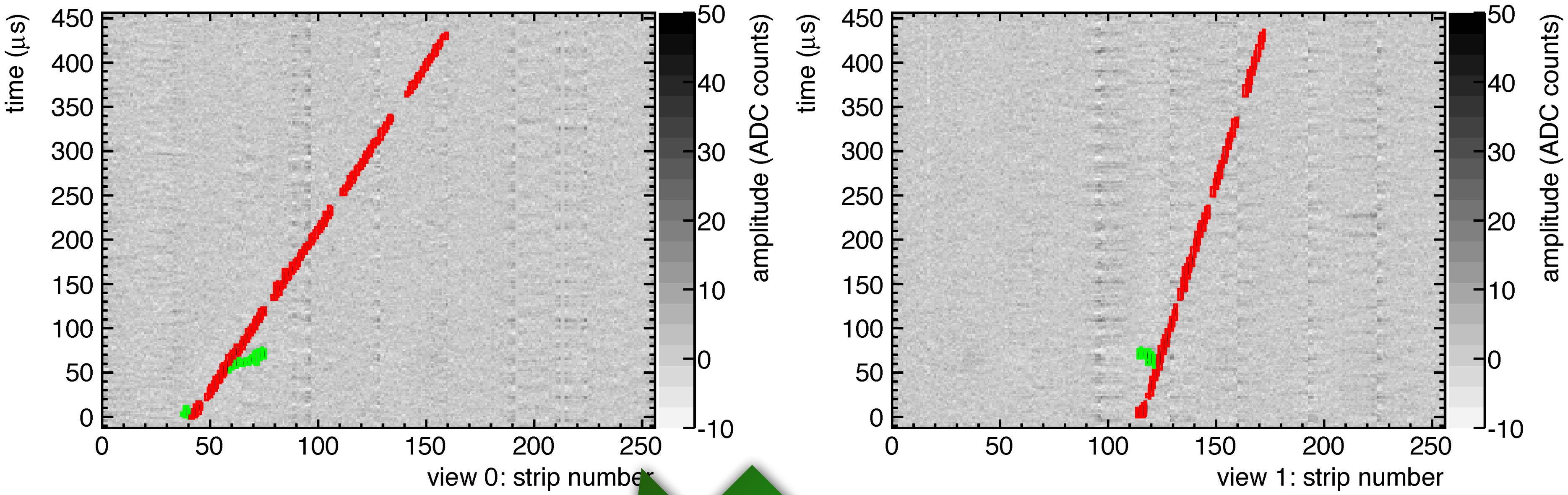






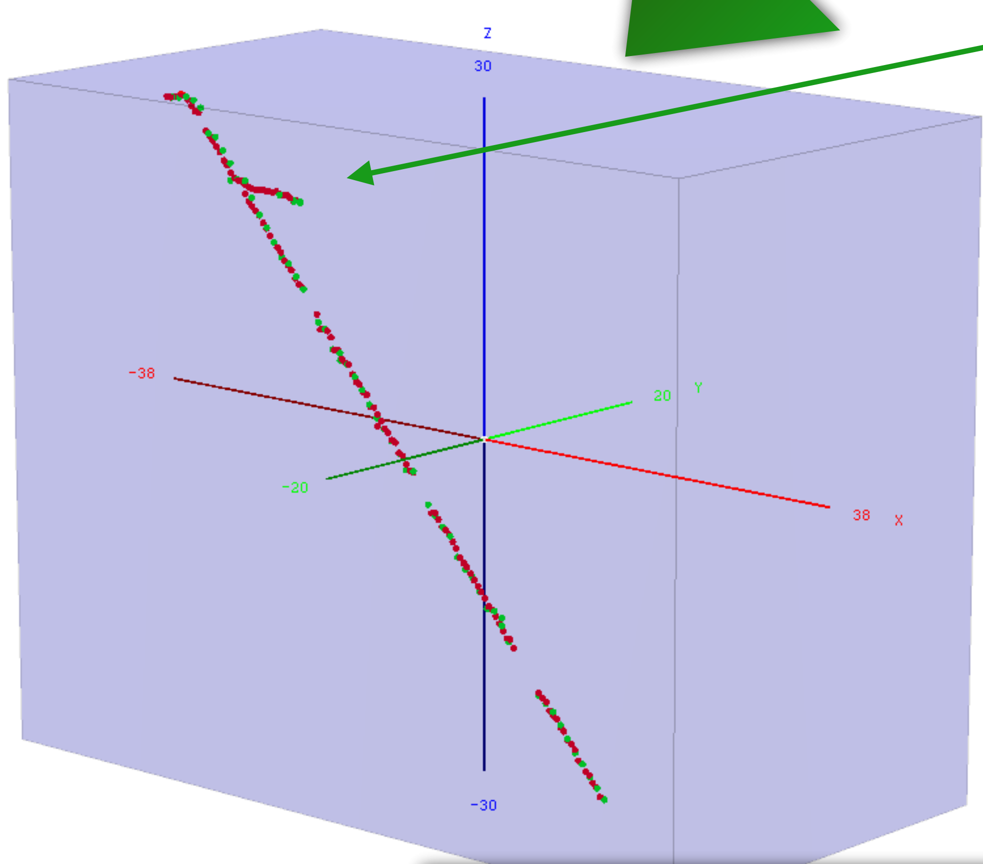
A. Badertscher et al. JINST 8 (2013)P04012

Delta-rays 250L prototype



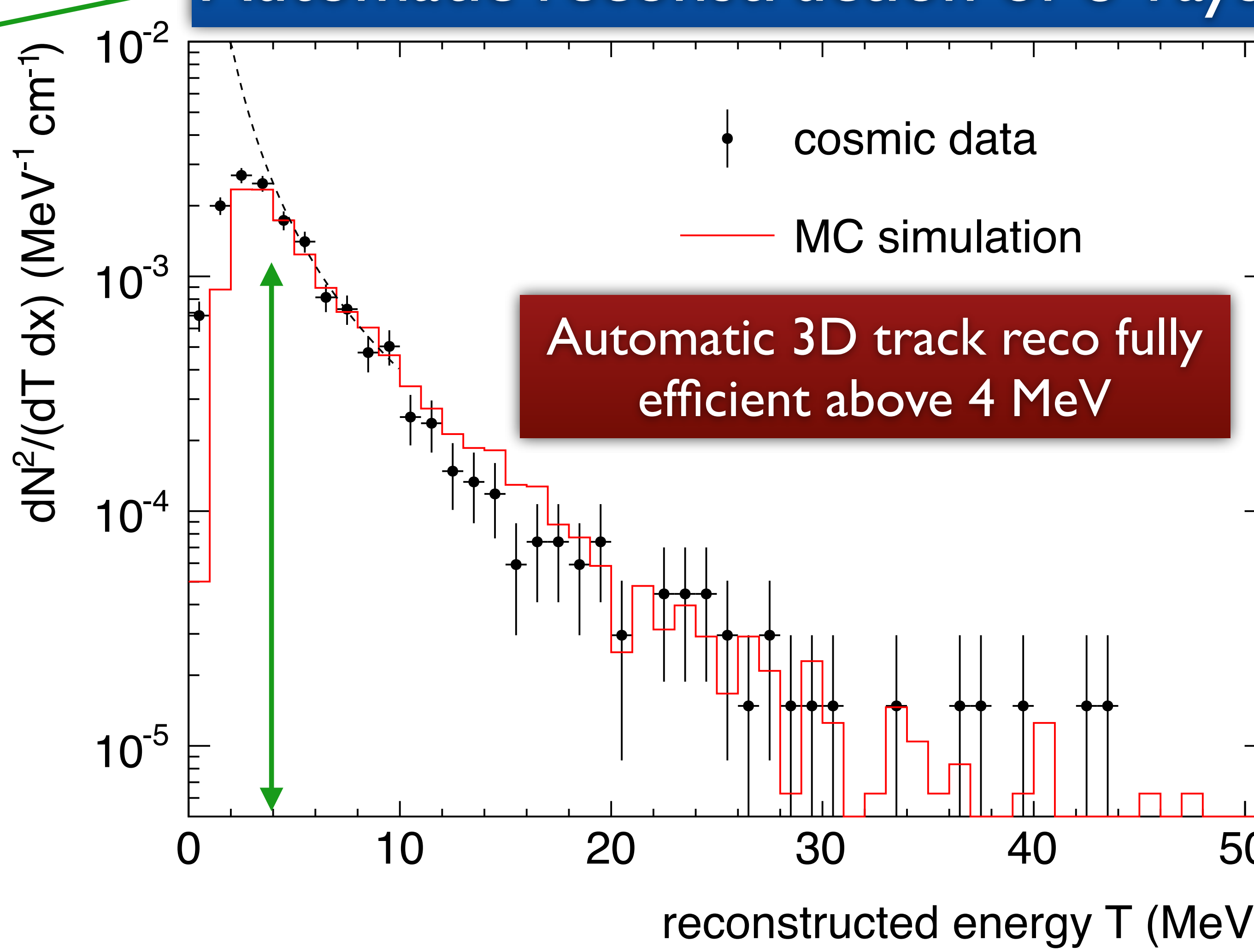
JINST 8 (2013) P04012

Event recorded exposed to cosmic rays



3D reconstruction

Automatic reconstruction of δ-rays



Automatic 3D track reco fully efficient above 4 MeV

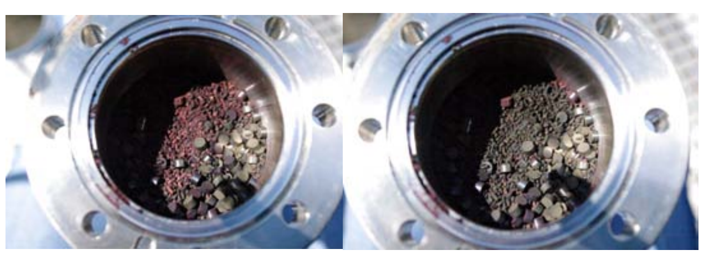
Purification system

Features

- independent gas and liquid purification circuits (needed to fill pure and keep< 1)
- It is kept cold with two cryocoolers (500 W, important for later underground operation)
- controlled by a PLC (programmable logic control, safety device)

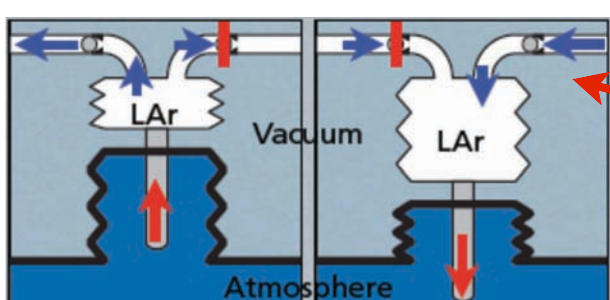
closed system: condenser (500 W cryocoolers)

Cu purification cartridge

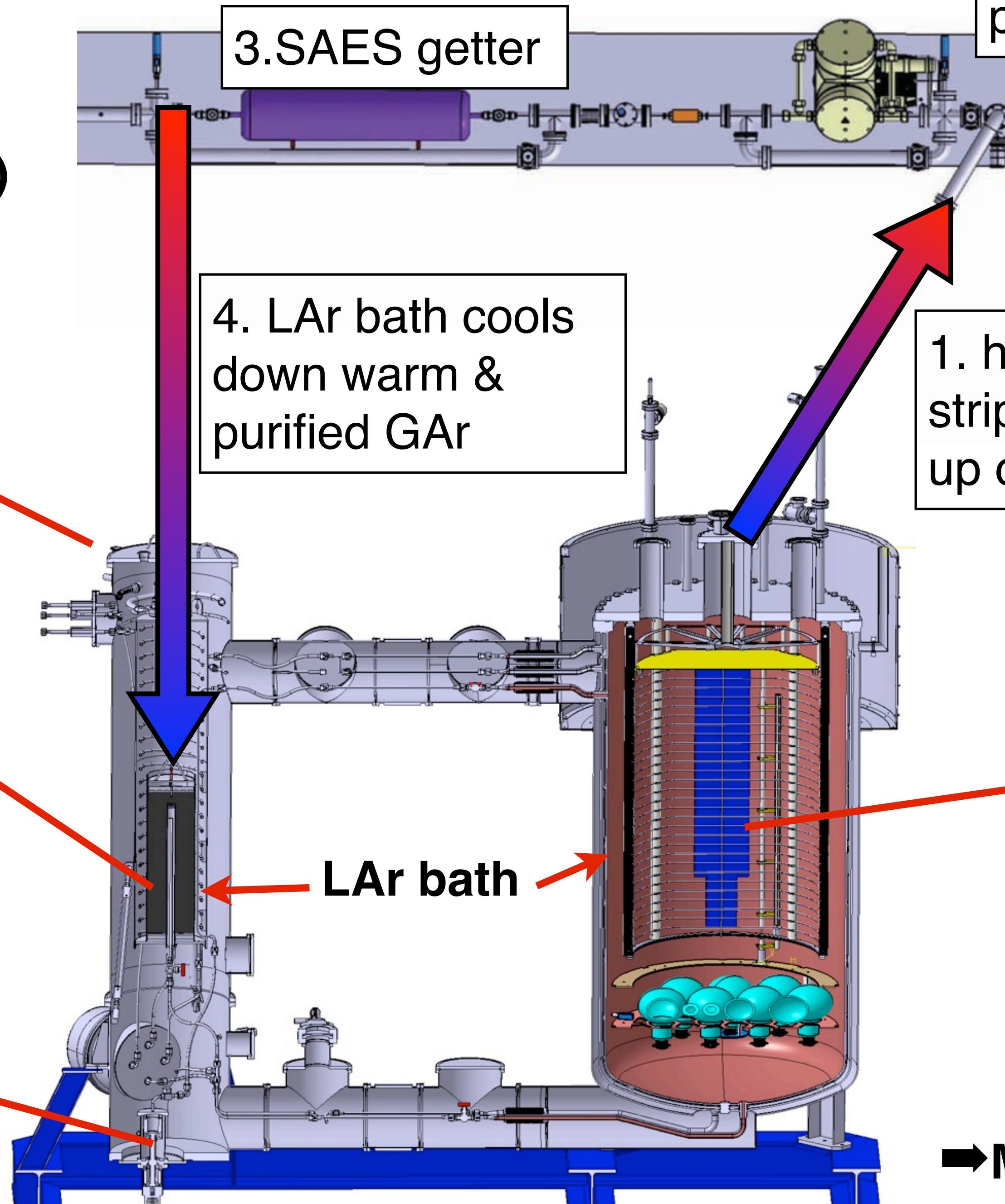


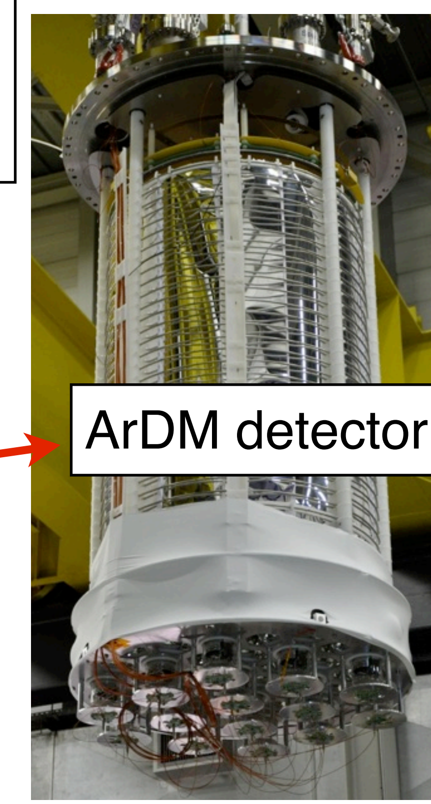
activated Cu (reddish) | after few seconds in air

LAr recirculation pump



Gas recirculation system





➡**More:** see poster “Cryogenic system of the ArDM detector”

Proof that purity can be achieved

impurities in LAr

Effect of electronegative impurities on the free electron lifetime τ_e:

$$\tau_e[\mu s] \approx 300\ \mu s\ ppb/[O_2]_{eq}$$

Assuming a constant density of impurities, the charge, collected on the anode, is attenuated by a factor $e^{-t/\tau}$

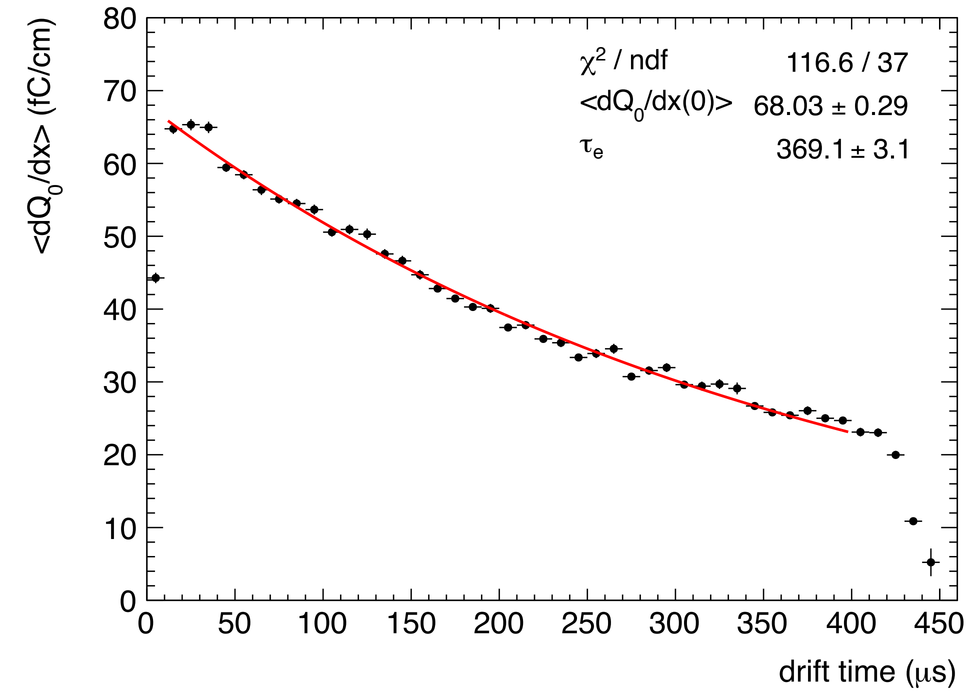
measurement

To measure the free electron lifetime, we reconstruct $dQ(t_{drift})/dx$ of crossing muon tracks:

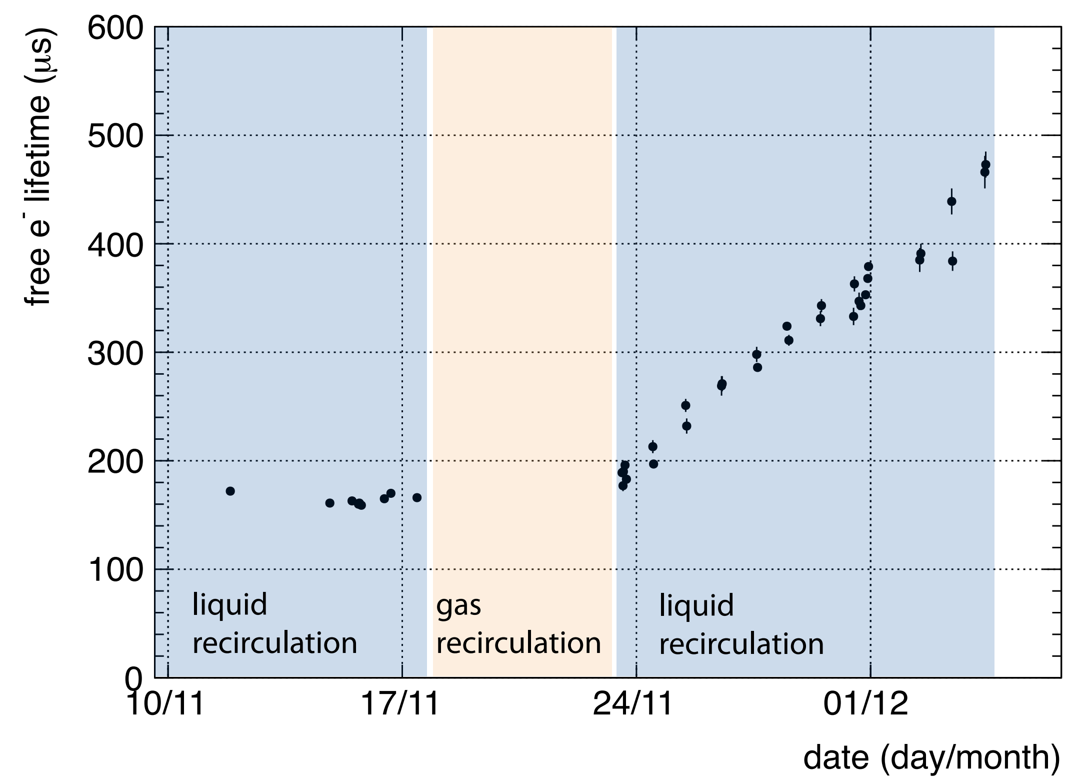
- $dQ \approx \Delta Q$= charge collected on each strip of the anode
- dx (corresponding ionization length) given by 3D track reconstruction

➡**Throughout the run the free electron lifetime improved from <200 μs ($[O_2]_{eq}$=1.5 ppb) to 500 μs ($[O_2]_{eq}$=0.6 ppb).**

single run lifetime fit

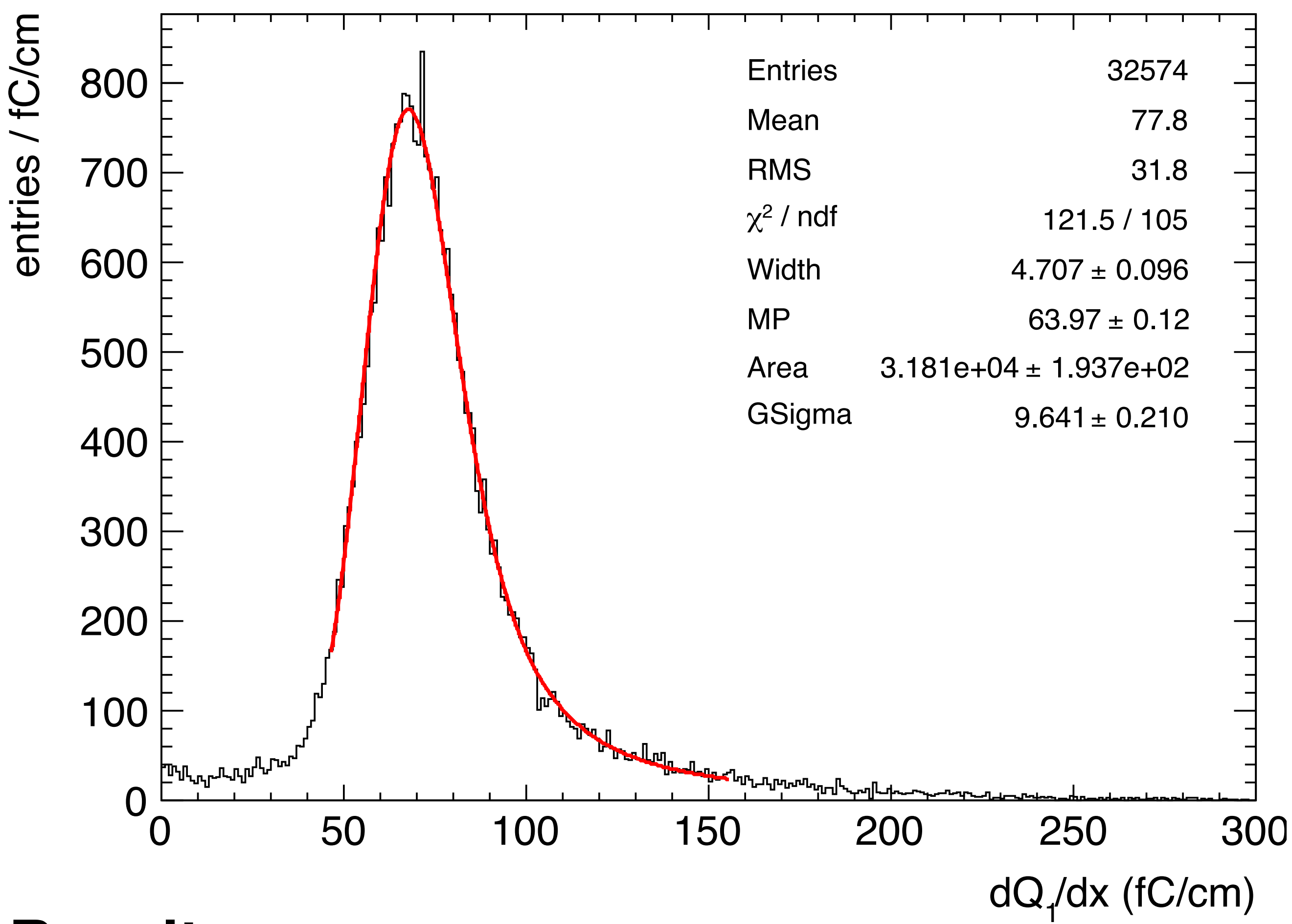


lifetime evolution

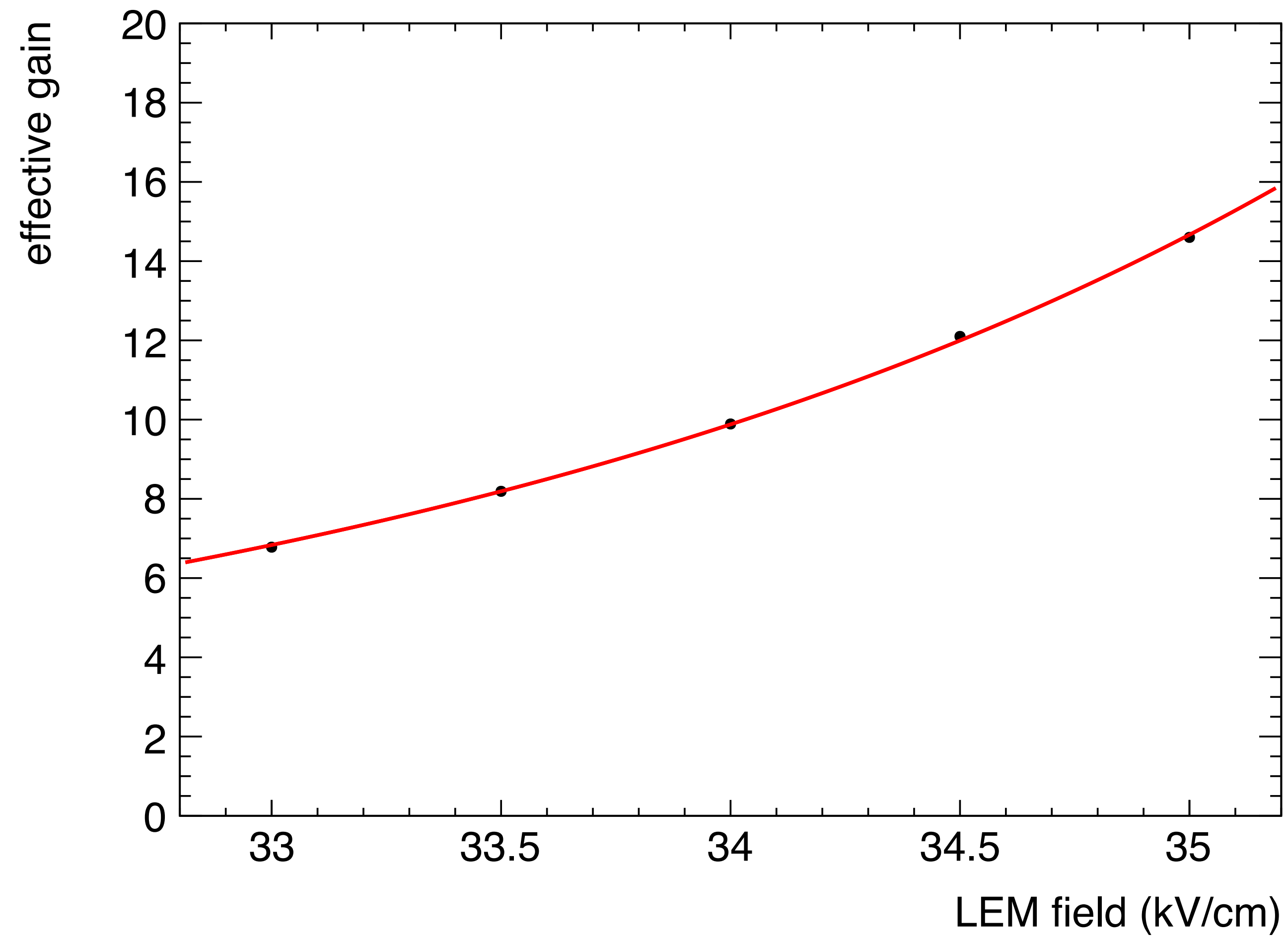


Gain achieved on 250L

After correcting for the free electron lifetime, a Landau function convoluted with a Gaussian could be fitted to the obtained dQ/dx distribution.



effective gain vs. LEM field

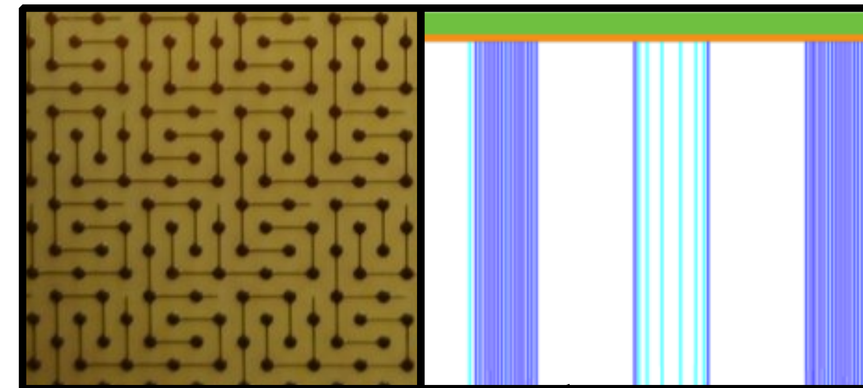


Results

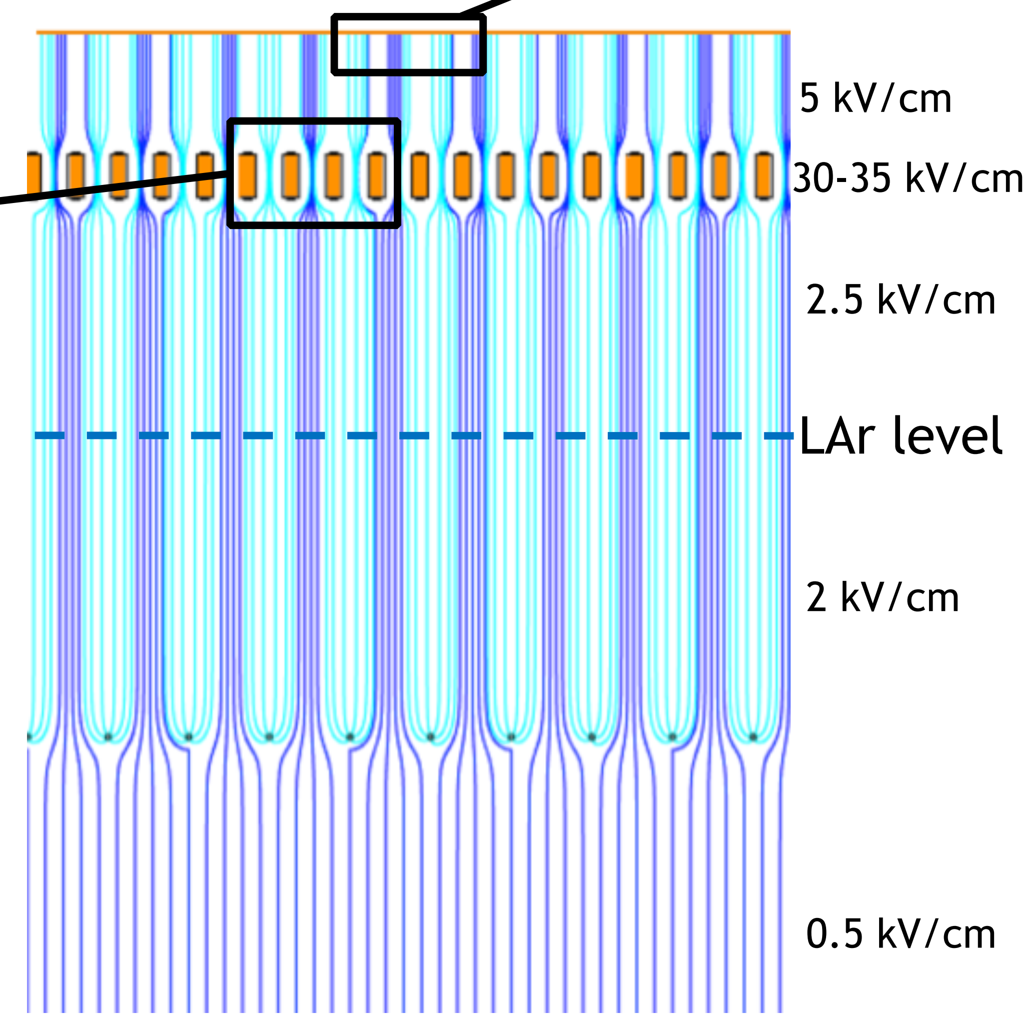
<dQ/dx>=146 fC/cm
➡effective gain≈14.6,
charge sharing between the two collection views: $(Q_1-Q_0)/(Q_1+Q_0)\approx 8\%$

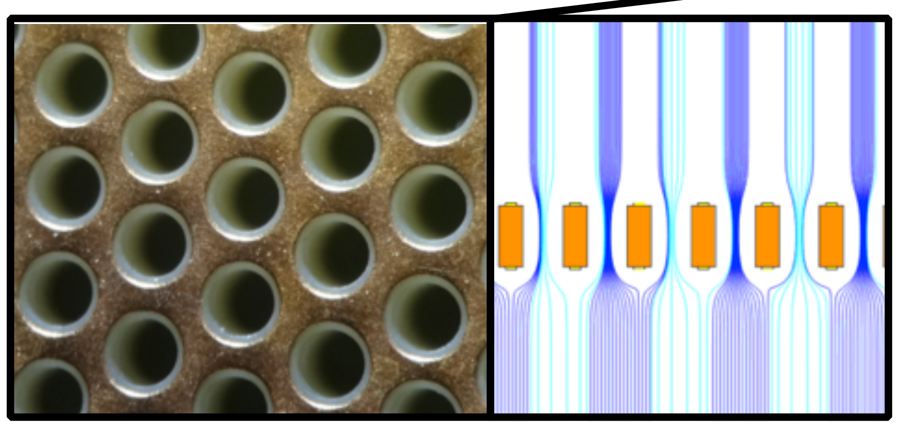
Simplified design with one extraction grid & 2D anode (2013)

4.) Charge collection on a multilayer 2D anode readout (symmetric unipolar signals with two orthogonal views)



3.) Charge multiplication in the holes of the Large Electron Multiplier (LEM)





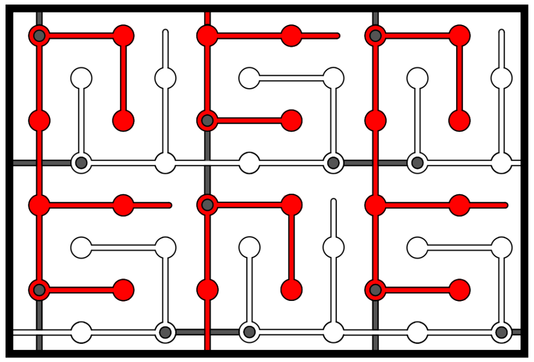
2.) Drift electrons are efficiently extracted into the gas phase

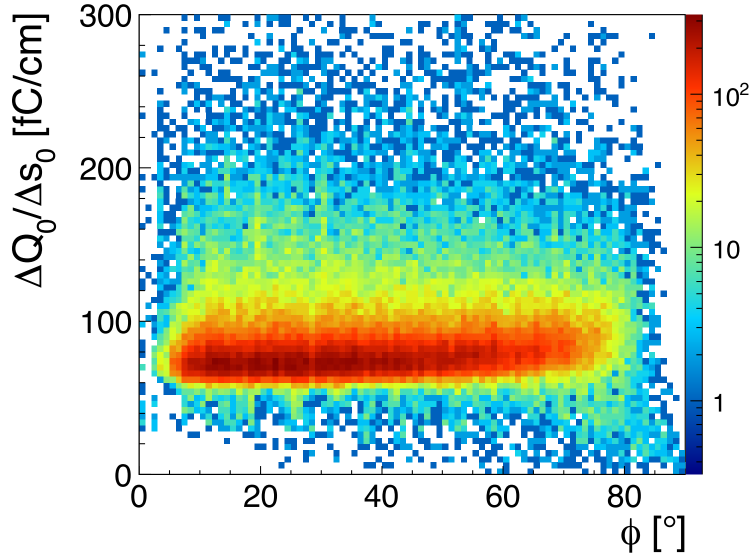
1.) Ionization electrons drift towards the liquid argon surface

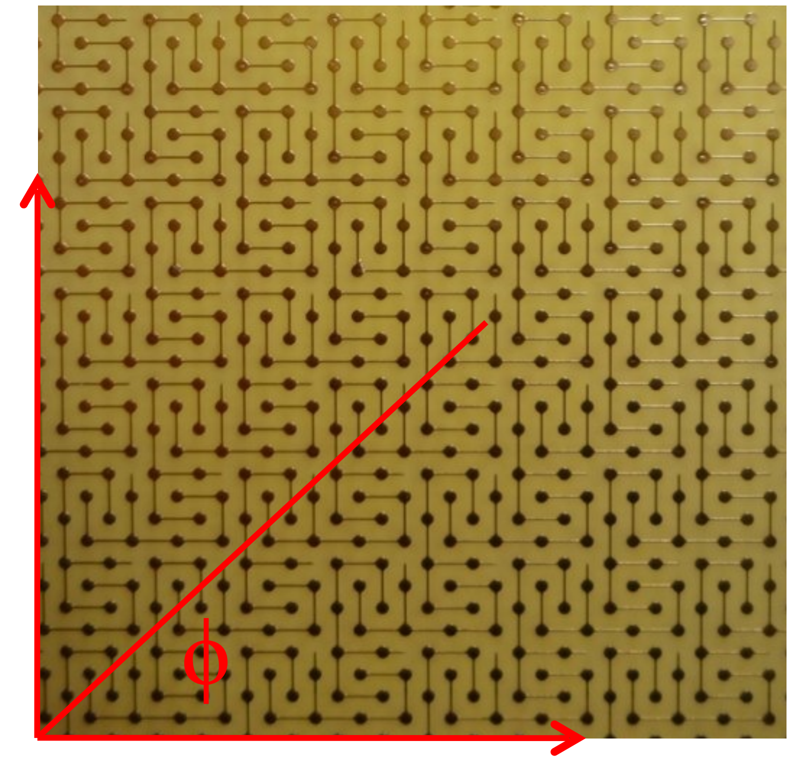
Optimisation of the anode (2014)

anode: compromise between resolution on charge measurement and capacitance

dC/dl ~ 150 pF/m







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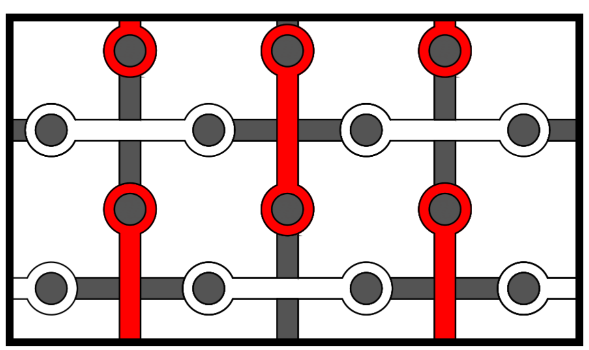
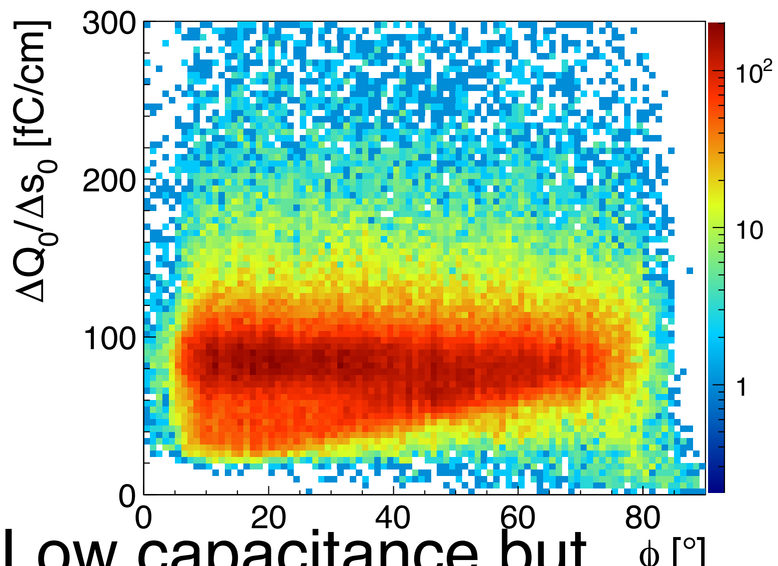
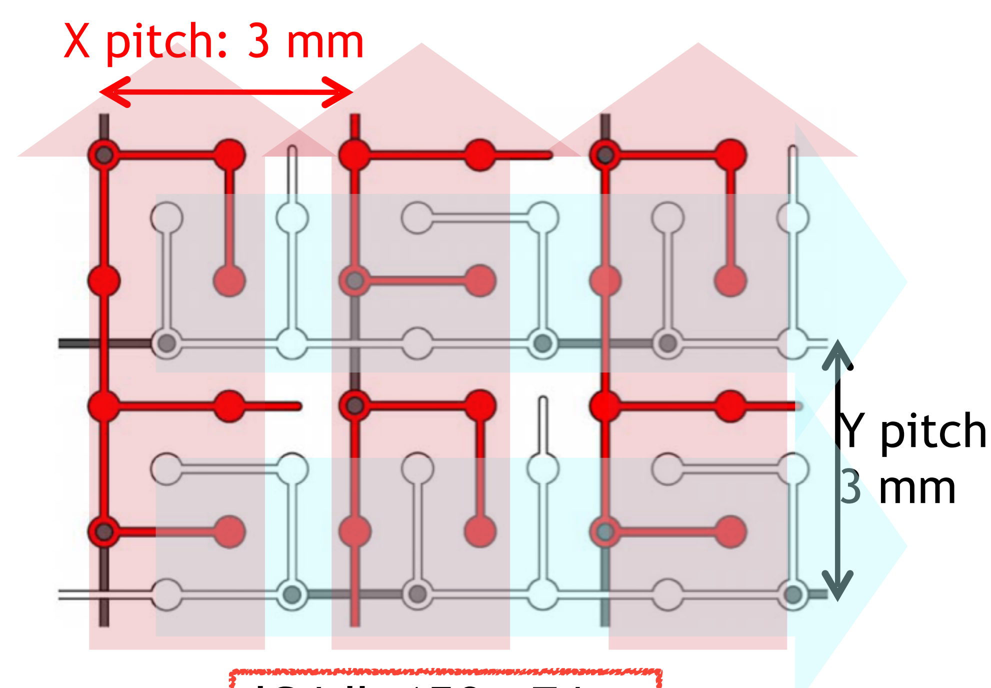
dC/dl ~ 100 pF/m





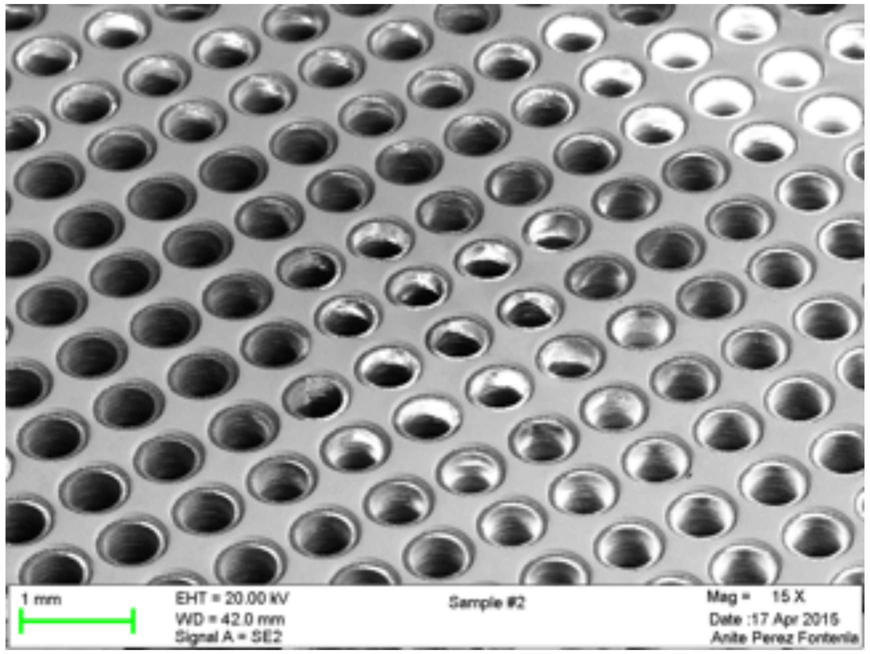
anode pattern too corse. Low capacitance but charge collection not uniform

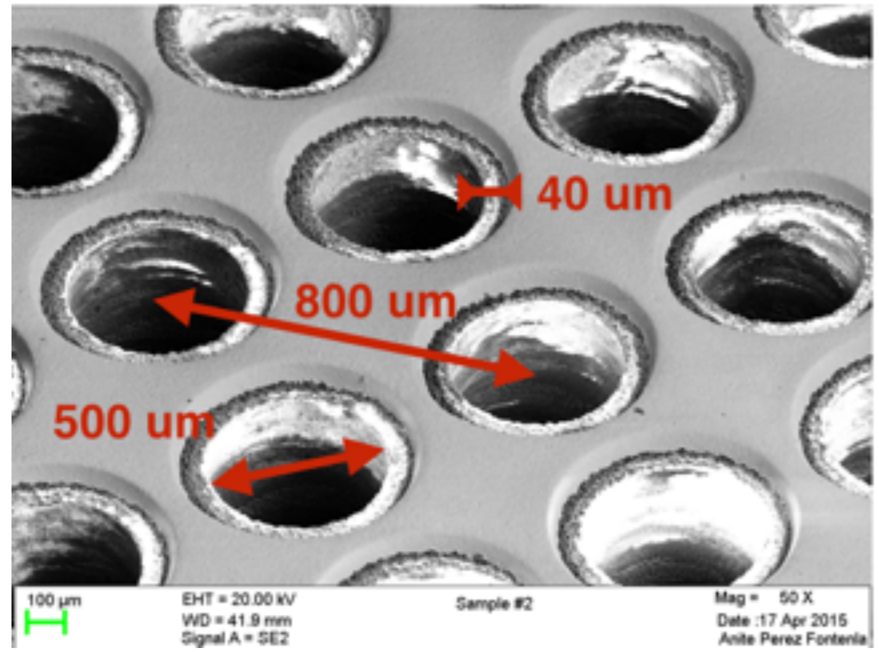


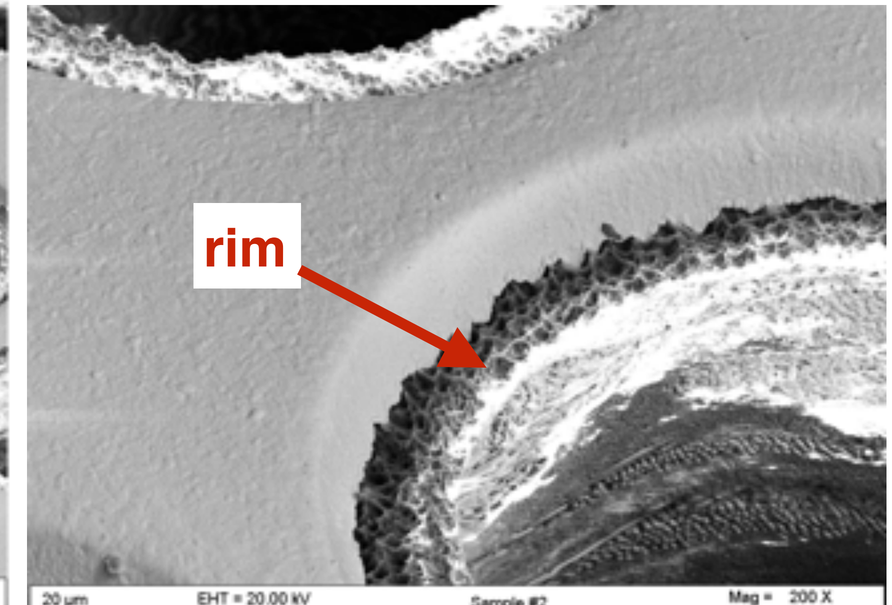
dC/dl~150 pF/m

Best solution to optimize capacitance and resolution

LEM geometry optimisation (2014)



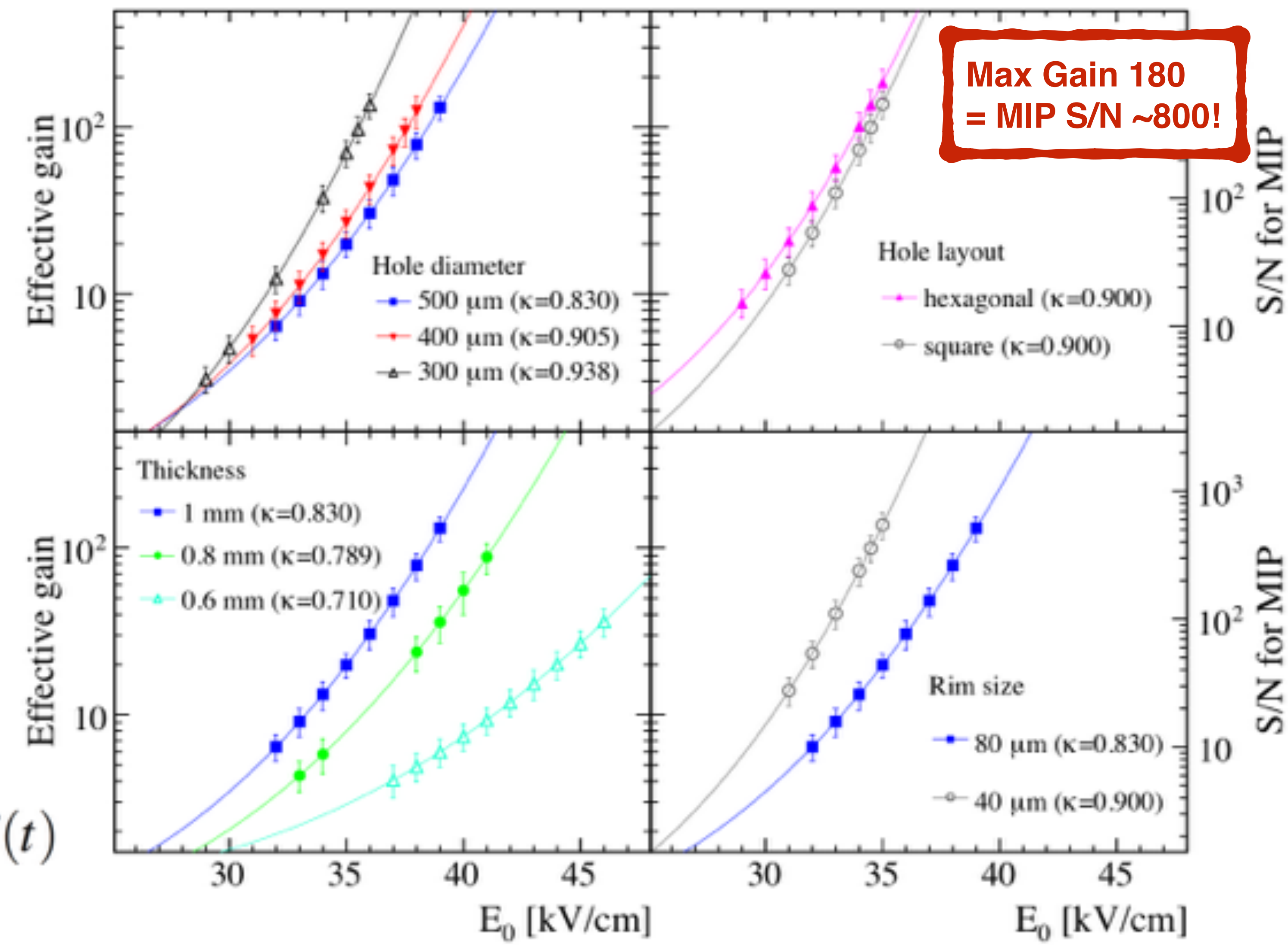




Optimisation from 10x10 cm² LEMs in dual phase operation

C. Cantini et al JINST 10 P03017 (2015)

effect of
- ✳rim size
- ✳hole diameter
- ✳hole layout
- ✳PCB thickness

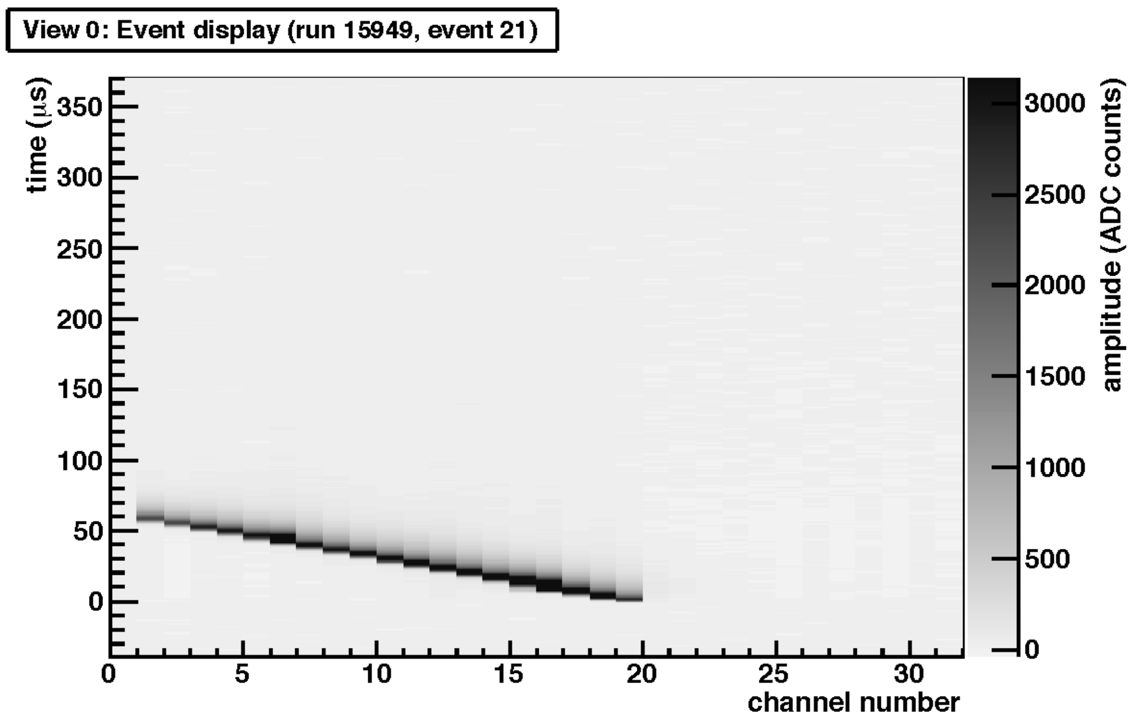


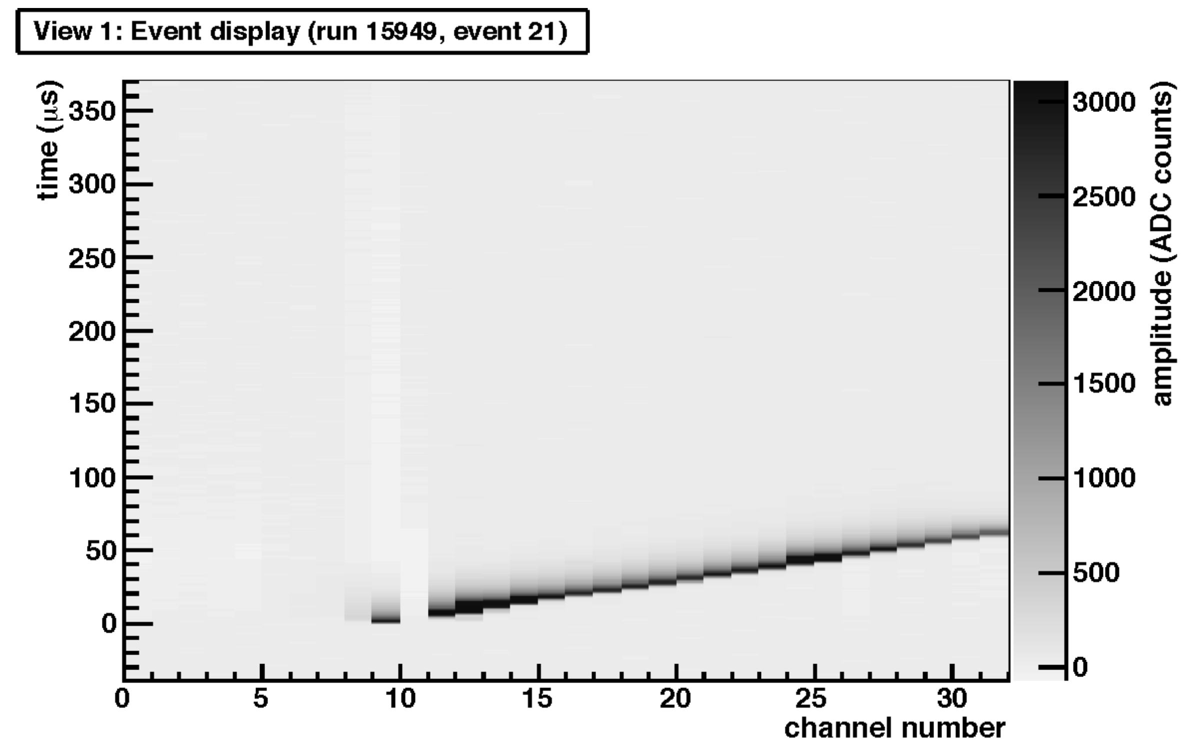
Fitting function:

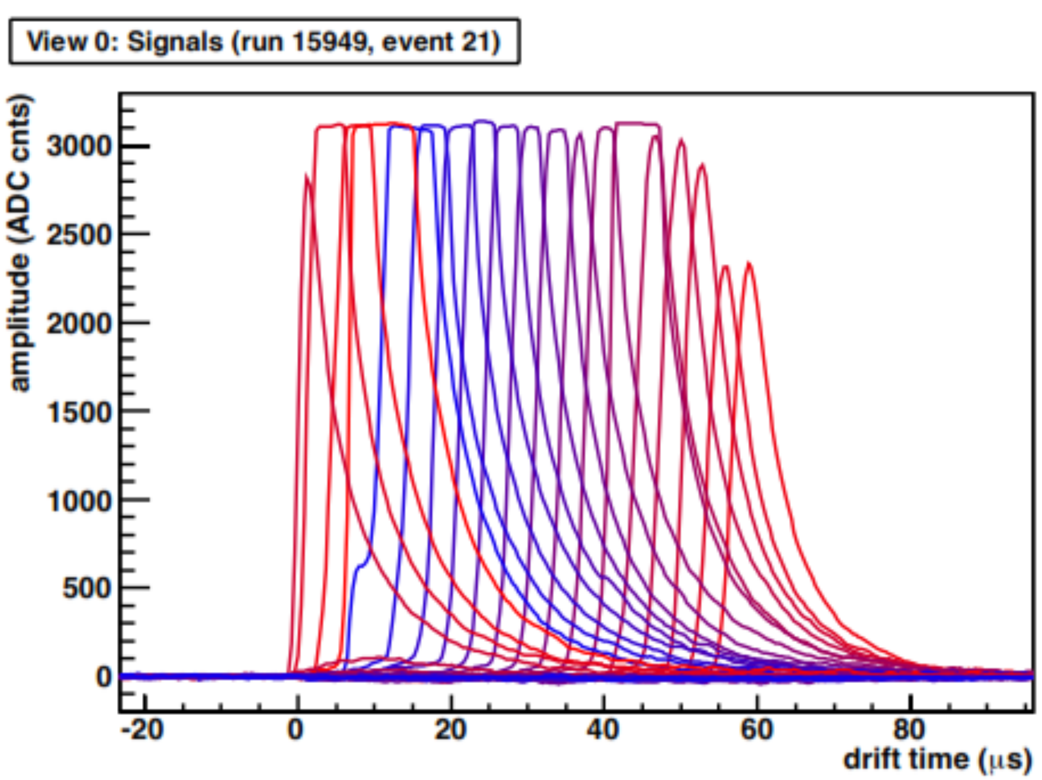
$$G_{eff}(E,\rho,t) \equiv \mathcal{T} e^{\alpha(\rho,E)x} \times \mathcal{C}(t)$$

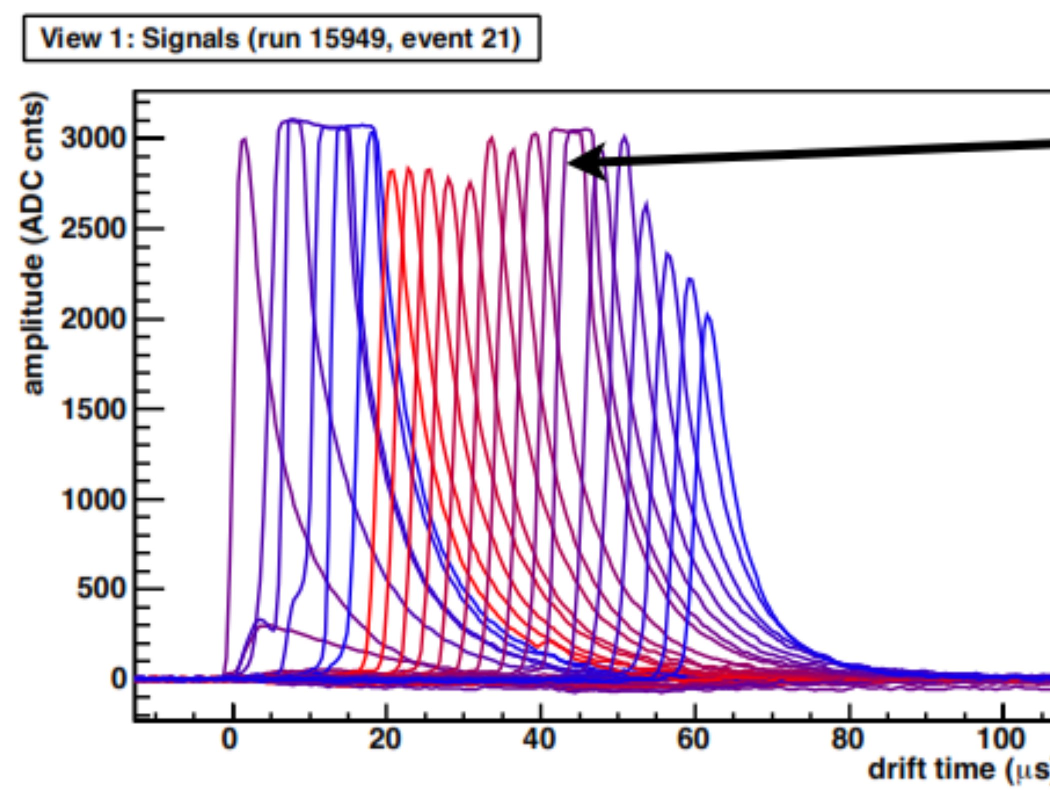
$$\alpha(\rho,E) = A\rho e^{-B\rho/E}$$

CR event with gain ≈180 !









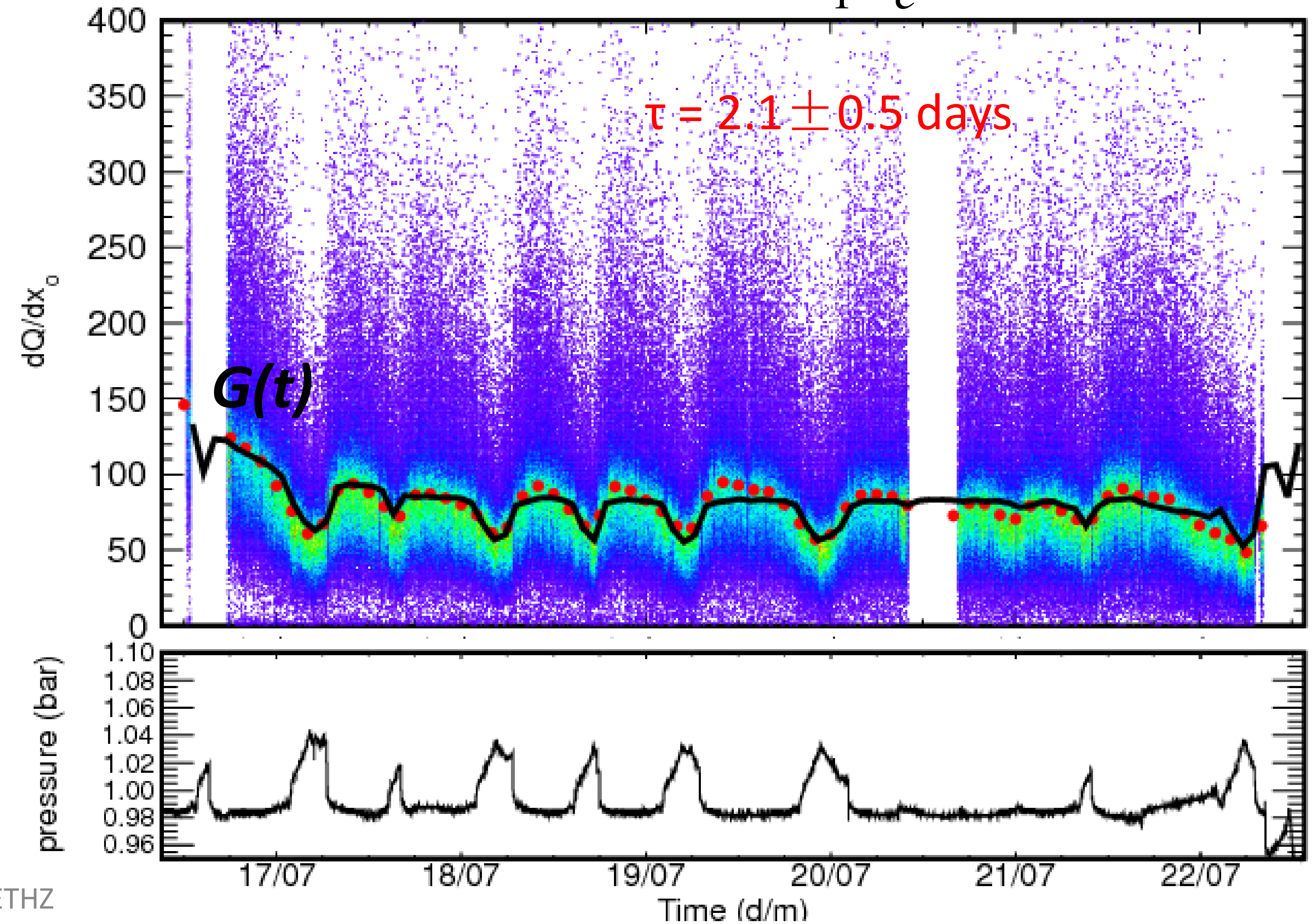
saturation
of the pre-amp

Stability of the gain

Gain of LEM depends on: 1. gas property (pressure, temperature, mixture…)
2. electric field across the LEM - E
3. effective length across the LEM – x

Described by function: $G = A \times e^{x \cdot \alpha(p,T,E)}$ where $\alpha(p,T,E) = \frac{Bp}{T} e^{-\frac{cp}{E}}$

To describe the initial decrease: $G(t) = G_{\infty} \times \frac{1}{1 - e^{-(t-t_0)/\tau}}$



July run: test
Anode B

Pressure inside

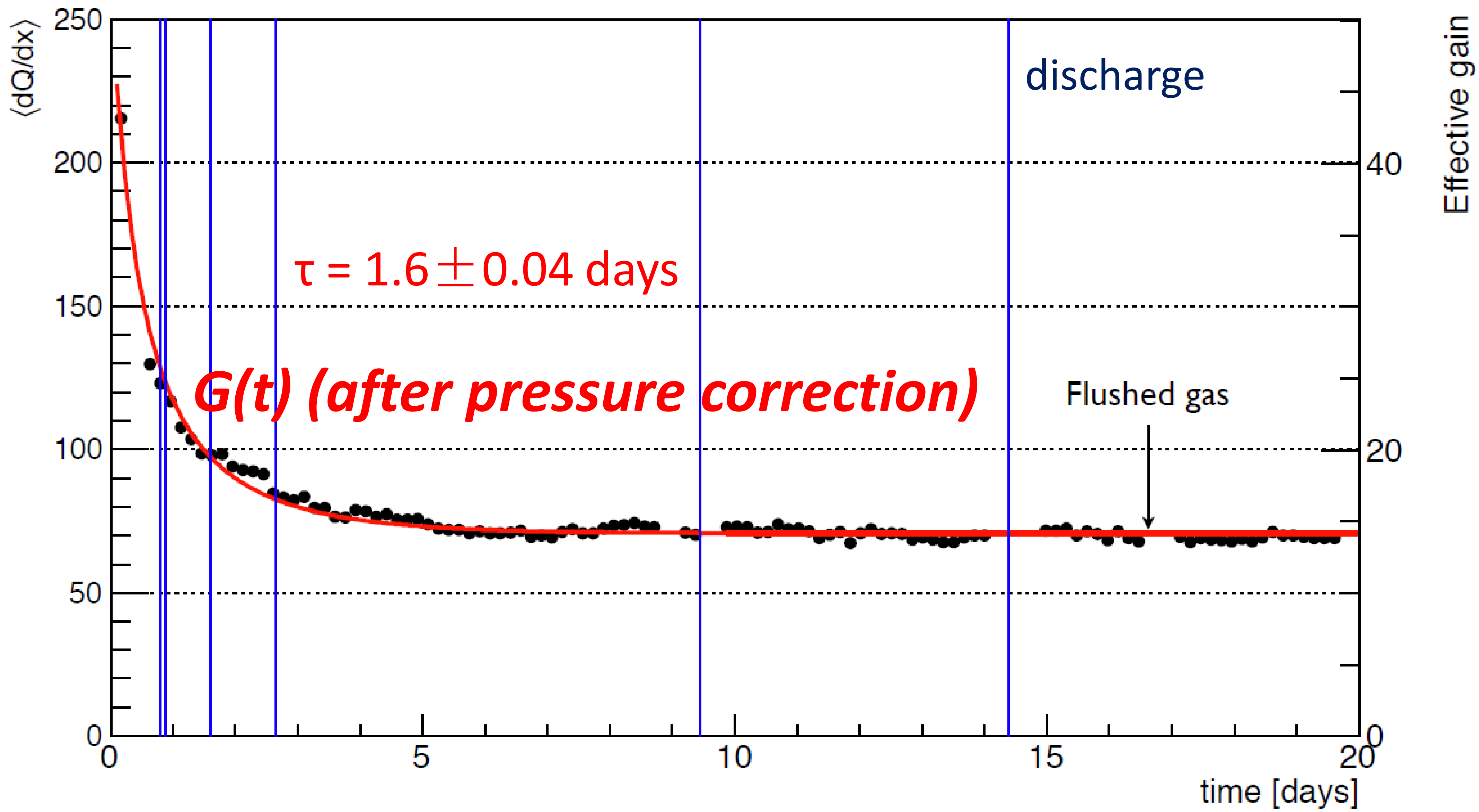
future detectors'll operate under controlled pressure

Gain and charging up effect

To describe the initial decrease: $G(t) = G_{\infty} \times \frac{1}{1 - e^{-(t-t_0)/\tau}}$

- ✓ Gain stabilizes at ~15 (at LEM field of 33 kV/cm) after an initial decrease with τ ~ 1.6 days
- ✓ Discharge does not affect the overall gain

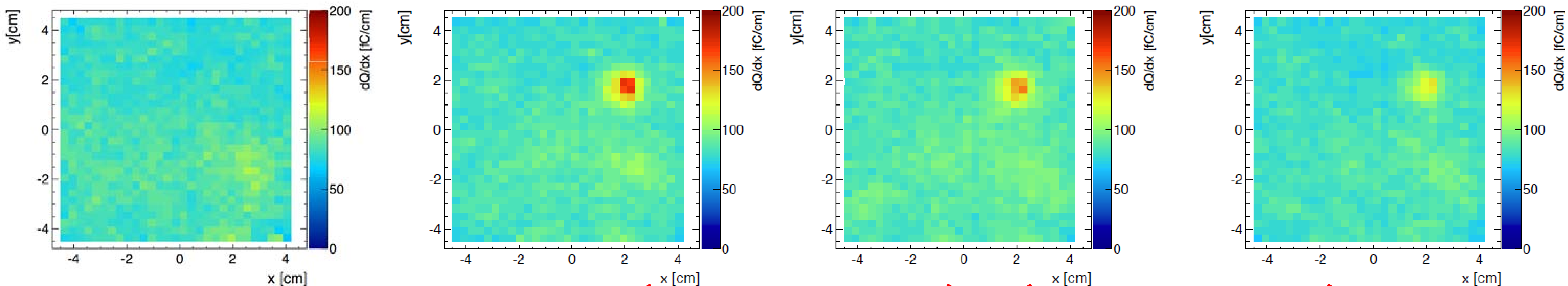
JINST 9 (2014) P03017



Why we believe it's charging up

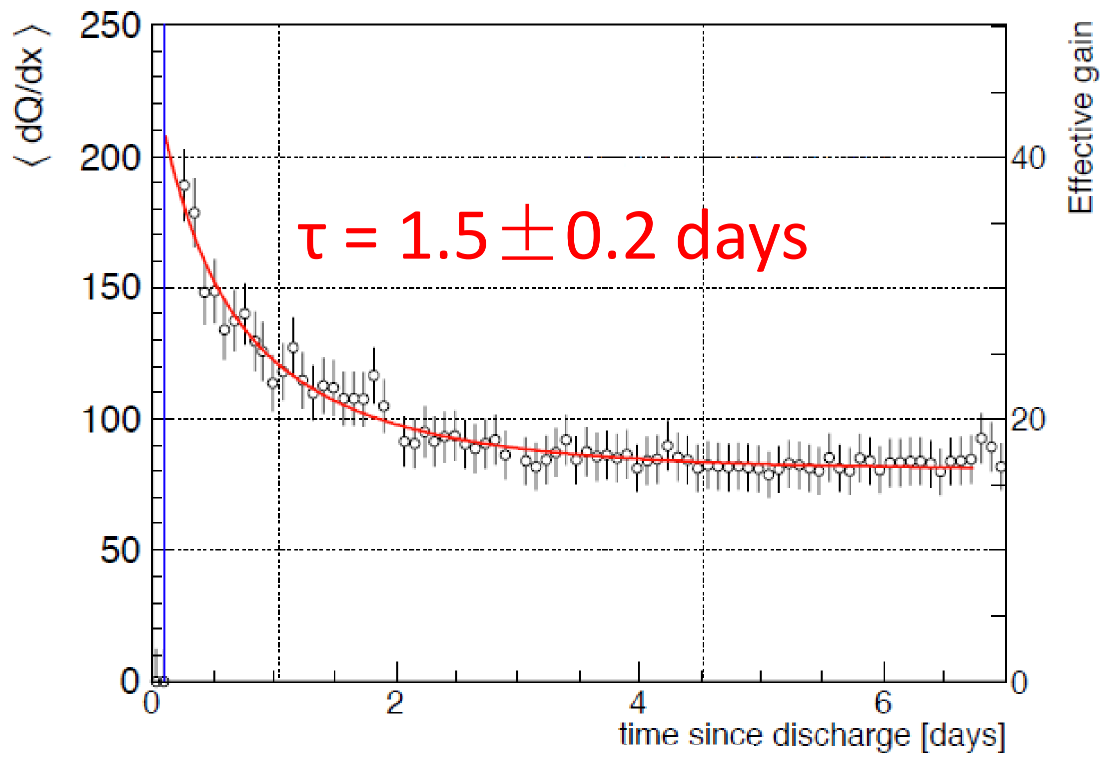
We studied sparks that occurred during long term runs

before discharge: when discharging: after discharge:



4 hours 4 hours

"hot spot" follows a similar decay:

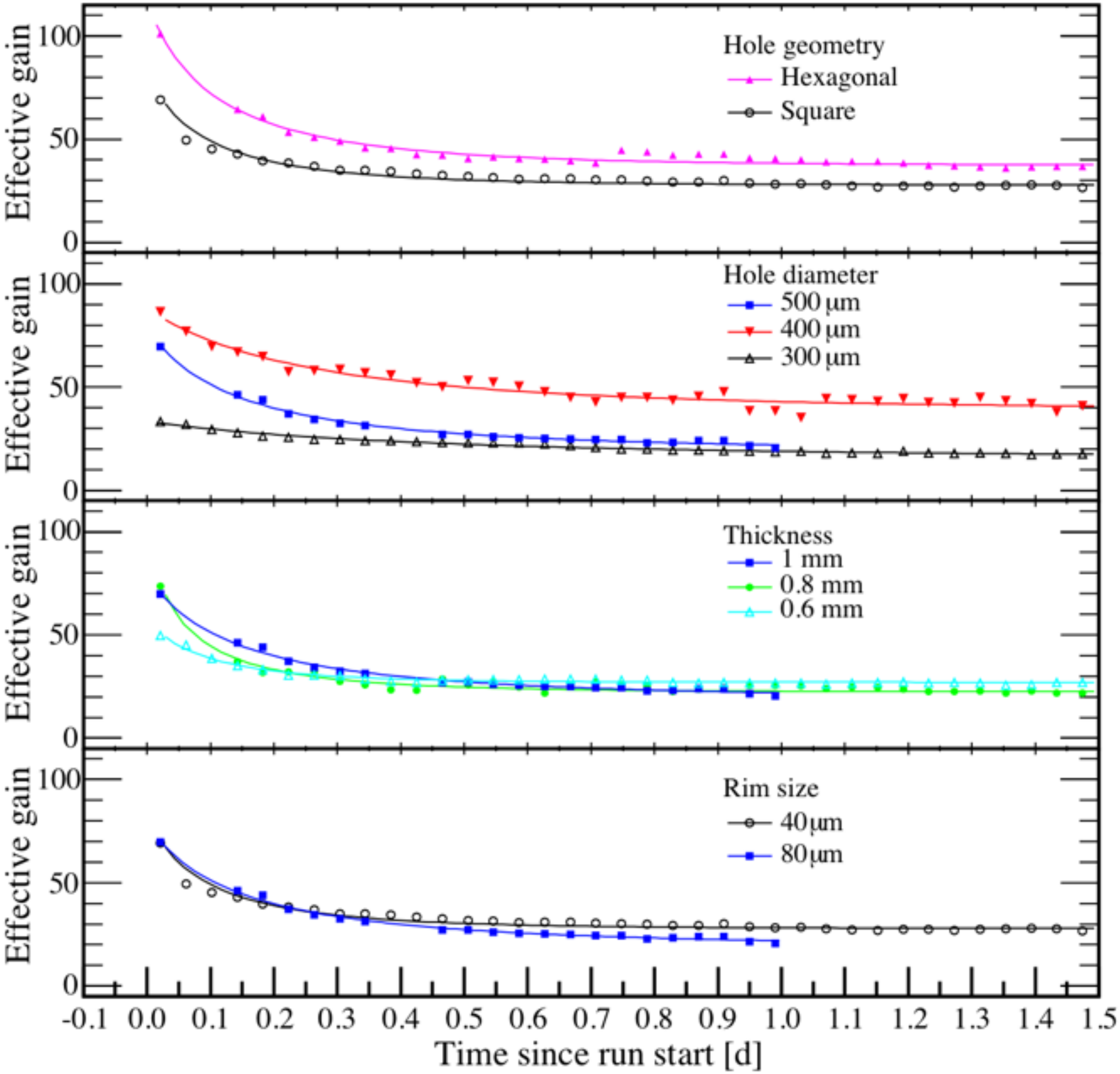


JINST 9 (2014) P03017

Summary of number of discharges:

LEM field	Run Time	$N_{discharge}$
33 kV/cm	46 days	8
34 kV/cm	7 days	0
35 kV/cm	7 days	1

Reproducibility of gain stability



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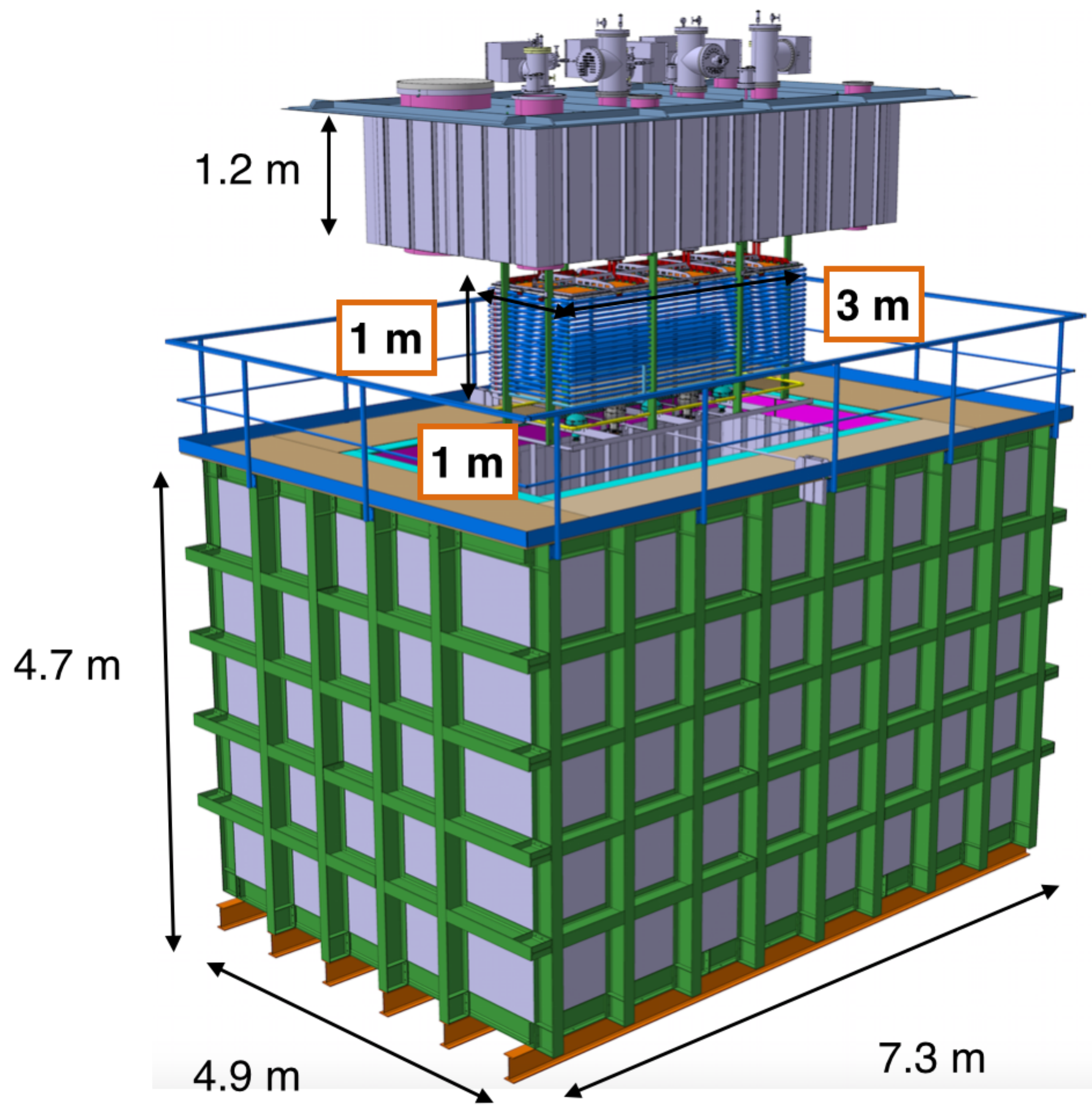
The LEMs had slightly different charging up characteristics but all could be **operated stably at gains of at least 20**.

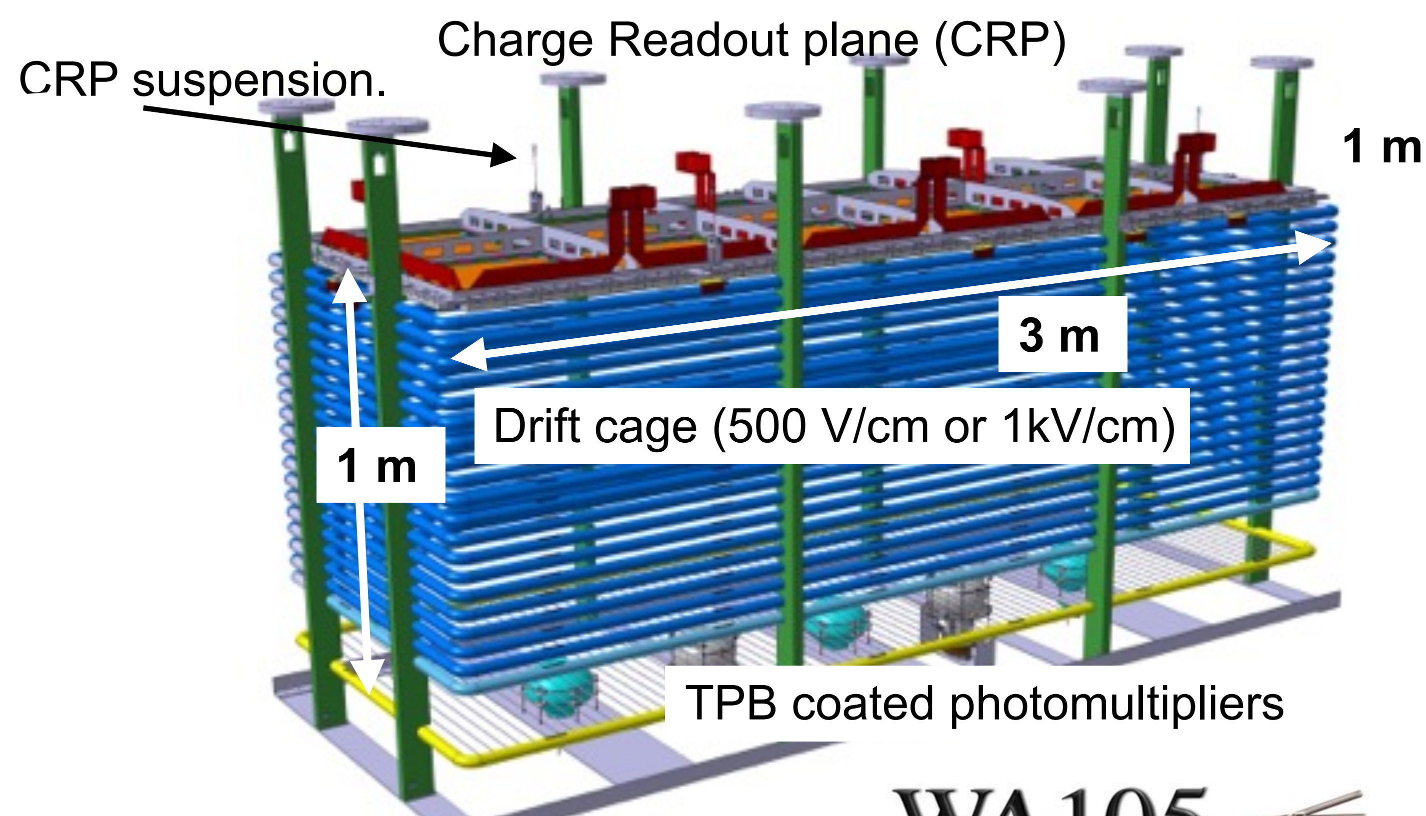
Current developments

WA105 3x1x1m3: A 25 ton dual phase TPC



Leak check Membrane:

i. GABADI & CEGELEC→ sensitive to 1e-5 (mbar l/s)
ii. CERN is improving the test in order to reach 1e-9 (mbar l/s)

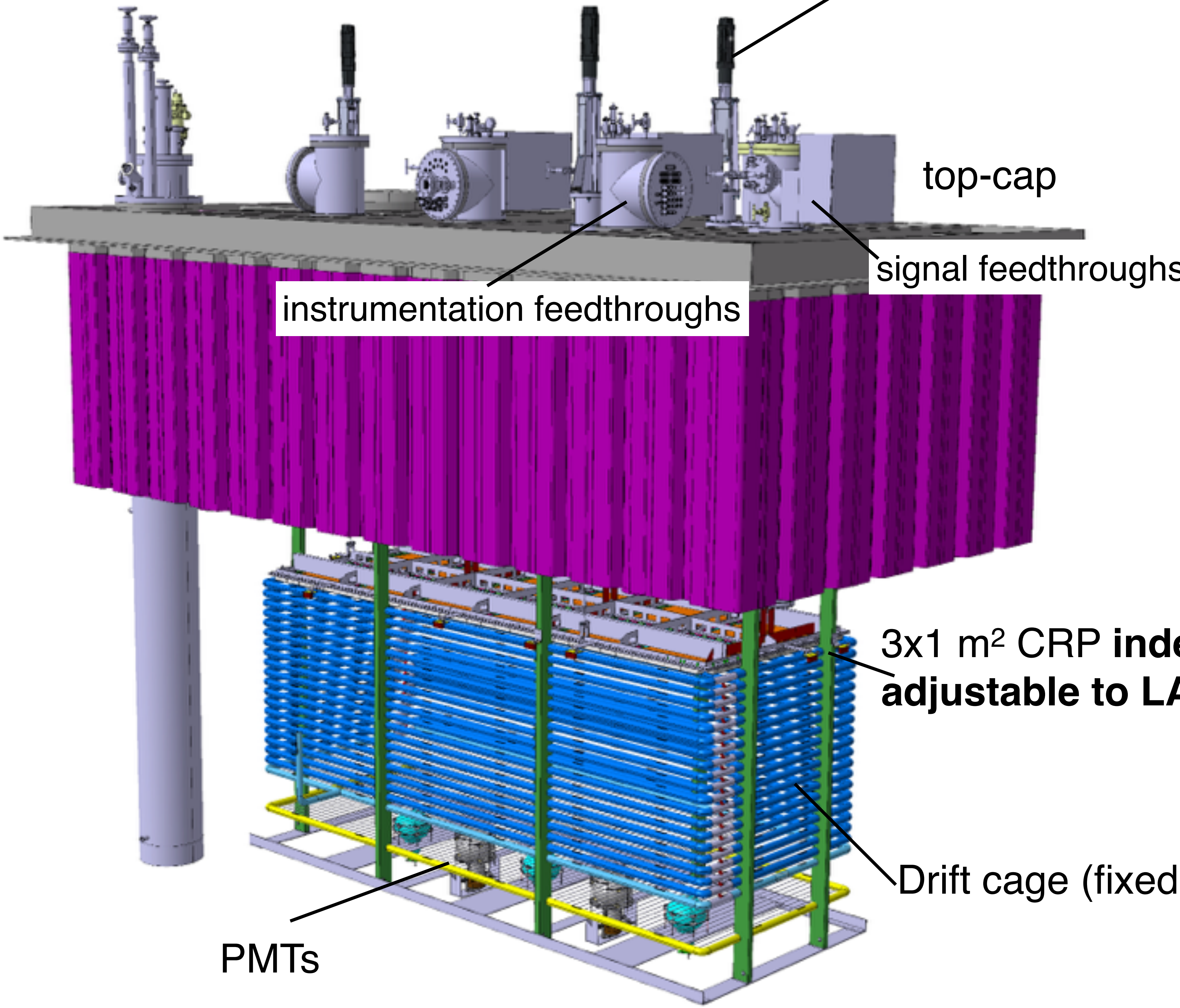


- First large scale of dual phase TPC
  - 25 ton total LAr mass
  - Active mass 4.2 tons
  - 3 mm readout pitch
  - 2 views
  - 1920 readout channels
  - (3+2) 8" PMTs

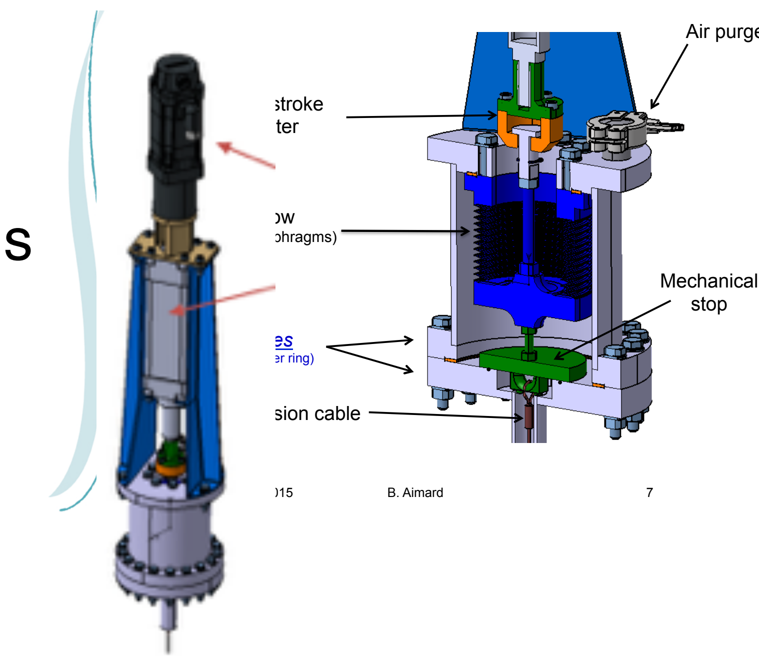
WA105

Hanging CRP + field cage

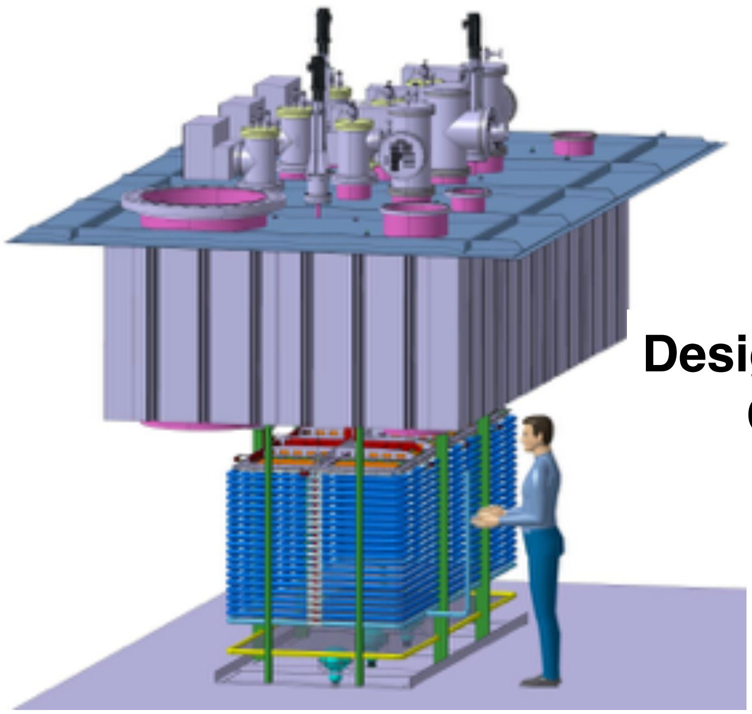
WA105



CRP suspension feedthrough

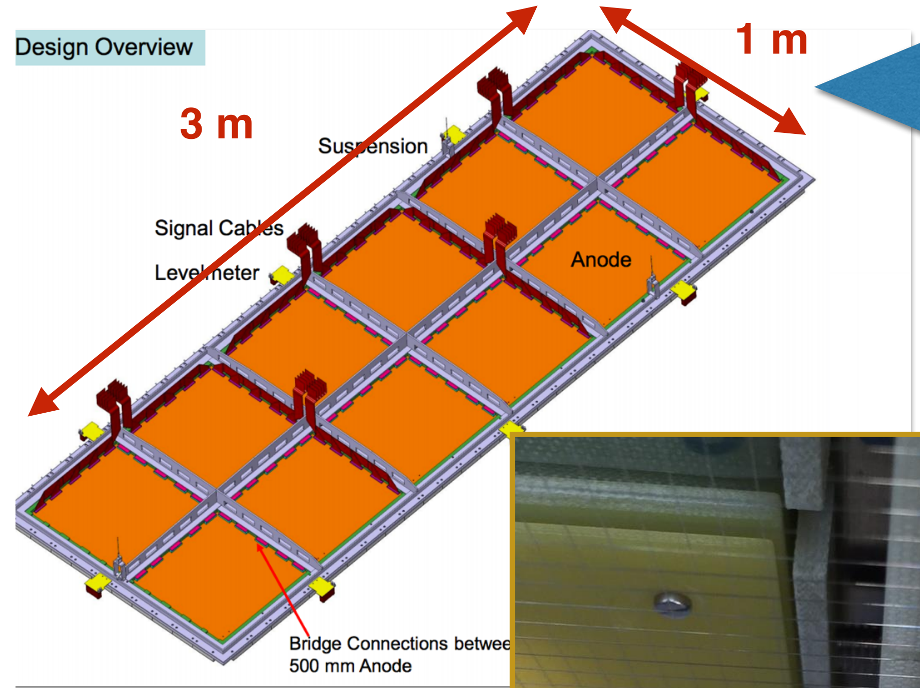


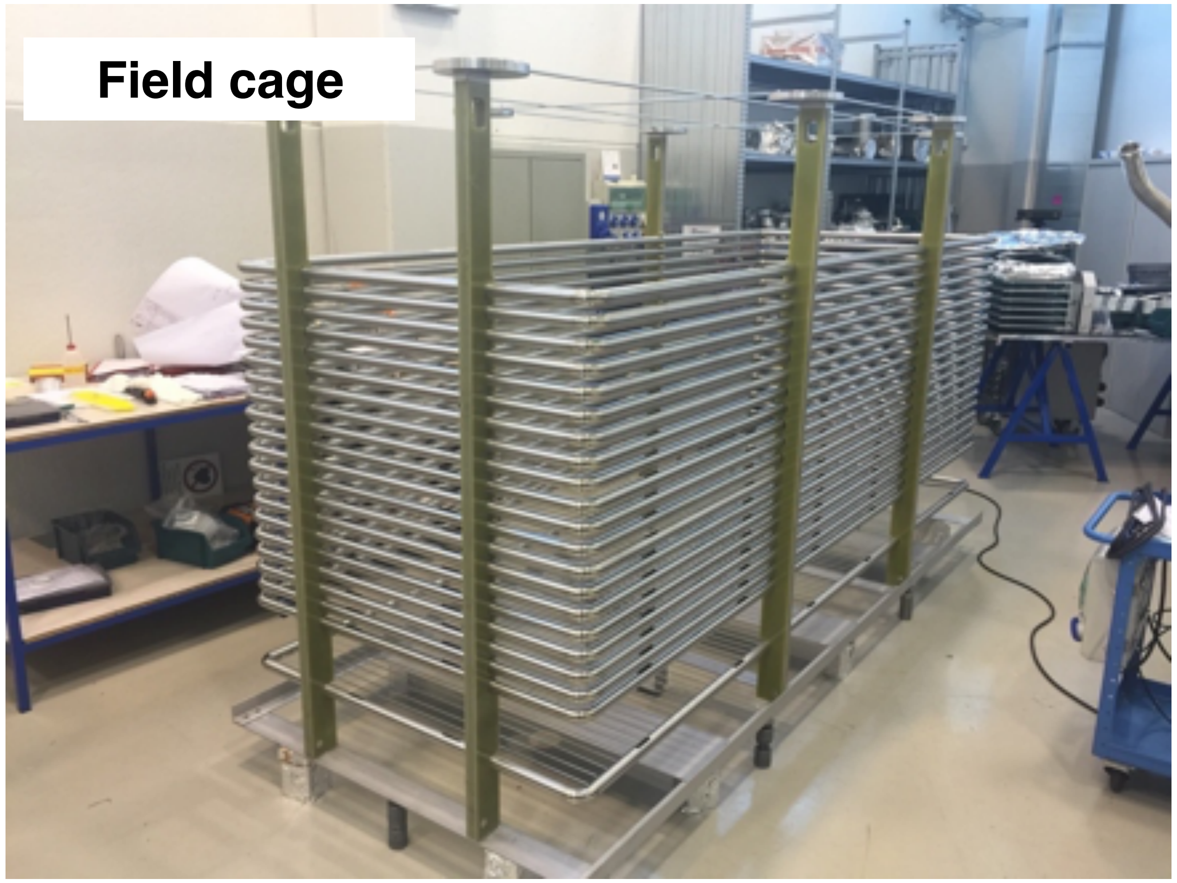
3x1x1m3 assembly (CRP+field cage) WA105



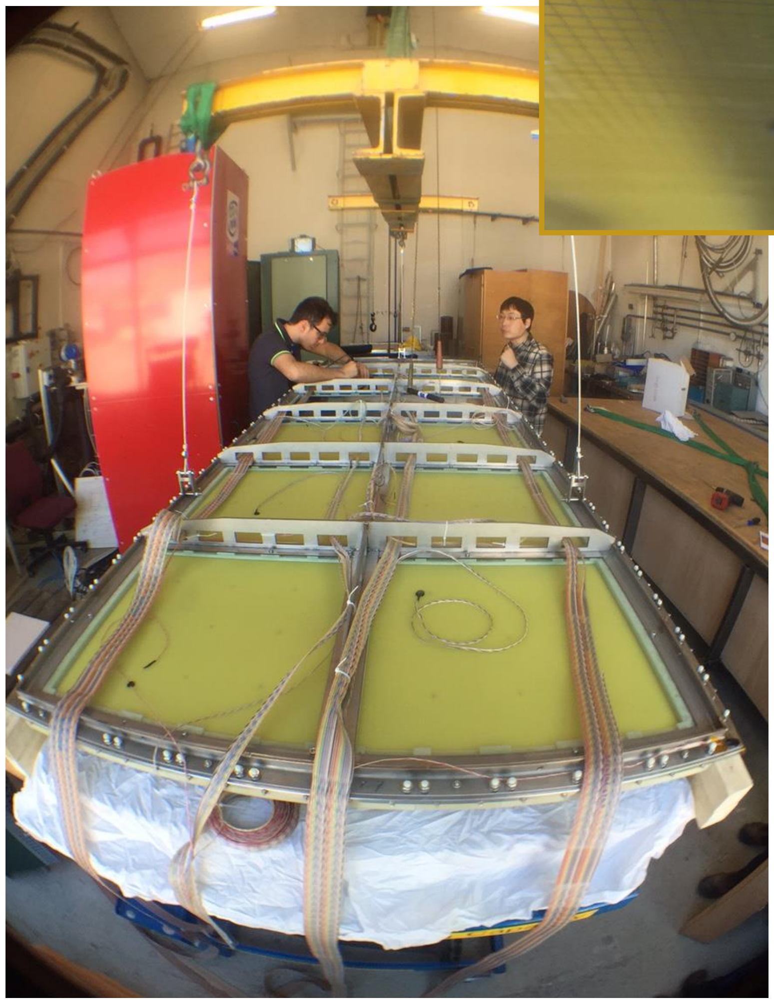
Design of 3x1x1m3 CRP plane

Suspended and adjustable to LAr level

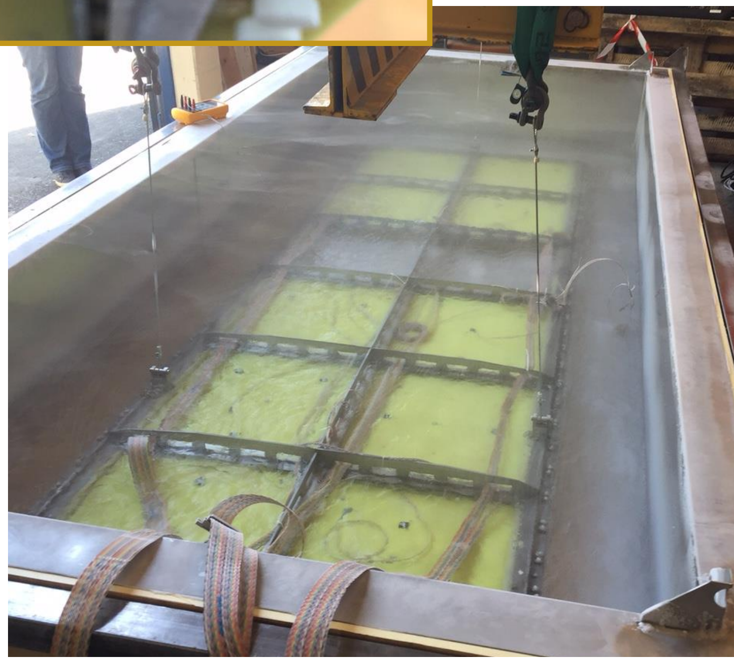




Field cage



CRP cold test



Immersed in LN2 to measure deformation

Extraction grid

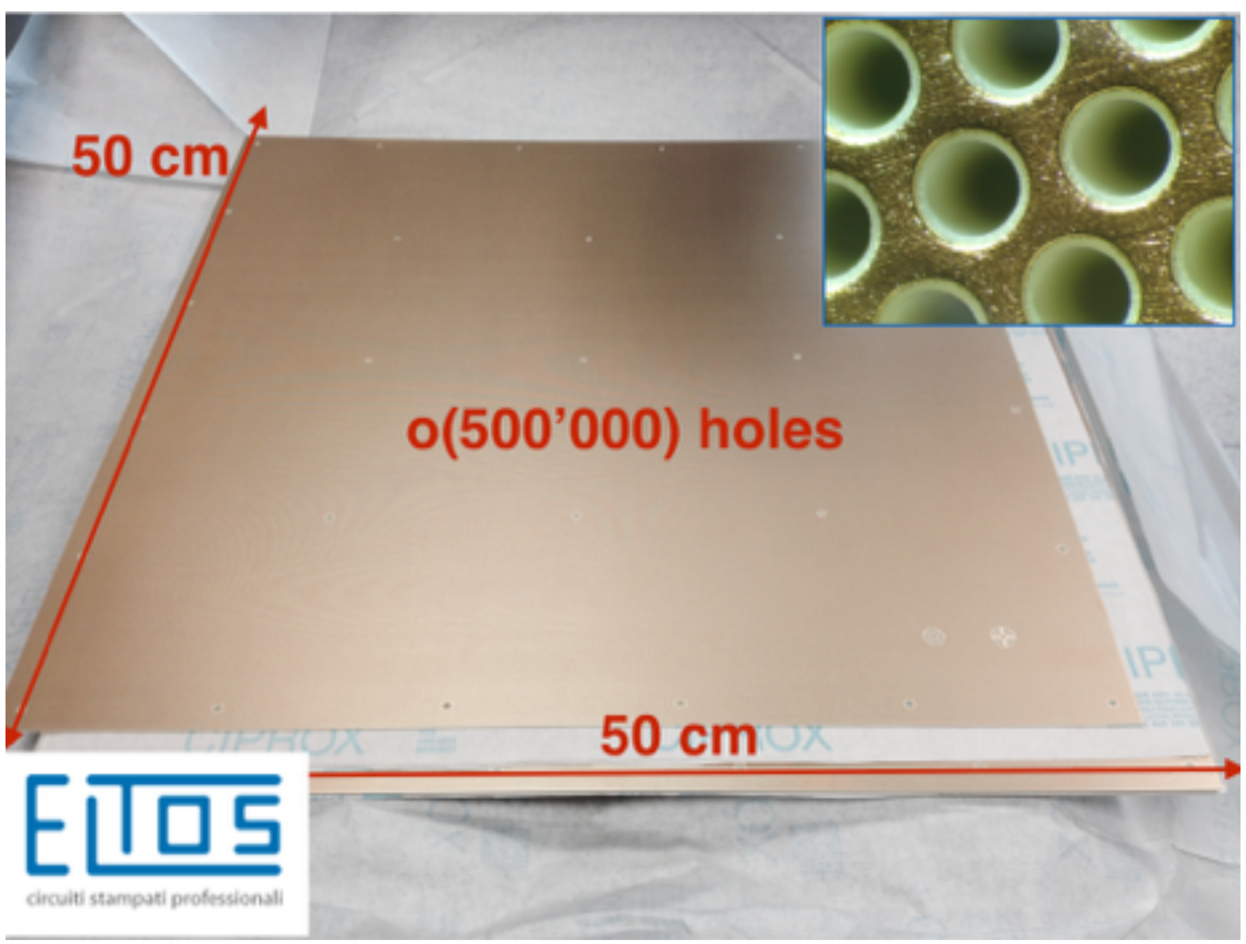
WA105

- 100μm diameter
- 3.125 mm pitch
- ~1 Kg Tension per Wire

50x50 cm² LEMs & anodes

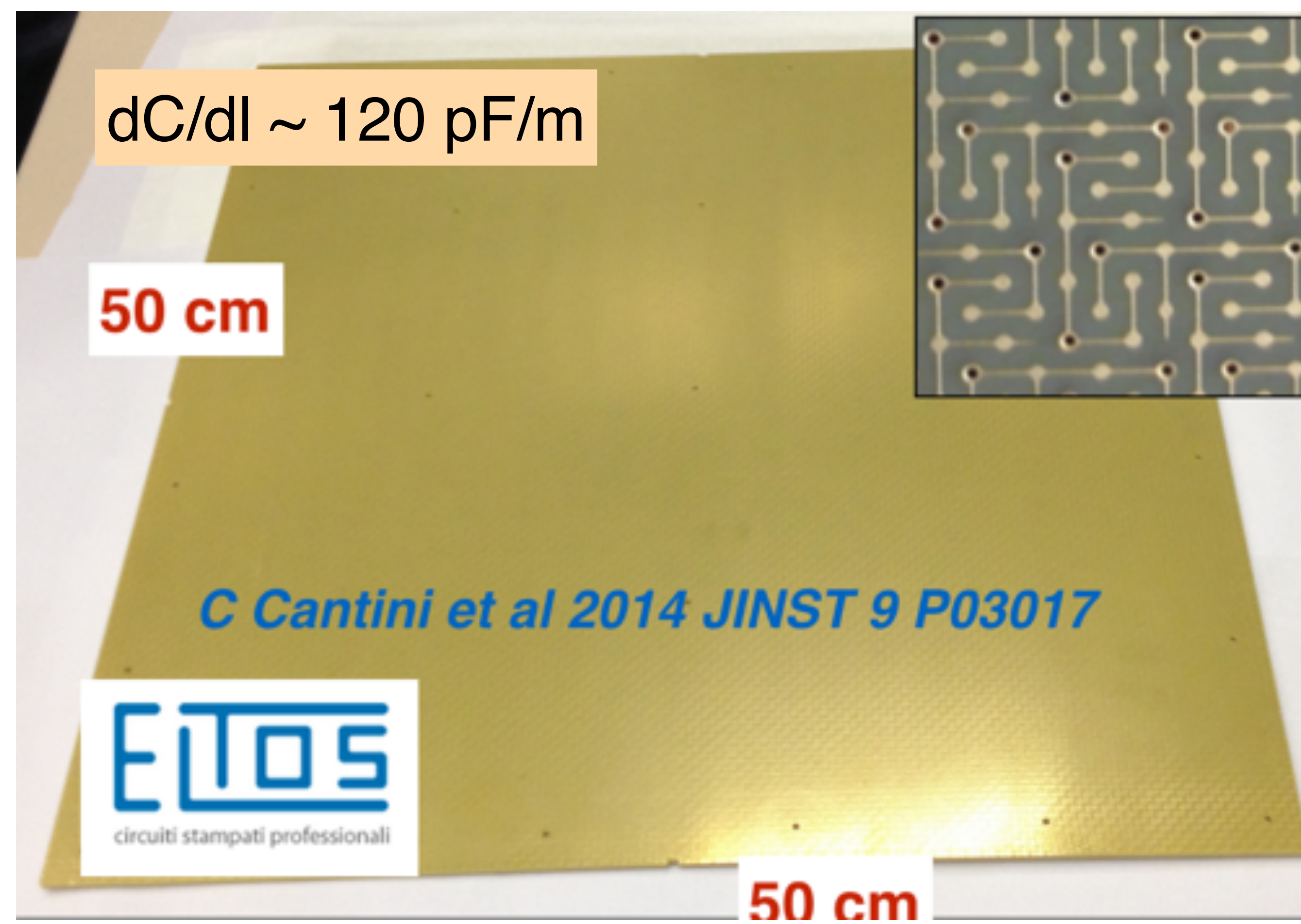
- ✓ PCB CNC drilled with o(150) holes per cm². 1 mm thick.
- ✓ 500 um hole diameter 800 um pitch.
- ✓ 40 μm dielectric rim around the holes to avoid edge-induced discharges
- ✓ powered at around 30 kV/cm
- ✓ design is the result of many years of R&D on smaller scale prototypes.
- ✓ See JINST 10 (2015) 03, P03017 for hole/rim size optimisation

50x50 cm² LEM



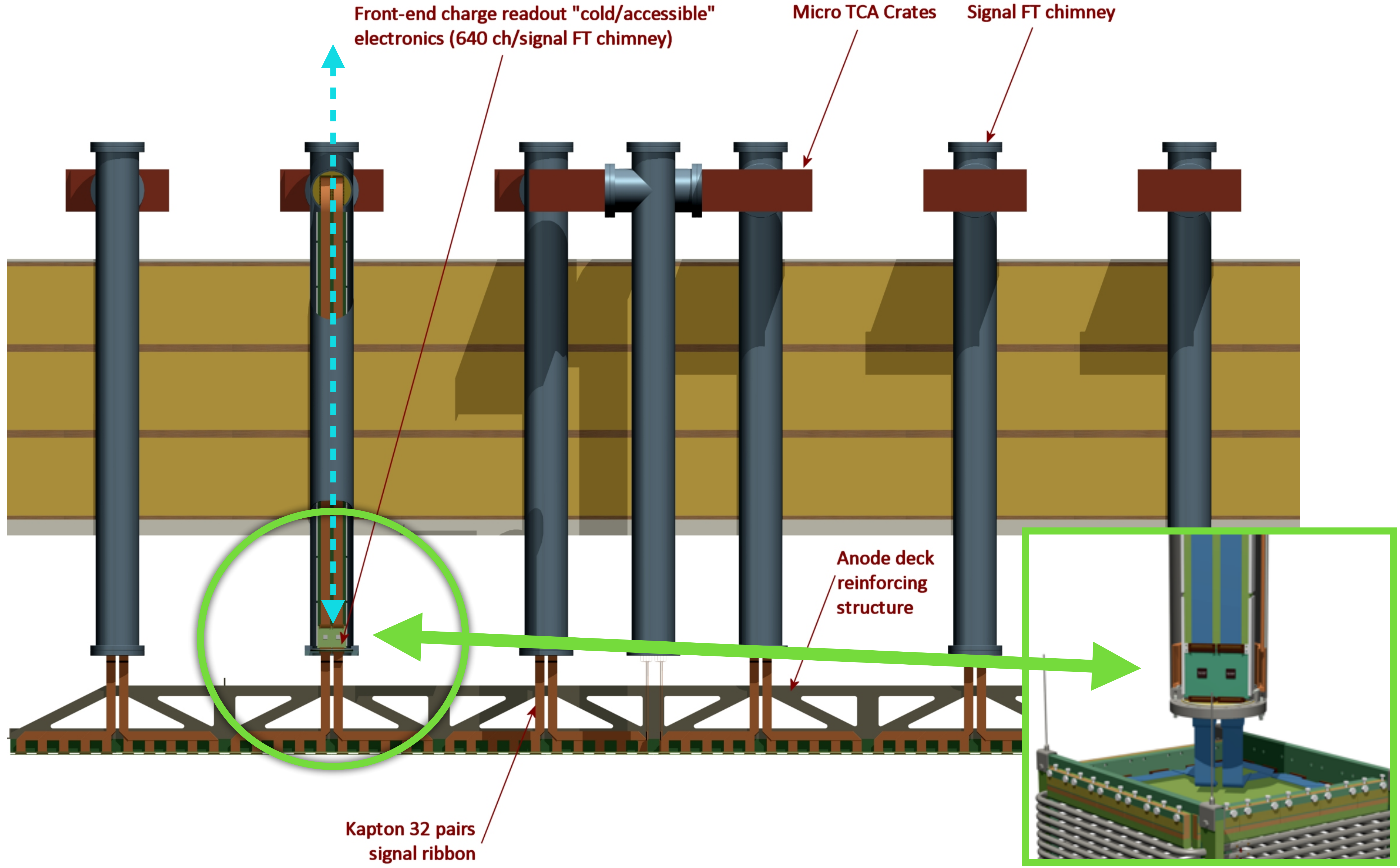
- ✓ "simple" multilayer PCB. 3.4 mm thick.
- ✓ 3 mm readout pitch
- ✓ Equal charge sharing on both collection views.
- ✓ low capacitance per unit length (~150 pF/m)
- ✓ design is a result of ~1 year R&D.
- ✓ relatively easy, cheap and fast to produce. All channels electrically tested by the company.
- ✓ soldering of the 20 KEL connectors at SMD CERN workshop. Takes about 2hrs for one board.

50x50 cm² Anode



Front-end electronics and chimneys

Cold electronics with "hot plug" accessibility



Front-end electronics and chimneys

Cold electronics with “hot plug” accessibility

Acquisition Electronics
MicroTCA Crate

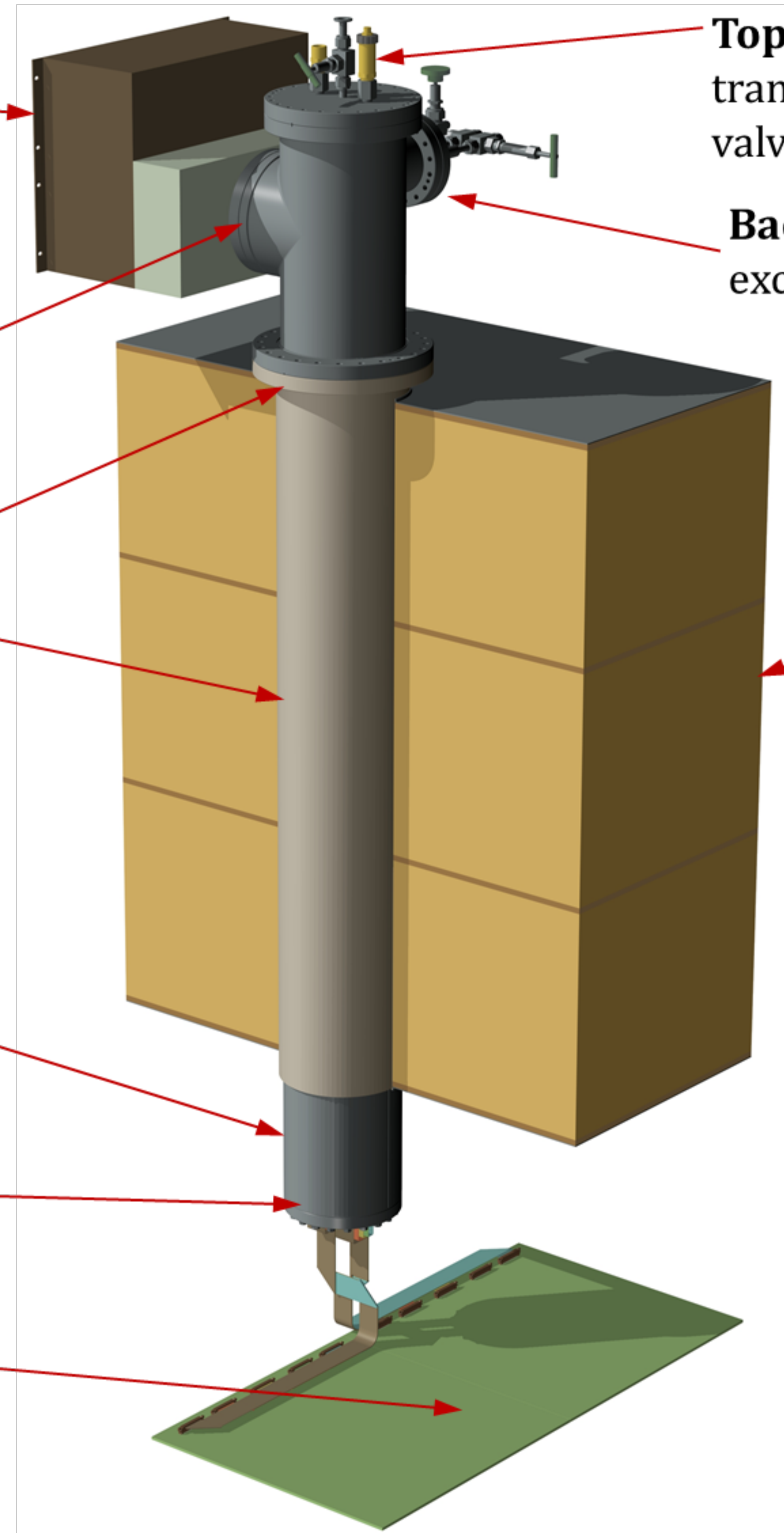
Side flange (custom**)** for warm SFT

D:219.1x215.1mm **top cap crossing tube**, welded to the top and bottom SS plates, with CF295 on top

D:204x200mm **chimney tube**, with CF295 on top

Bottom flange (custom) for cold SFT

Pair of 0.5mx0.5m **CRPs** (total number = 12)

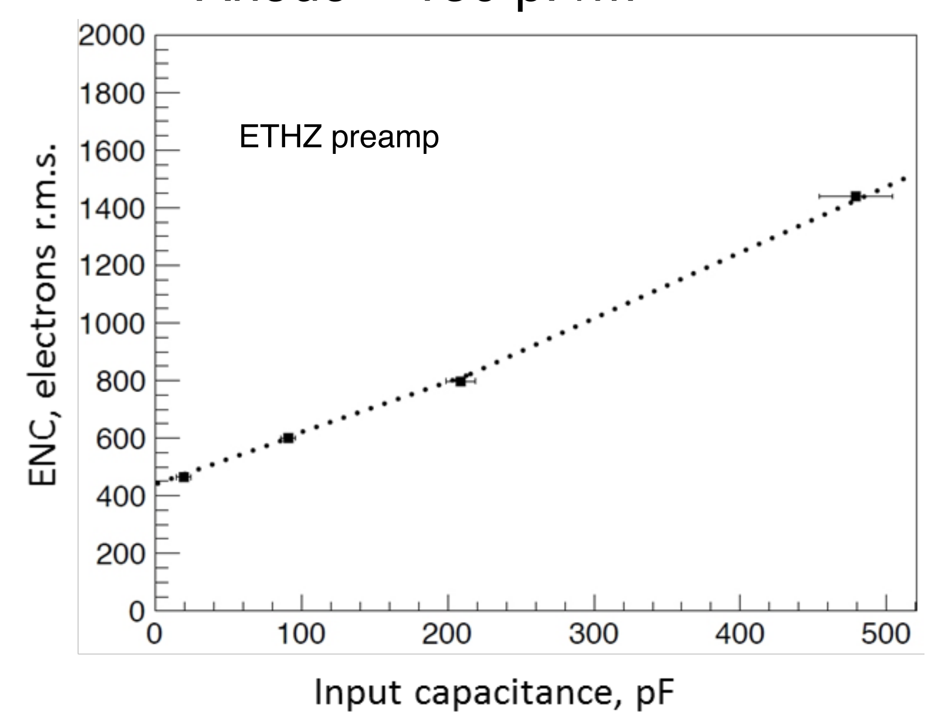


Top flange (CF253): pressure transducer, vacuum port, overpressure valve

Back flange (CF152): LAr heat exchanger, N_2 flushing ring

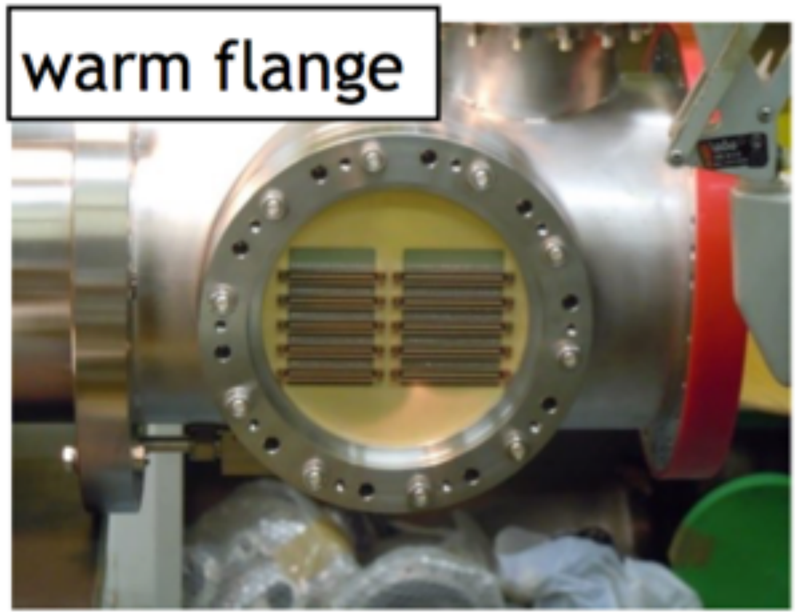
~1.2 m thick **top cap insulation**

Cable length = 0.5-0.75m
≡ 21.5-32.5pF
Anode = 150 pF/m

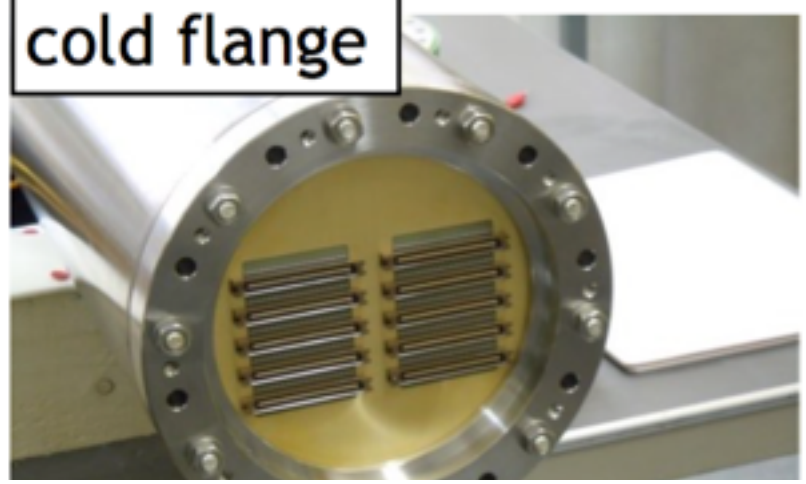


First chimney produced & tested

warm flange

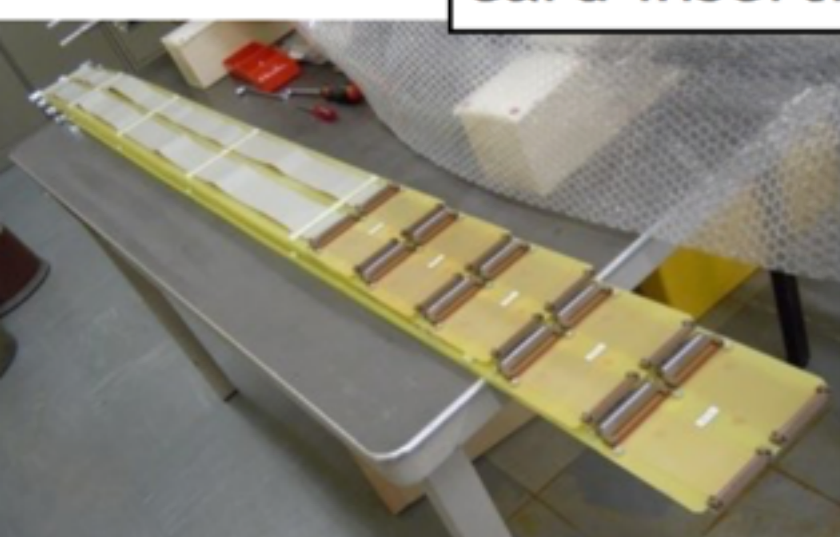


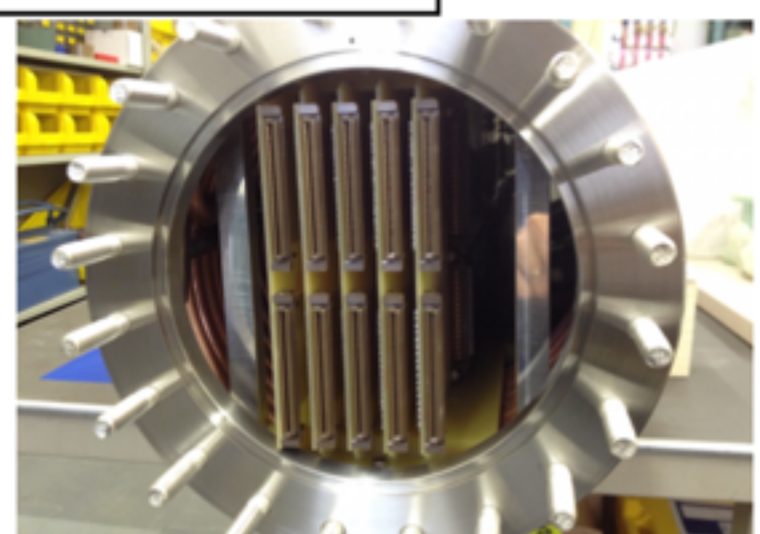
cold flange

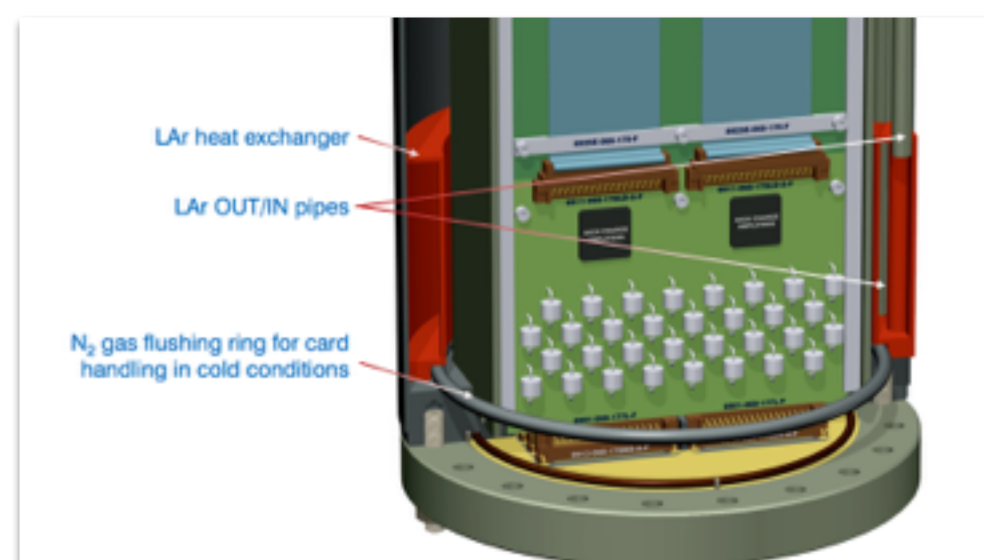


critical parts:
-card insertion over 2 meters. Had been tested in warm and is ok. Connectors each have 2 pairs of pins free, one will be used to light an LED to signal that the contact is ok.
-vacuum tightness of PCB flange: tested in warm and cold up to 1e-9 mbar l/s.

card insertion from top



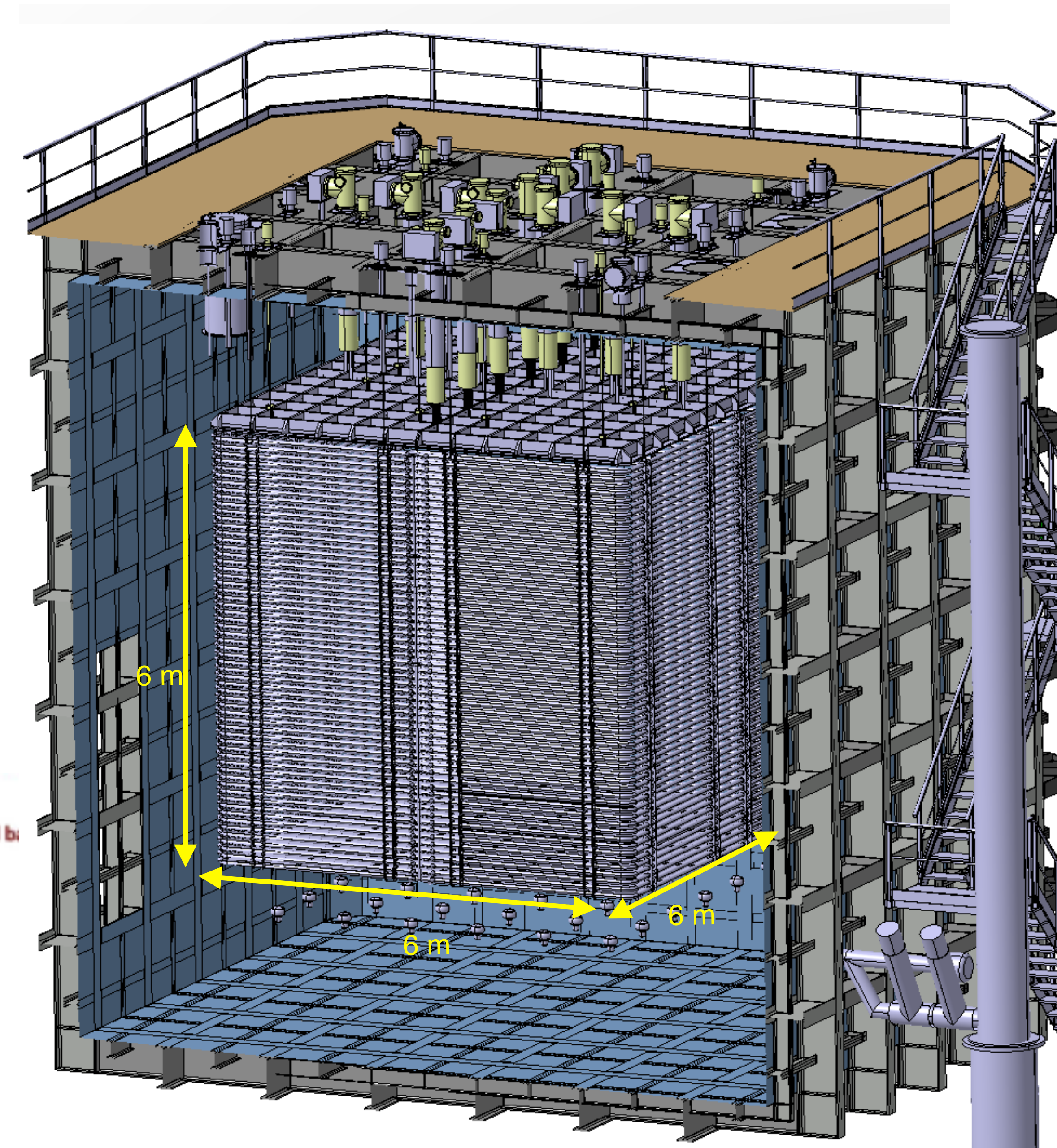




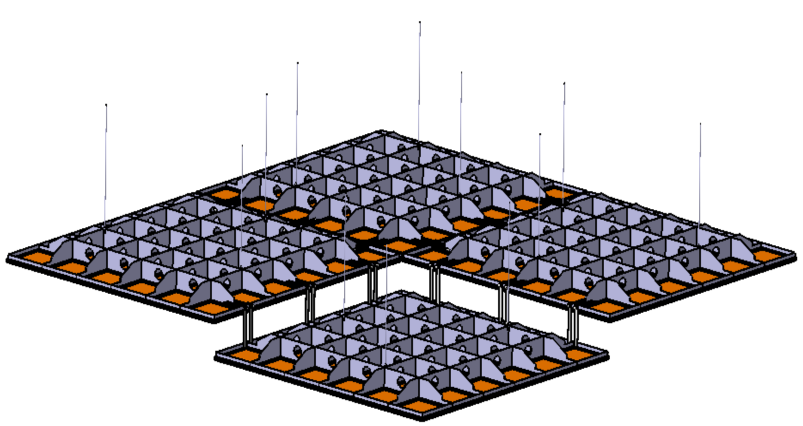
ProtoDUNE dual phase demonstrator

Main Goals:

- Validate construction techniques and operational performance of full-scale dual-phase TPC prototype modules for DUNE FD
- Collect and analyze the beam test calibration data necessary for understanding the deep-underground data to be collected with the large-scale detector modules



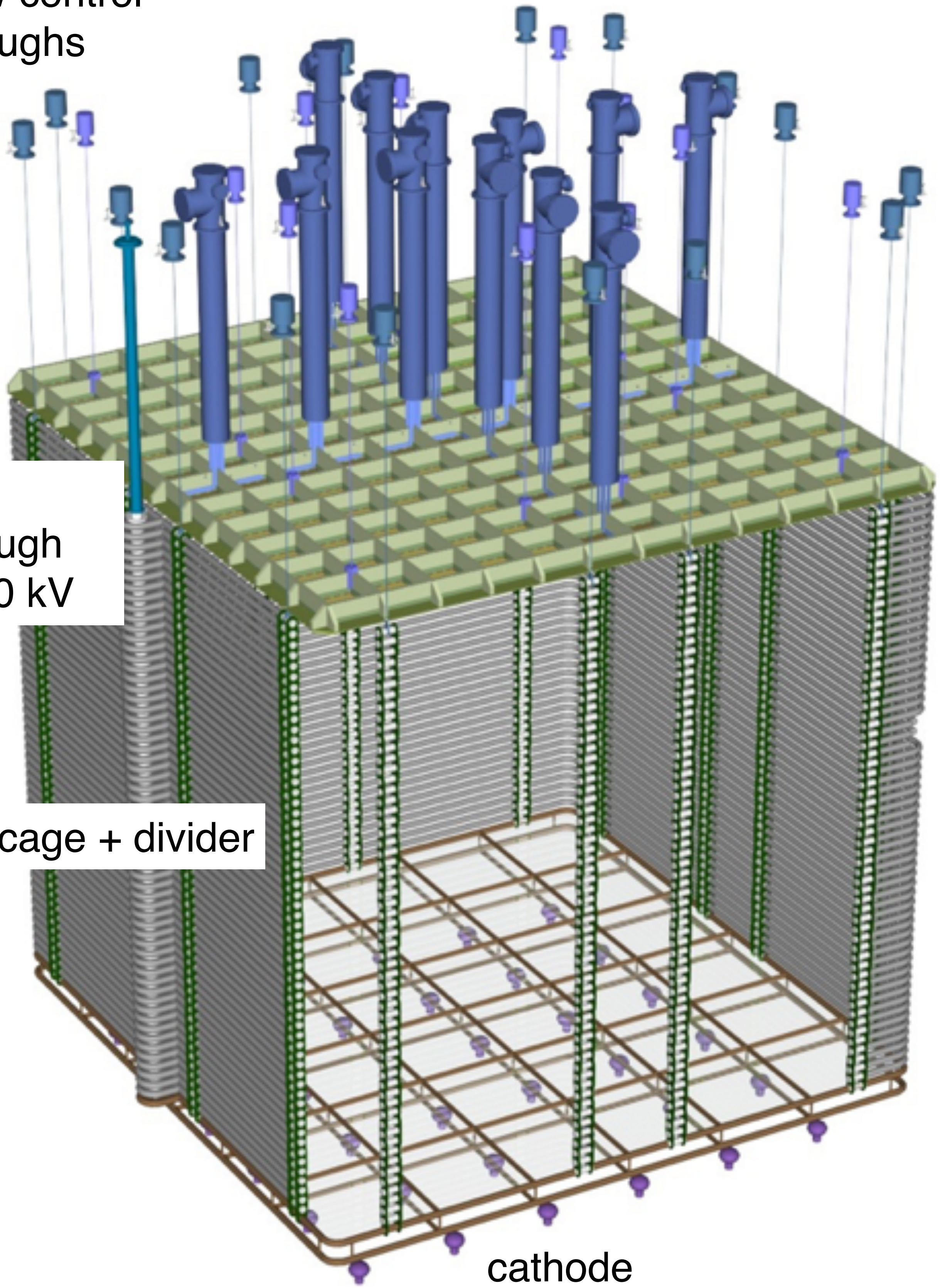
Readout composed of 4 3x3 independent CRP readout units, each acting as an independent detector



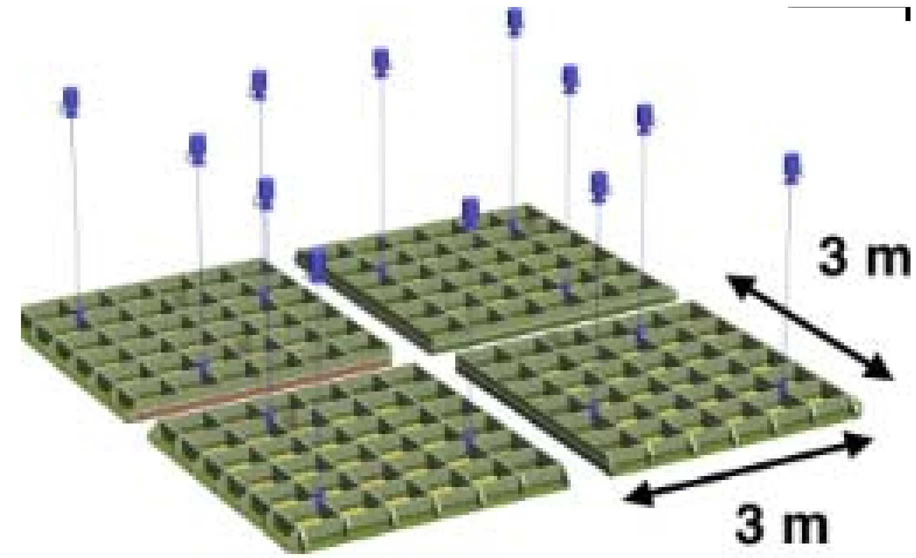
Some detector parameters:

- Insulated membrane tank
  → inner volume 8.3x8.3x8.1 m^3
- Active area 36 m^2
- Drift length 6 m
- Total LAr mass 705 ton (~300 ton active)
- Hanging field cage & readout plane
- # of signal channels: 7680 in 12 signal FT
- # of PMTs: 36

Elements of protoDUNE DP

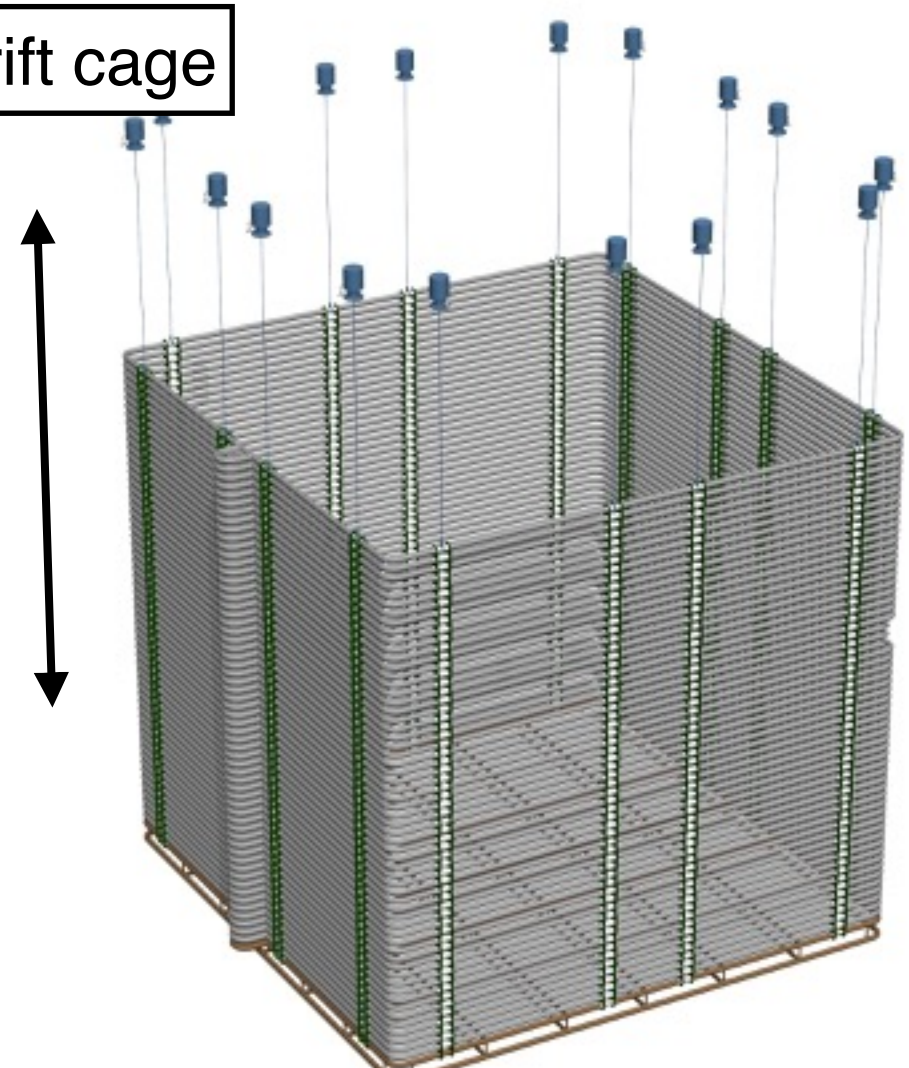


CRP (charge readout plane)



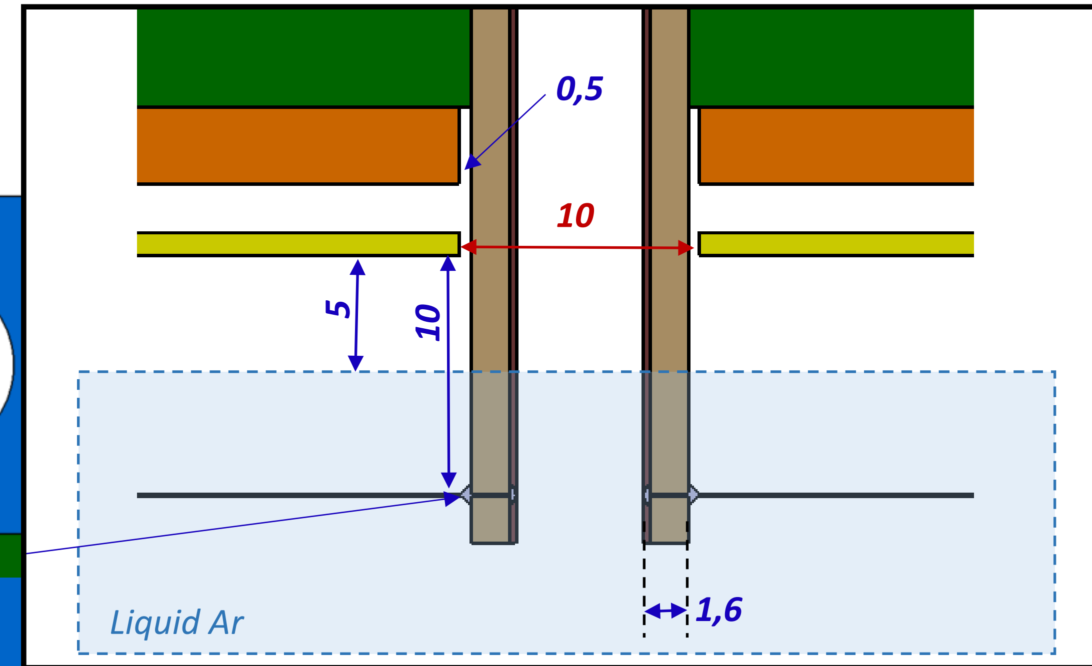
Drift cage

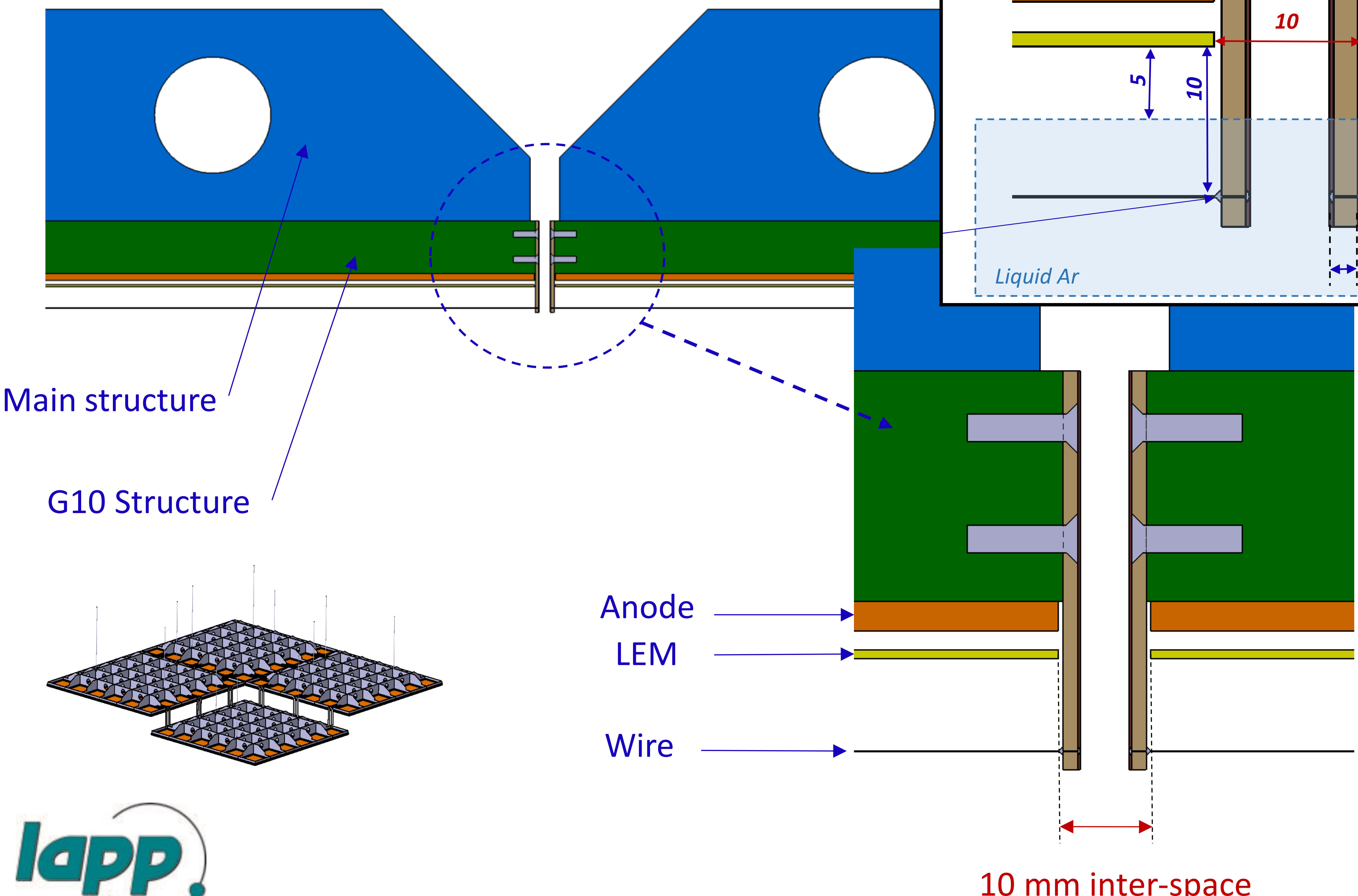
6m



Interspace with "wave-breaker"

- *3x3 modules design induces a space between modules*
  - *Max inter-space value : 10 mm*

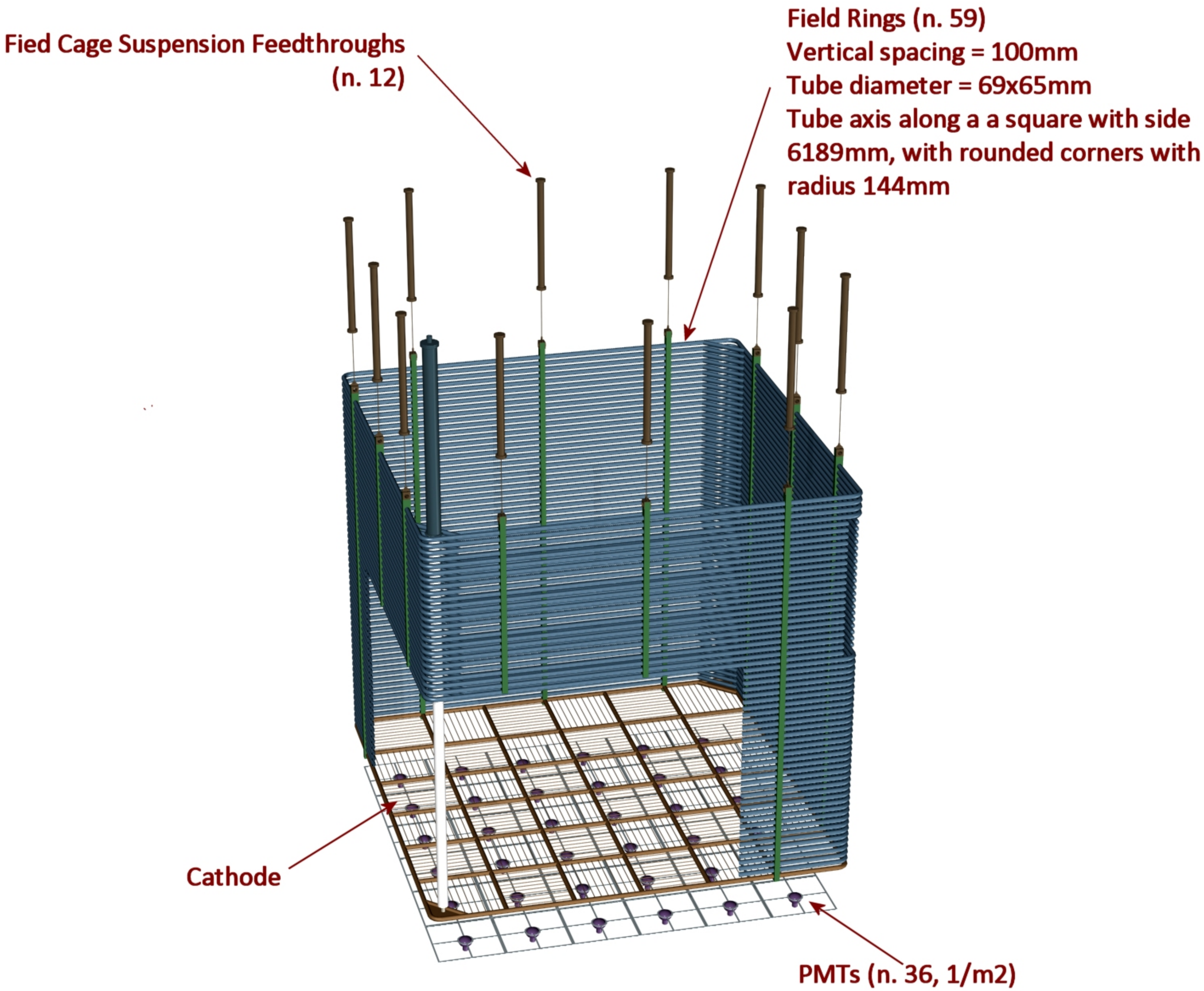


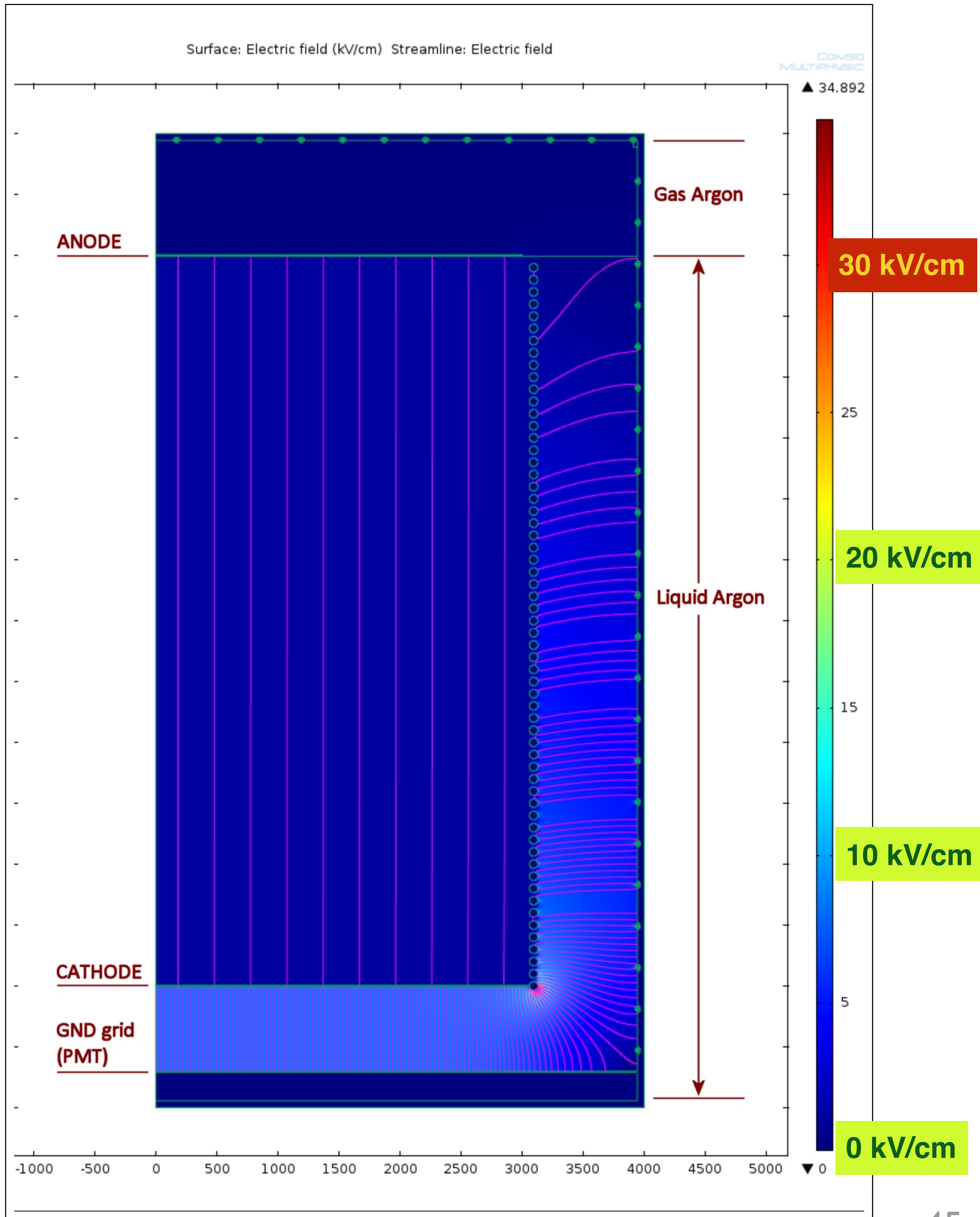


9

Drift field cage design and HV

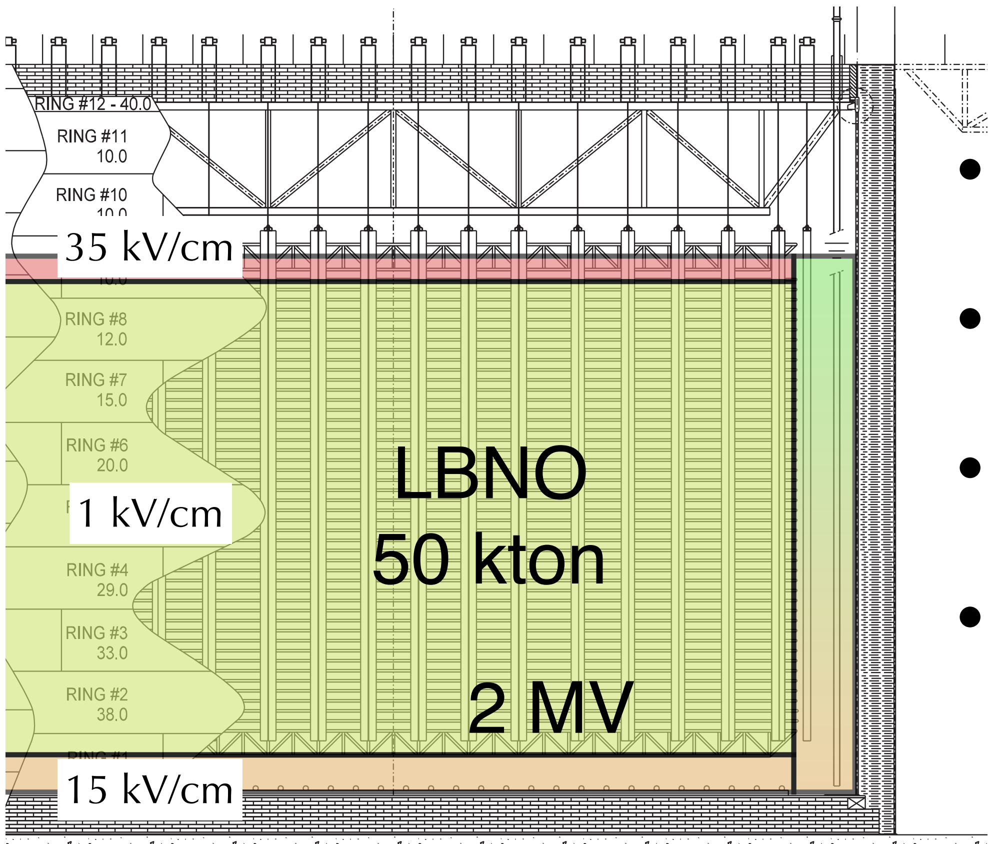
- Drift field = 0.5-1 kV/cm (with 300-600 kV on cathode)
- Homogeneous drift field created by suspended field cage made of 60 equally spaced SS electrodes (69mm diam, 100mm pitch)
- Electric field < 30 kV/cm anywhere



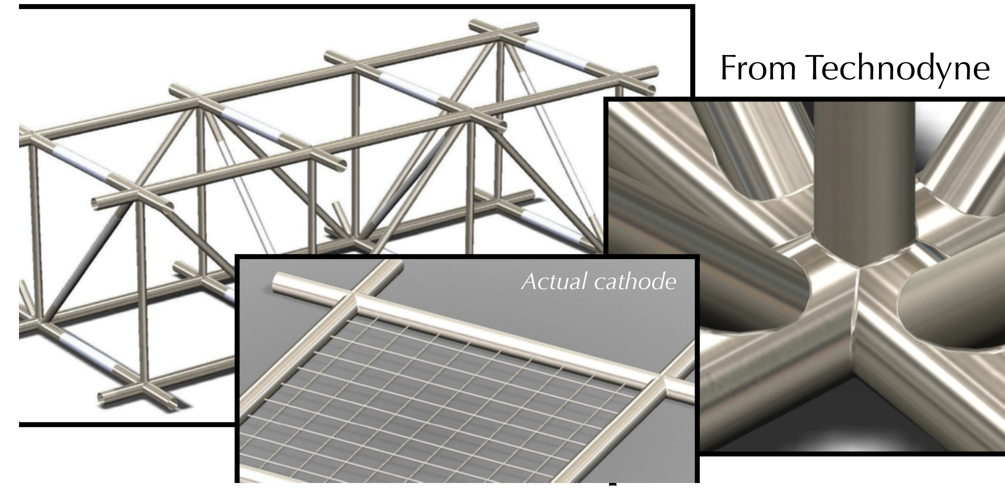


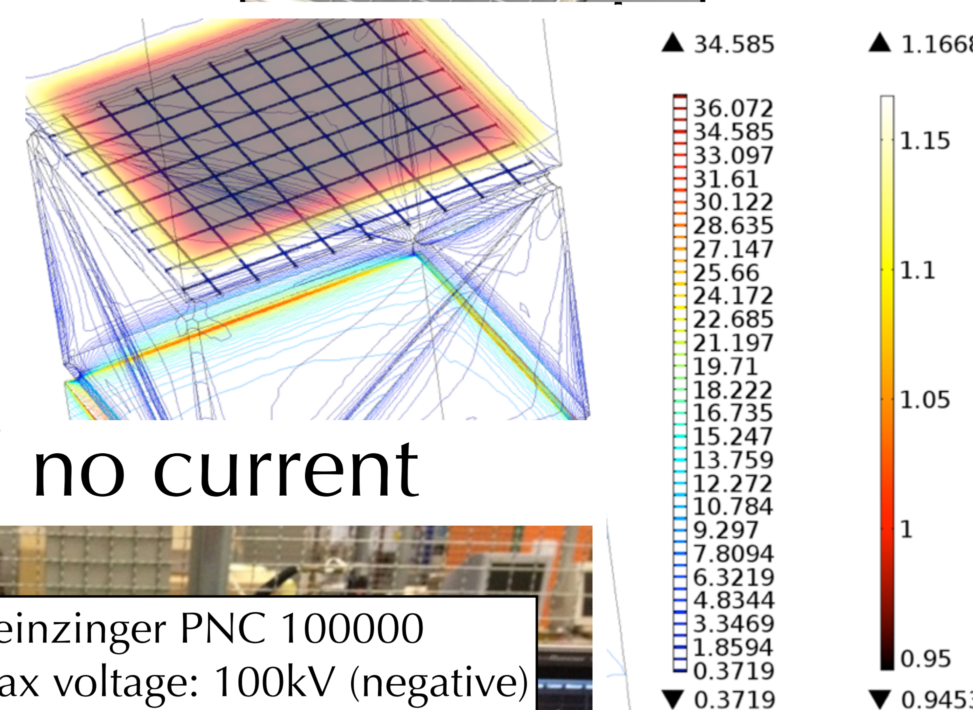
High fields in liquid argon medium

arXiv:1401.2777

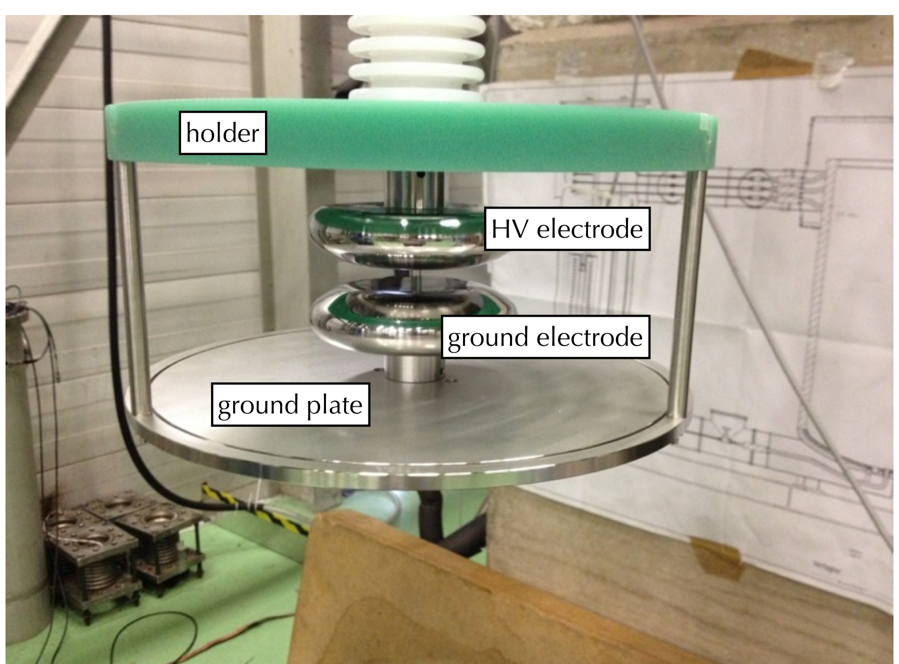


- The maximum average electric field is in vapor!
- Largest average electric field in liquid ~15kV/cm
- Sharp edges imply large electric field
- Caution designing the electrodes

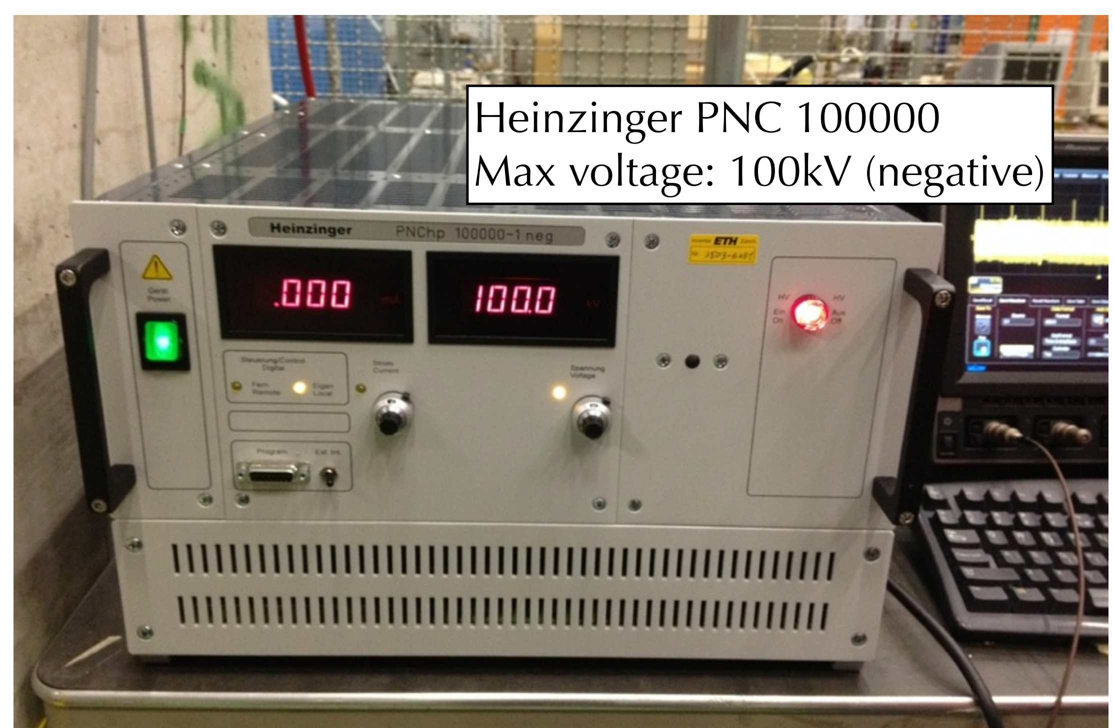




The chamber

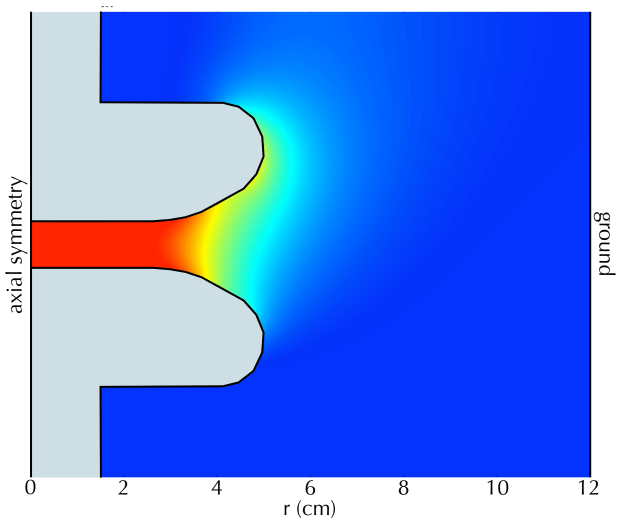


100kV/cm and no current

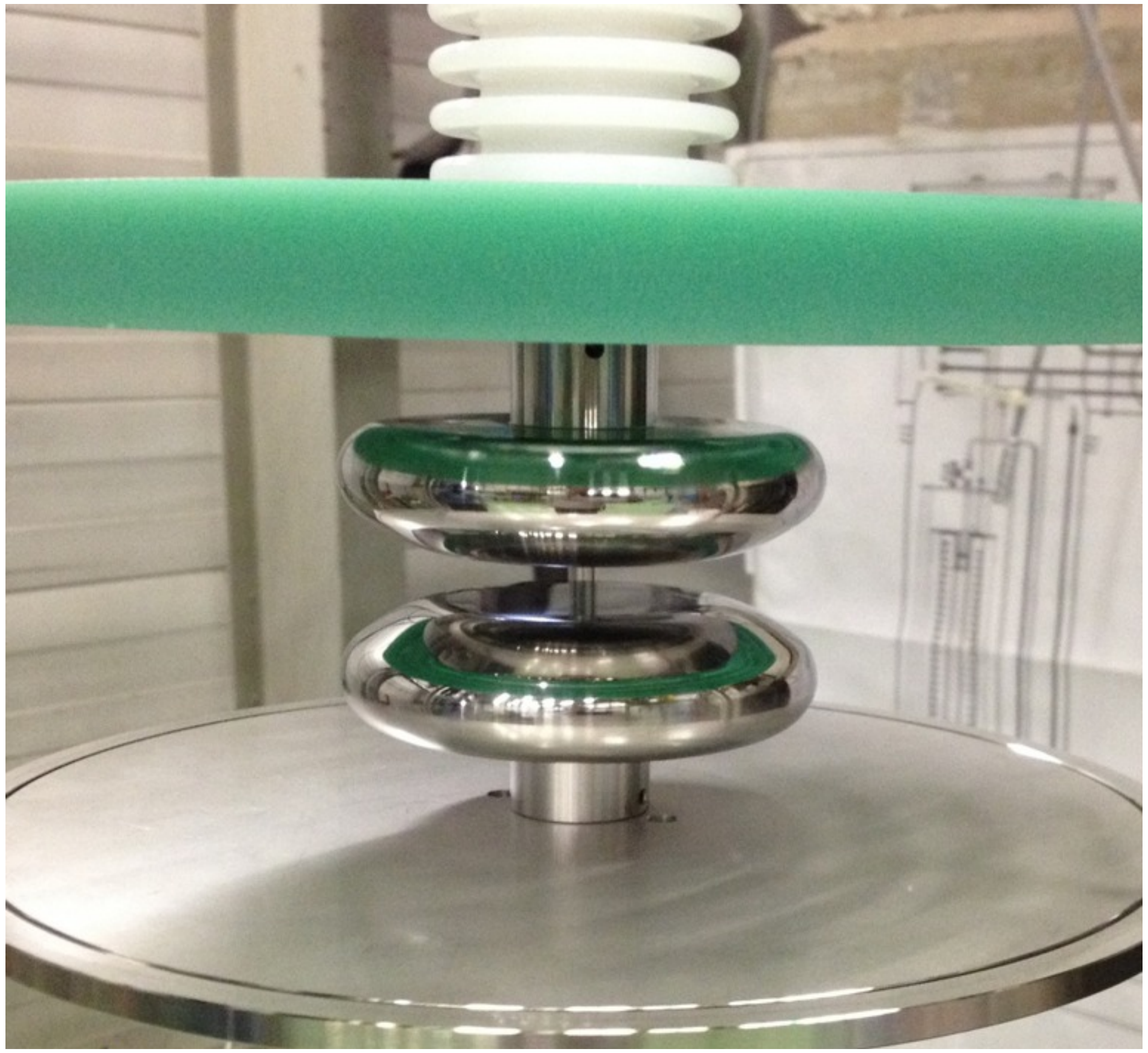


Test with Rogowski profile

LAr electrical rigidity tests at 100kV



/. Rogowski, Arch. Electrotech., 12(1923), 1



Evidence of electric breakdown induced by bubbles in liquid argon

F. Bay, C. Cantini, S. Murphy, F. Resnati, A. Rubbia, F. Sergiampietri, S. Wu
http://arxiv.org/abs/1401.2777

- **Held 100 kV (limit of the supply) for four hours**
- **In boiling LAr, breakdowns were observed at fields as low as 40 kV/cm**

20 cm^2 profile, 1 cm gap

Compilation&measurements by LHEP

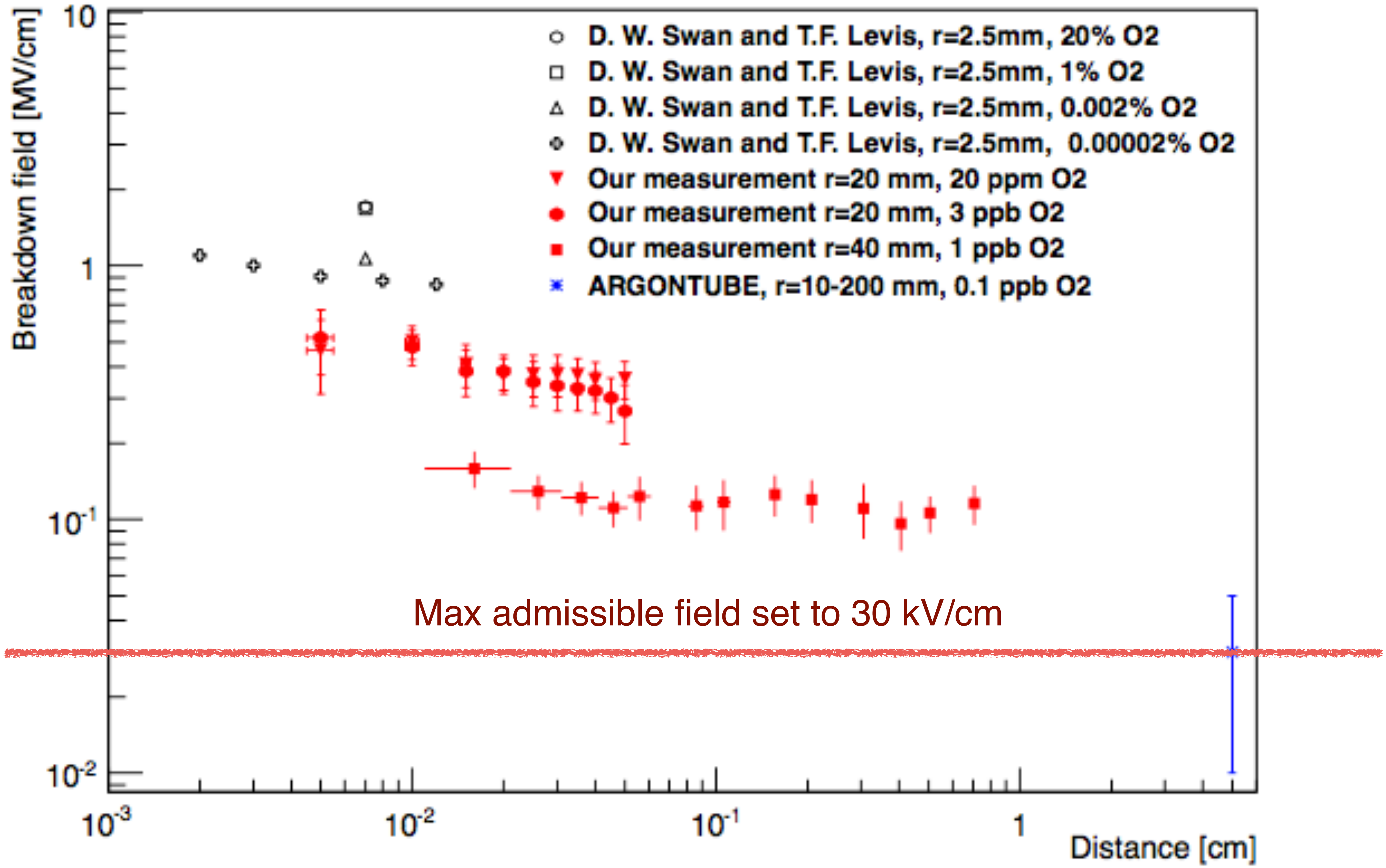
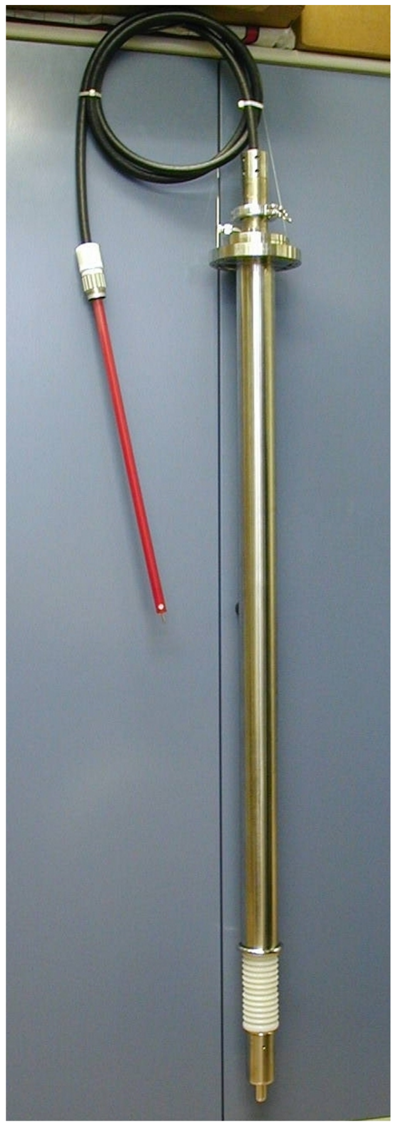
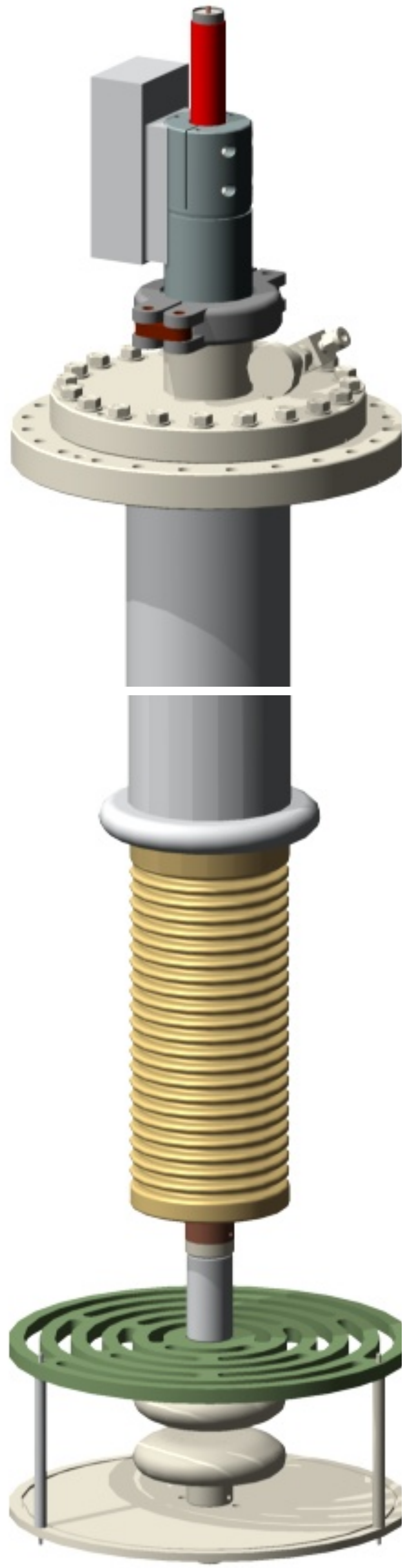


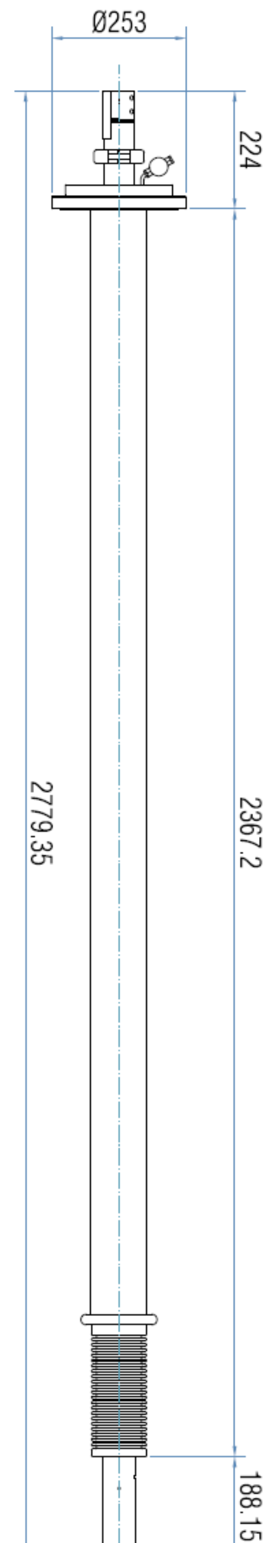
Figure 7. Compilation of the experimental data on the electric strength of liquid argon including results from our measurements.

300 kV high voltage test

HV FT for ICARUS (1999)
150 kV







F. Sergiampietri

HVFT for 300kV
with Rogowsky
profile electrodes

-300kV High Voltage Power Supply
(from HEINZINGER)

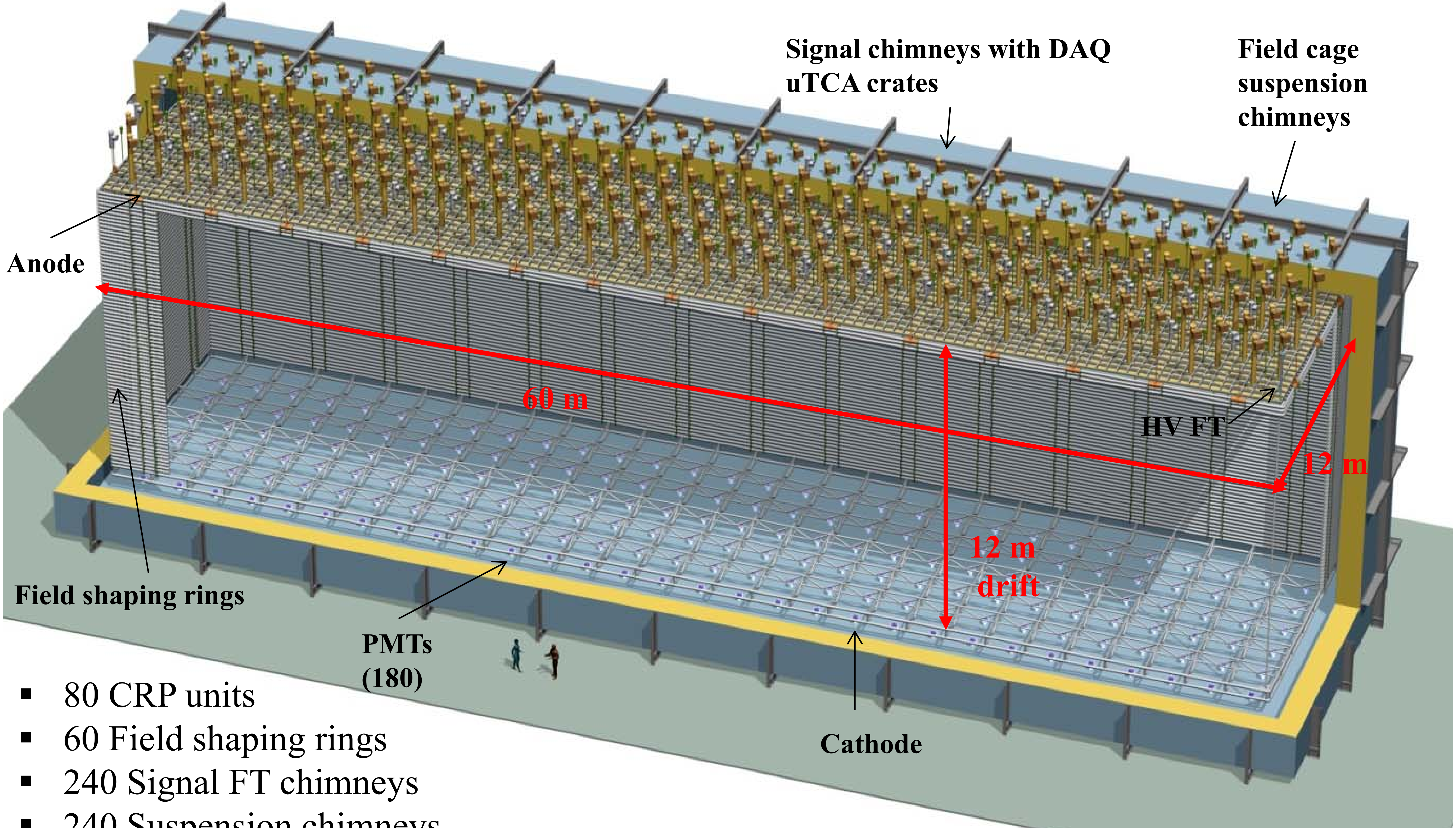
Residual ripple: ≤0.001% U_{NOM} ± 50mV
Residual Ripple at -300kV ≤3V ± 50mV

Can be reduced by the RC filter in the load:
with a fieldcage-to-GND capacitance of 5.5nF and a switchi
frequency of 34kHz, a series resistor of ~1kΩ is required.

Final goal

DUNE FD dual phase design

Active LAr mass: 12.096 kton, fid mass: 10.643 kton, number of channels: 153600



- 80 CRP units
- 60 Field shaping rings
- 240 Signal FT chimneys
- 240 Suspension chimneys
- 180 PMTs

4

Conclusions

- ★ The LAr TPC is truly **a new instrument for discoveries**. In recent years, the technology has developed into a very mature technique for running or planned experiments at Fermilab and CERN.
- ★ The LAr TPC offers truly **unique** "bubble-chamber-like" **tracking performance**, as well as **excellent calorimetry** – these features will be **fully exploited to reach the science goals** of next generation experiments, such as MicroBooNE, SBN and DUNE.
- ★ Thanks to worldwide efforts and supported by the big science projects, significant R&D continues to be performed. In this context, **there is now a unique and timely opportunity to further develop the noble liquids, and in particular liquid Argon TPCs**.
- ★ Since many years, we have been working on the successful development of the Dual Phase LAr TPC and we have a clear path to develop a 300-ton scale device by 2019. This is very exciting – Anyone interested in welcome to join!

Thank you for your attention !

Courtesy PvZ

input:

$K = 10^{-4}\ cm^3/s$

$\tau = \infty$ ms

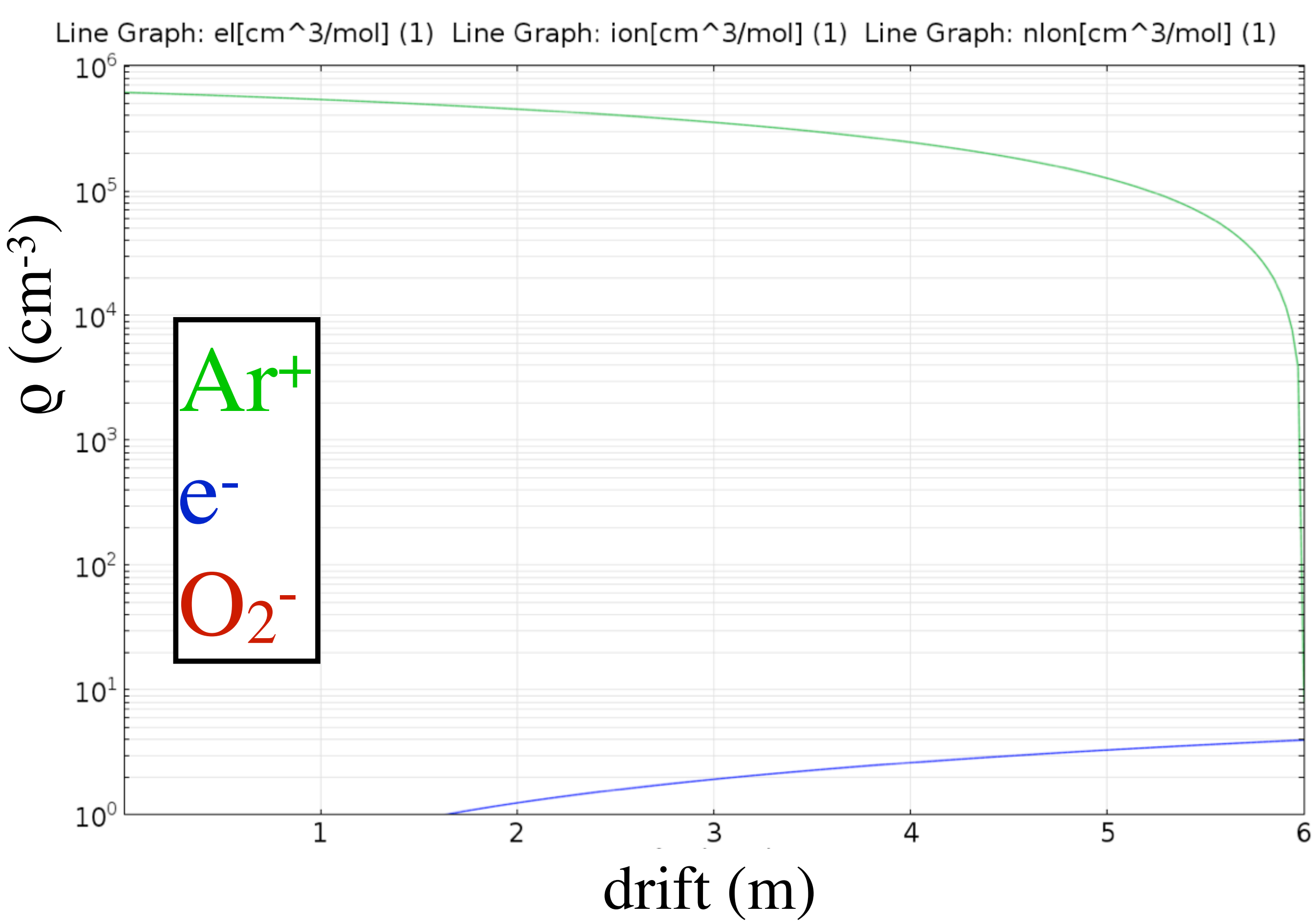
$G = 1$

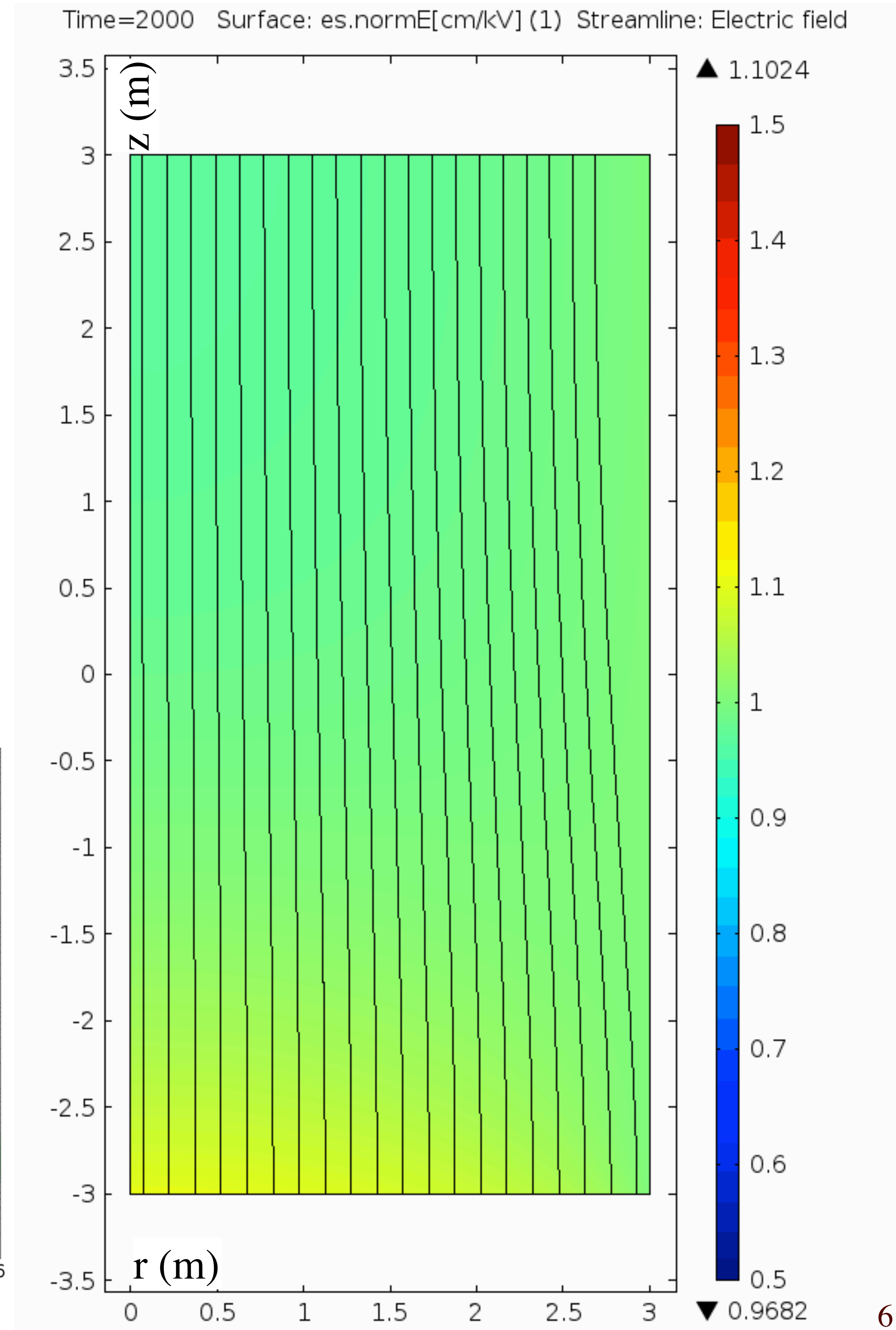
output:

$E_{nominal} = 1$ kV/cm

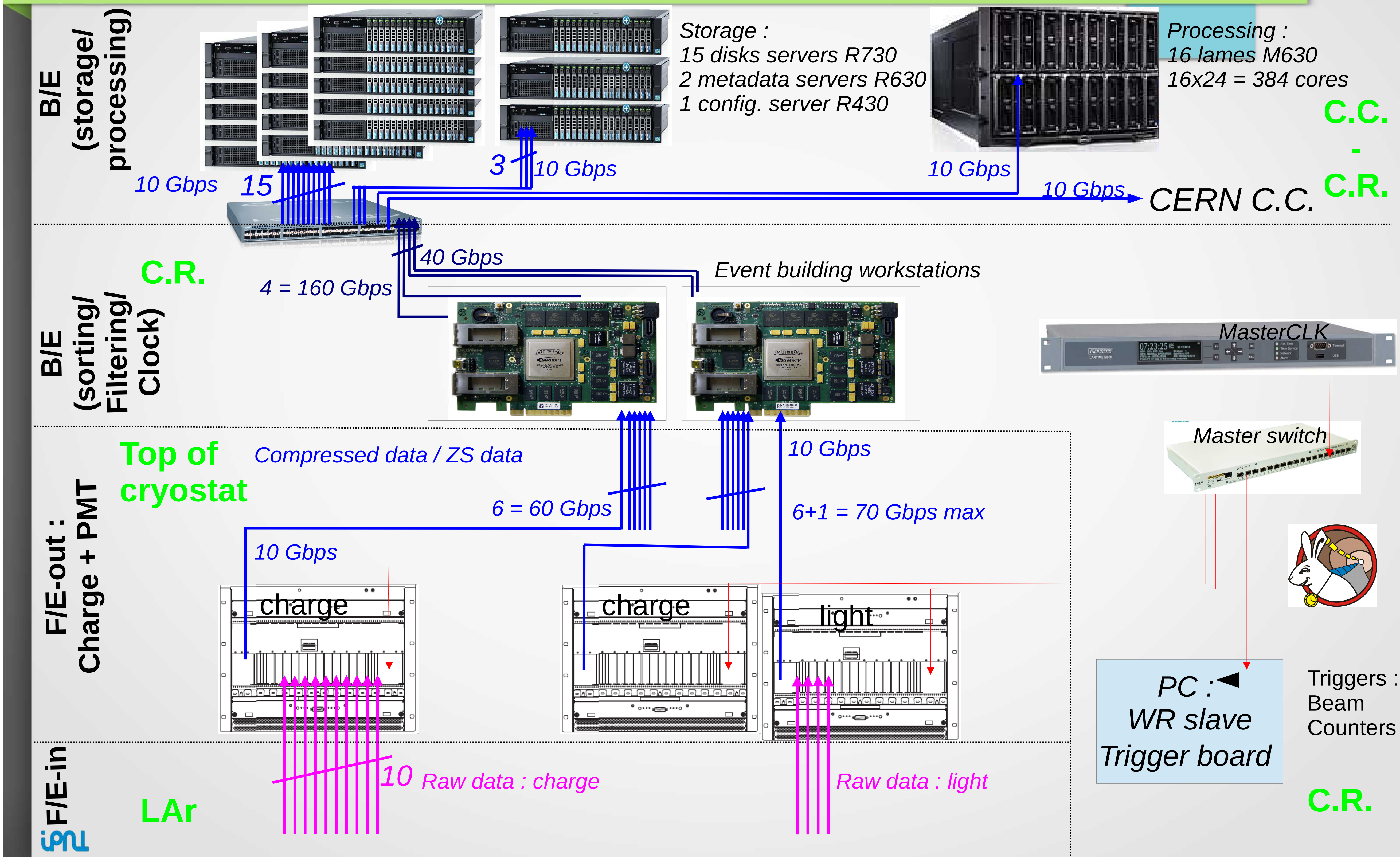
$E_{min} = 0.968$ kV/cm

$E_{max} = 1.102$ kV/cm



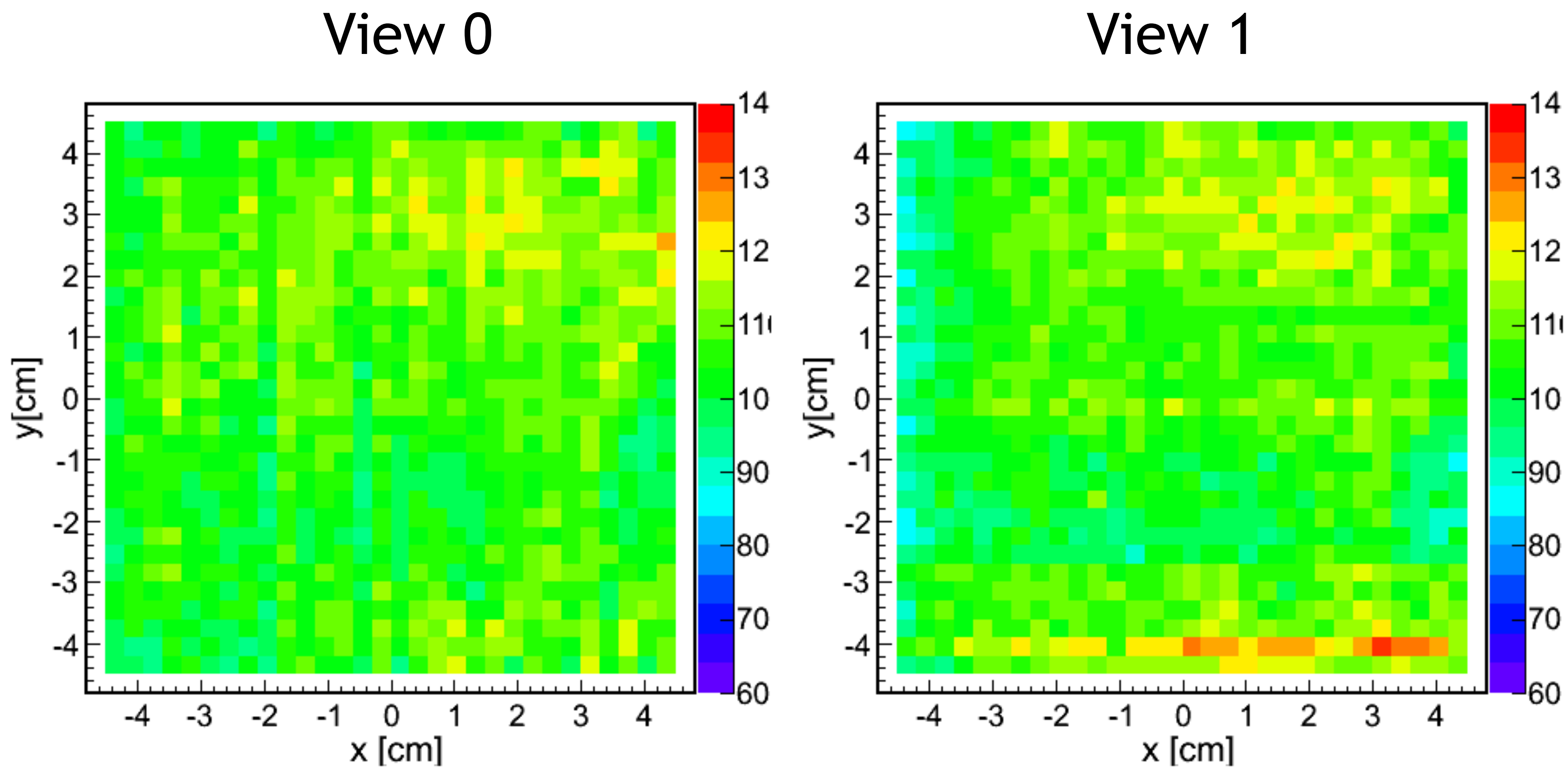


WA105 data network

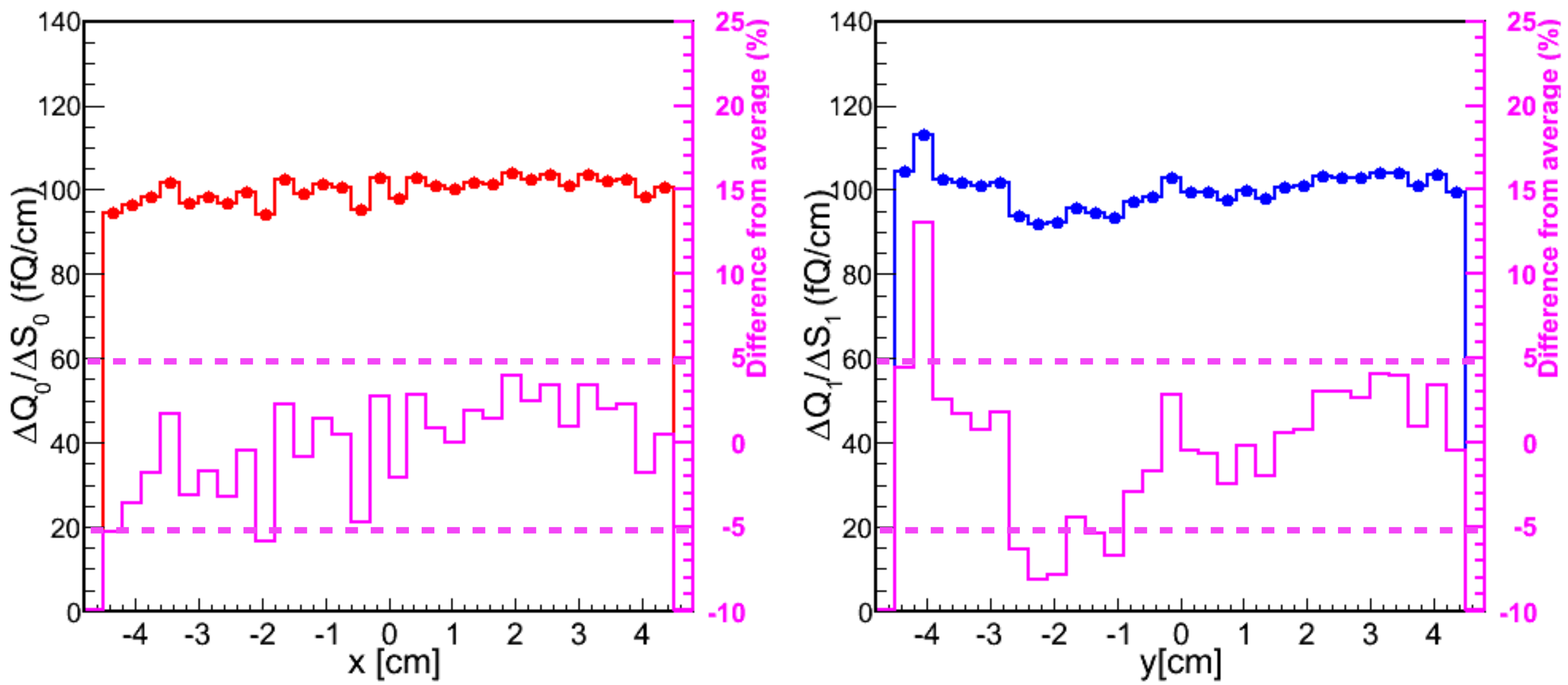


Gain uniformity

<dQ/dx> (fC/cm) (normalized to 100 fC/cm):



Projections on X and Y axis:

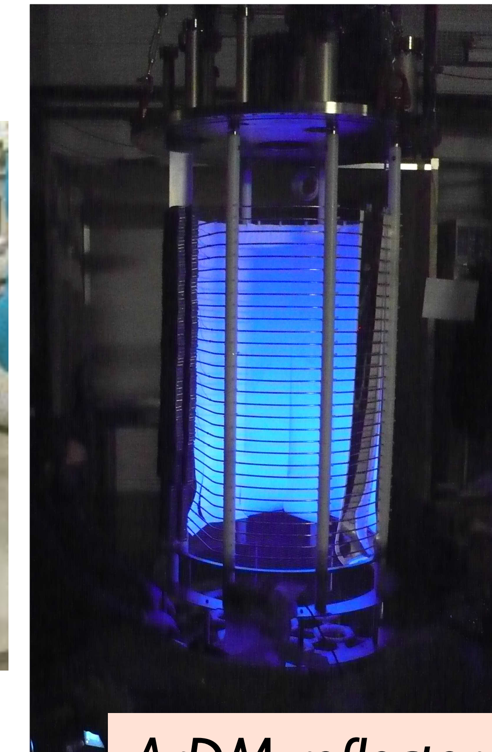


Scintillation light detection

- Liquid Ar is an excellent scintillator
  - 1 MeV dE/dx → ~24,000 photons (at 500 V/cm field)
  - ¼ of the photons are prompt (6ns) around 128nm
  - Rayleigh/Absorption length ~66/>200 cm

Hamamatsu R5912MOD02

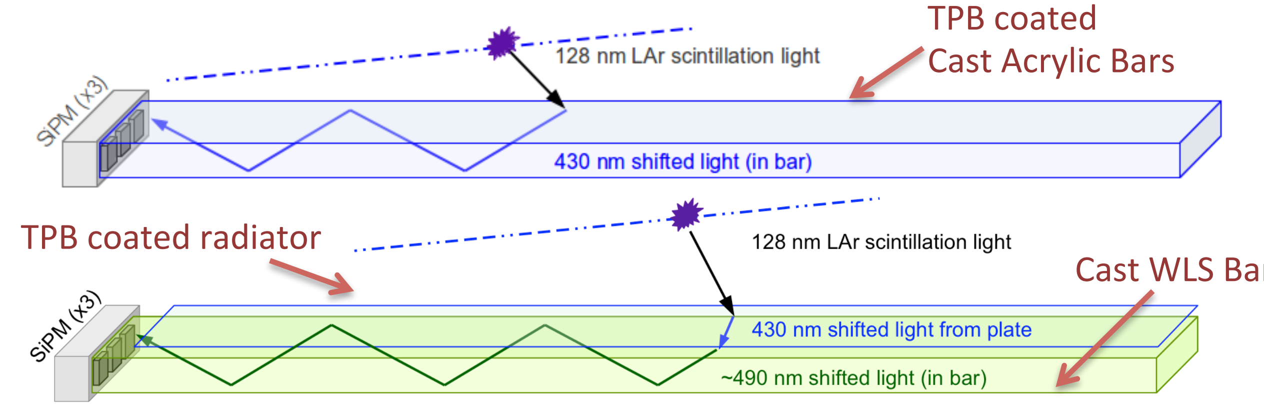
ArDM 8" coated PMT



ArDM reflector

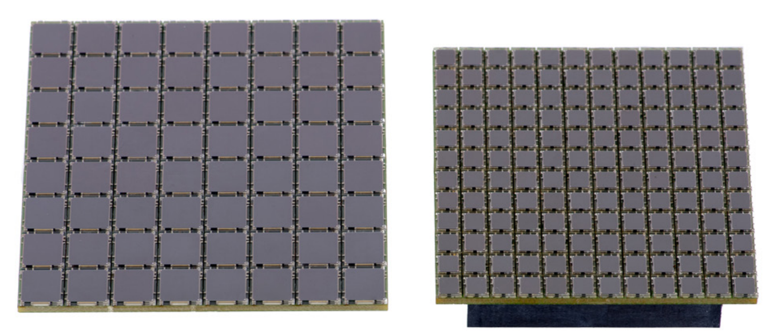
1. Direct detection with WLS-coated PMTs + reflectors

2. Hybrid light guide collection + SiPMs



3. Direct detection with SiPMs with WLS

Is it competitive with PMT? yes for very low background application (e.g. DM)



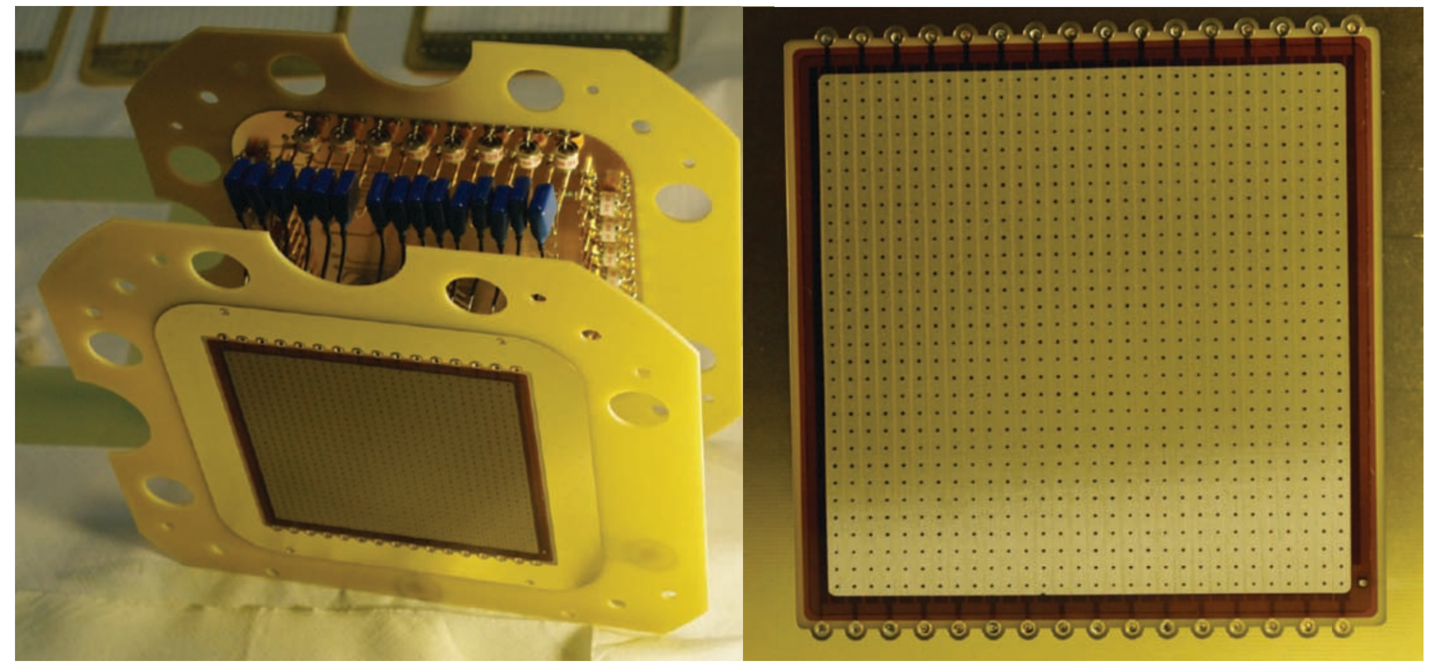
SensL

Many ongoing R&D efforts: large area, high LY, robust, cheap, SiPMs at cryo T,…

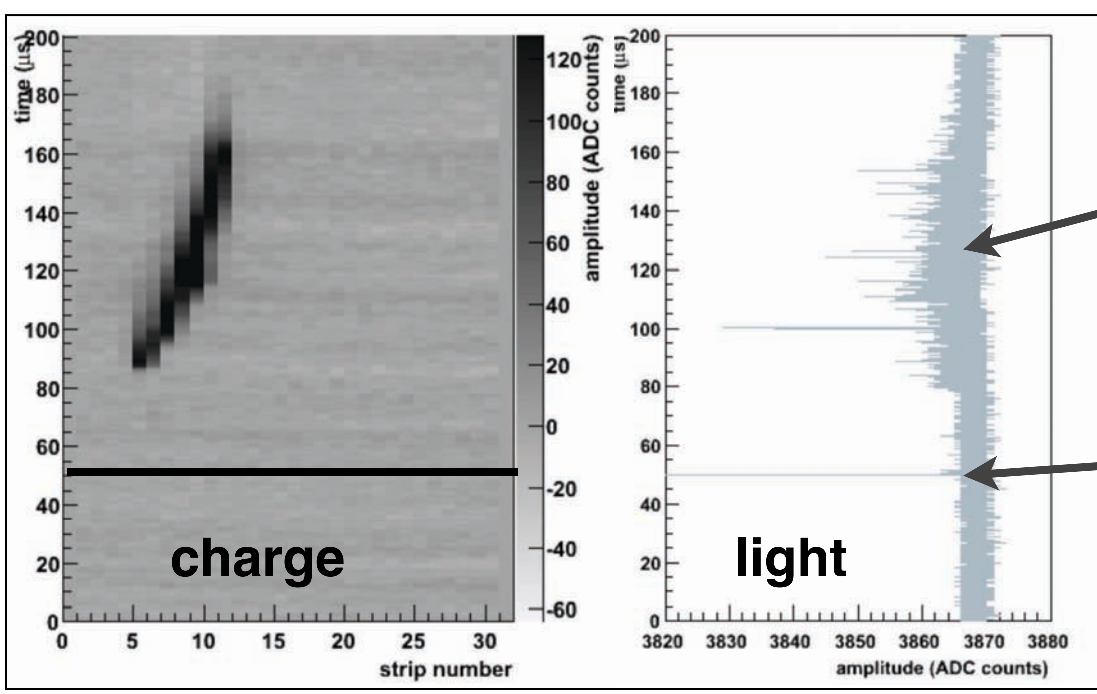
Alternative charge readout R&D: First test with a MicroMeGas

First test of a MicroMeGas as charge readout of a double phase argon TPC (87 K, 1 bar):

- LEM and anode replaced with micromegas (produced by the PCB workshop at CERN)
- readout: 30 strips, 3 mm wide (only one view)
- spacers: diameter=450 µm, pitch=3 mm and gap=100 µm (128 µm)
- mesh: wire pitch=63 µm, wire diameter=18 µm



recorded cosmic muon event



secondary scintillation light produced in GAr (field between extr. grids and micromegas)
➡ proportional to charge

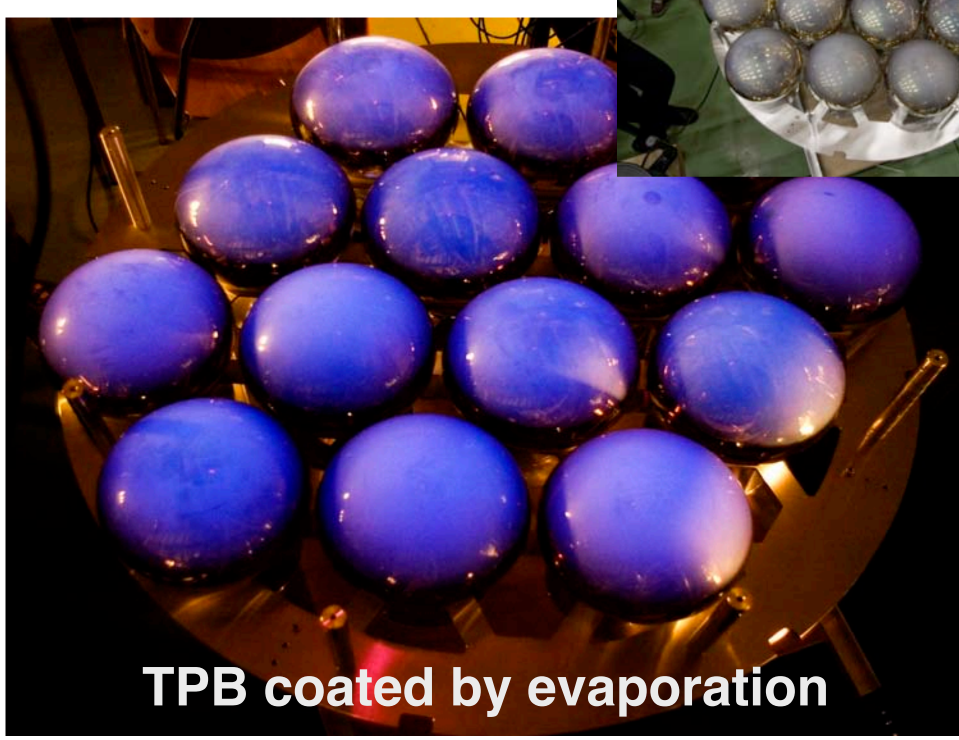
prompt scintillation light produced in LAr
➡ used as trigger

Collaboration with CEA-Saclay

ArDM: Scintillation light R&D

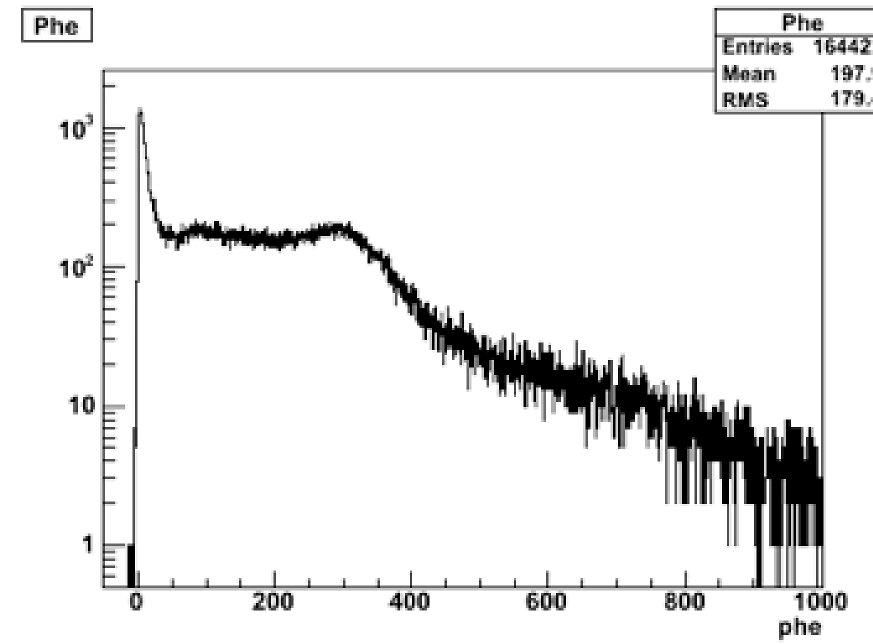
- LAr emission spectrum peaked at 128 nm
- The WLS TPB (tetraphenyl butadien) is used to shift the light to the visible(430 nm)
- indirect light: 15 cylindrically arranged overlapping foils of TTX (120x25 cm²) coated with 1.0 mg/cm² TPB by vacuum evaporation
- direct light: The PMTs are coated with TPB by evaporation

PMT array



14 low radioactivity Hamamatsu 8" PMTs [R5912-02MOD]

Na22 spectrum



Preliminary yield with 14PMTs: ≈0.7 p.e./keVee

neutron appearance with ext. AmBe source