ArgonCube

Modular scalable LAr TPC
with pixelized charge readout

FNAL, 25.09.18

Igor Kreslo
AEC/LHEP University of Bern
on behalf of ARGONCUBE collaboration:

Bern, BNL, CSU, EMPA, FNAL, I3N, Iowa, Harvard, JINR, LBNL, METU, Sheffield, SLAC, South Carolina, Stony Brook, Syracuse, TUBITAK, UTA, Yale

Liquid Argon as detection medium

Density 1.4 g/cm^3 X_o = 14 cm λ_{INT} = 83.5 cm

dE/dx = **2.1 MeV/cm** for MIP

Primary ionisation Q_0

W_i = **23.6 eV**

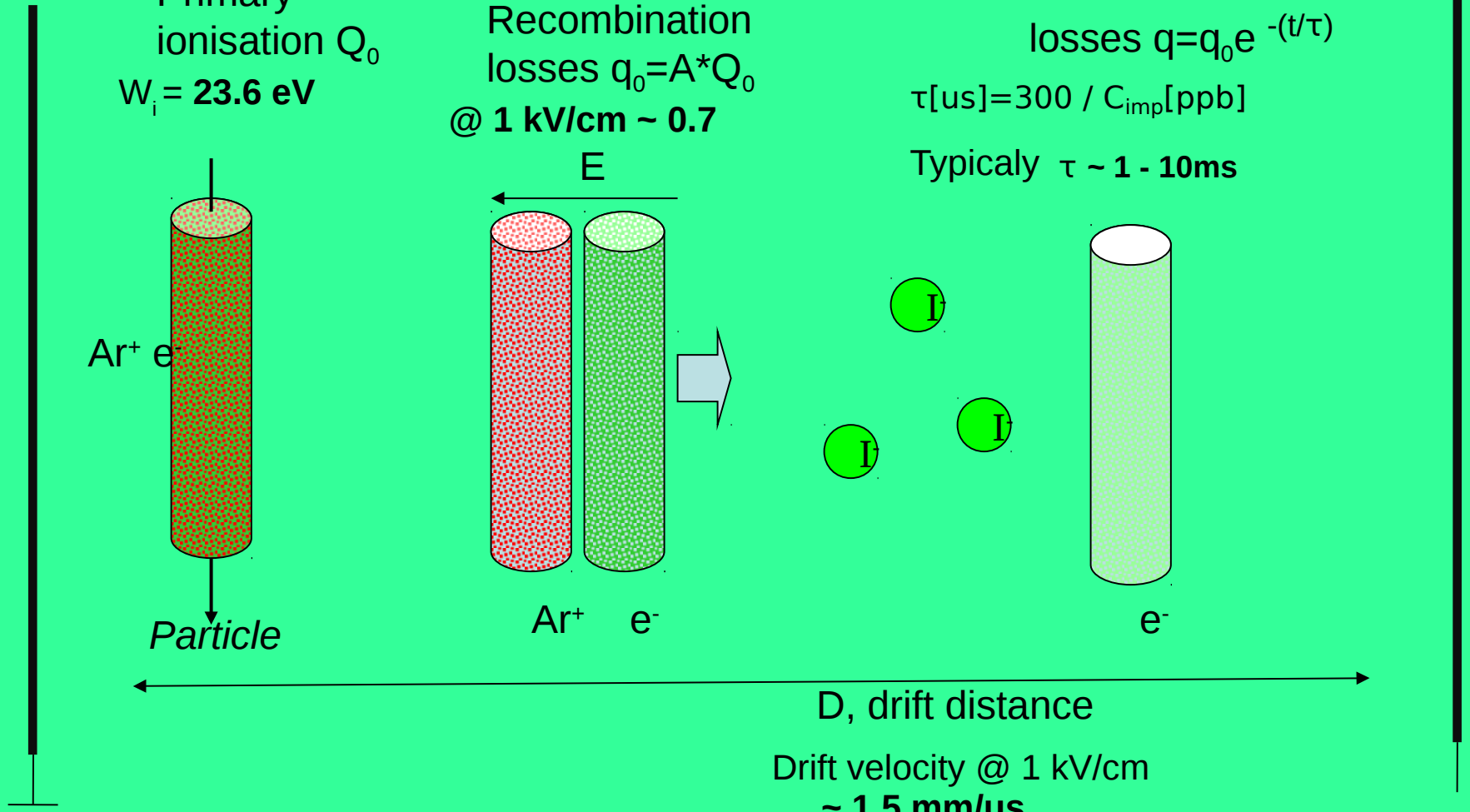
Recombination losses $q_0 = A * Q_0$

@ 1 kV/cm ~ 0.7

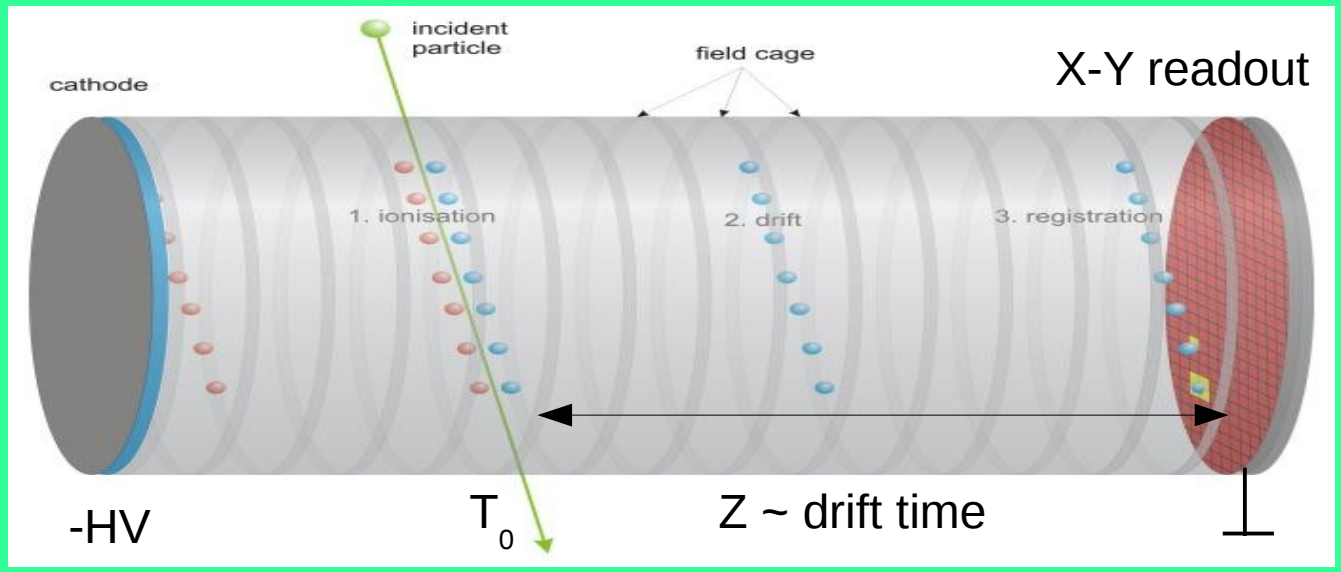
Attachment losses $q = q_0 e^{-(t/\tau)}$

$\tau[us] = 300 / C_{imp}[ppb]$

Typicaly τ **~ 1 - 10ms**



Liquid Argon Time Projection Chamber

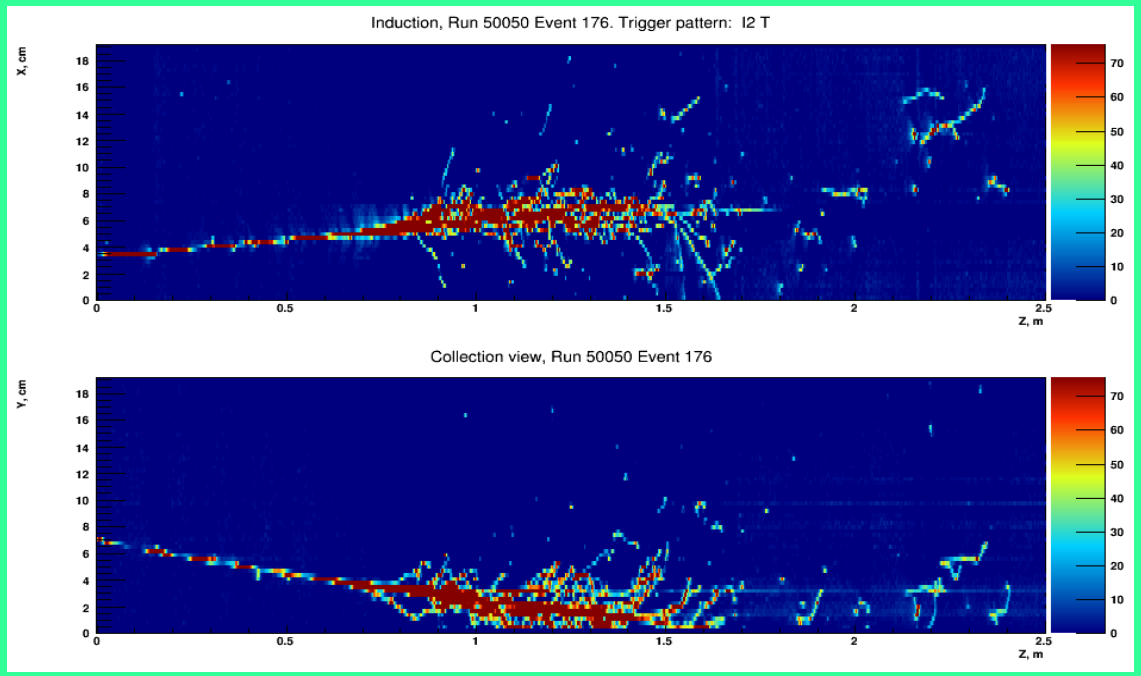


Recombination
field dependent,

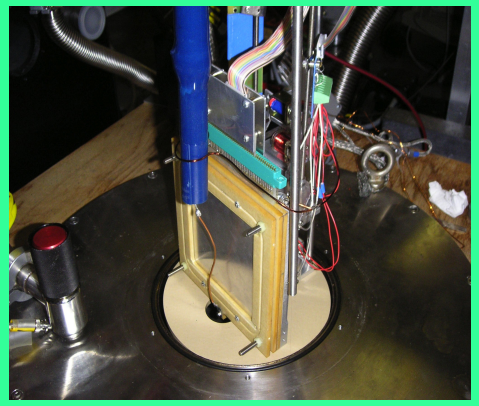
Charge yield (MIP)
~ 6400 e/mm (1 fC/mm)

T_0 by scintillation (**5000 γ/mm**)

Charge readout:
X: Induction (non-destructive)
Y: Collection

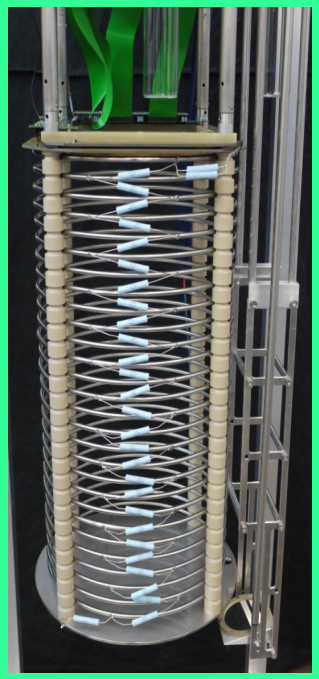


Evolution of LAr TPCs at Bern



L=0.5 cm

L=25 cm



L=57 cm

ARGONTUBE
L=500 cm

JINST 4, P07011 (2009)

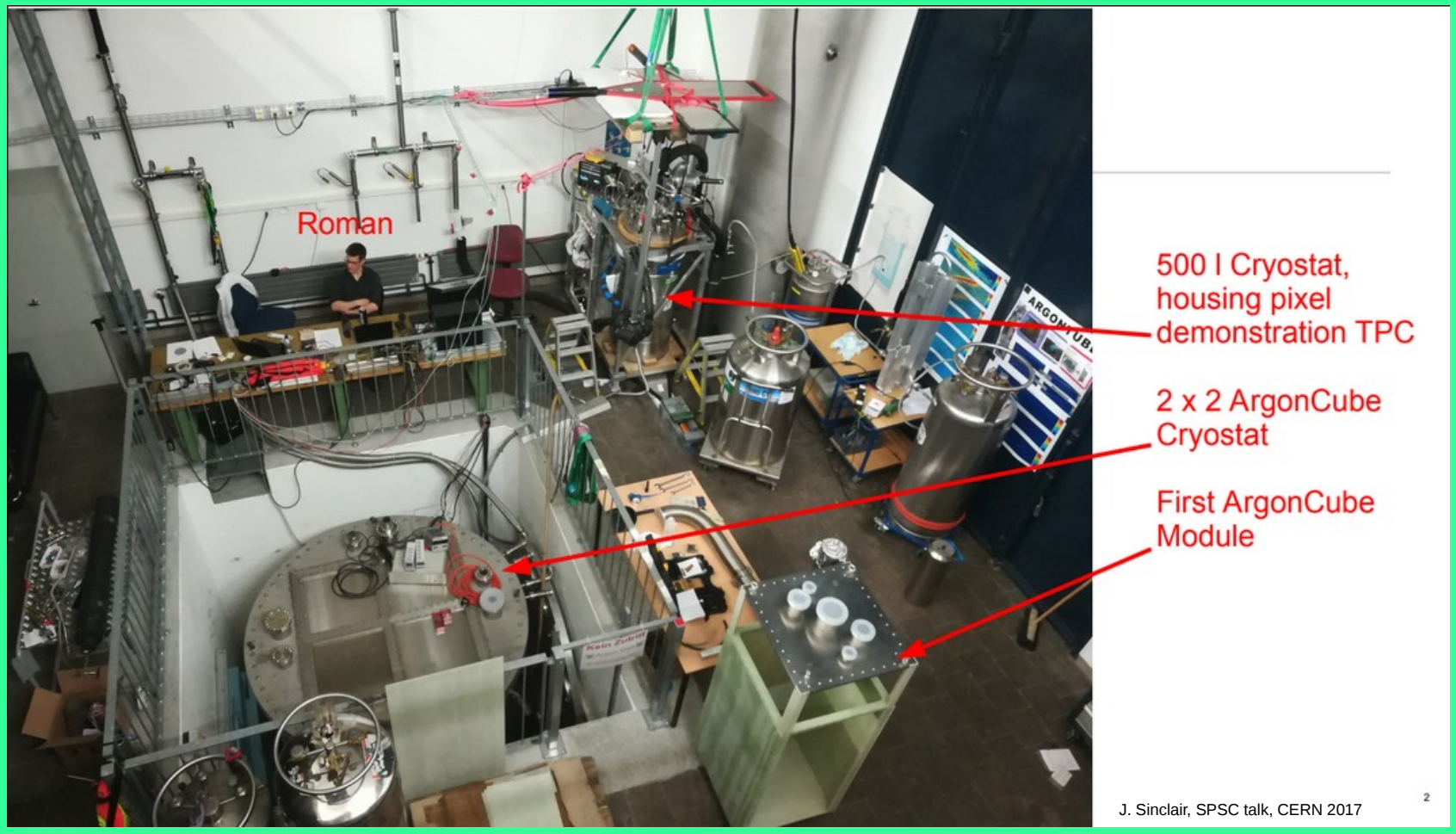
New J. Phys. 12, 113024 (2010)

JINST 5, P10009 (2010)

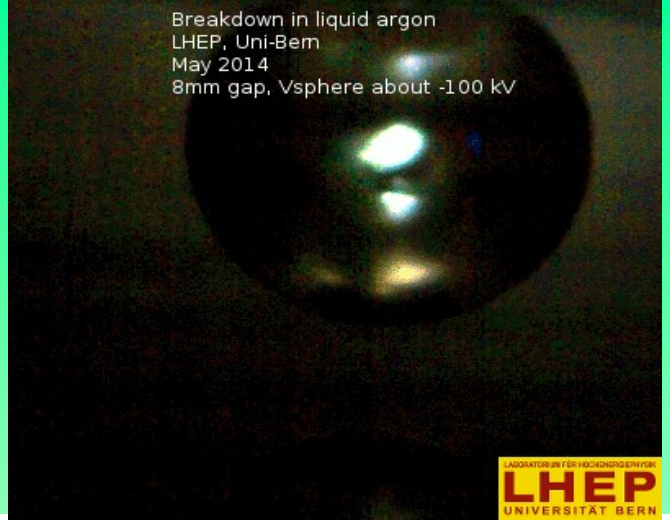
JINST 7 (2012) C02011

JINST 1307 (2013) P07002

Laboratory for High Energy Physics
University of Bern
Cryogenic detector design and test facilities



Breakdown in liquid Argon: detailed study at Bern



1. Abnormally low dielectric strength at long distances

2. Studied V/A characteristics

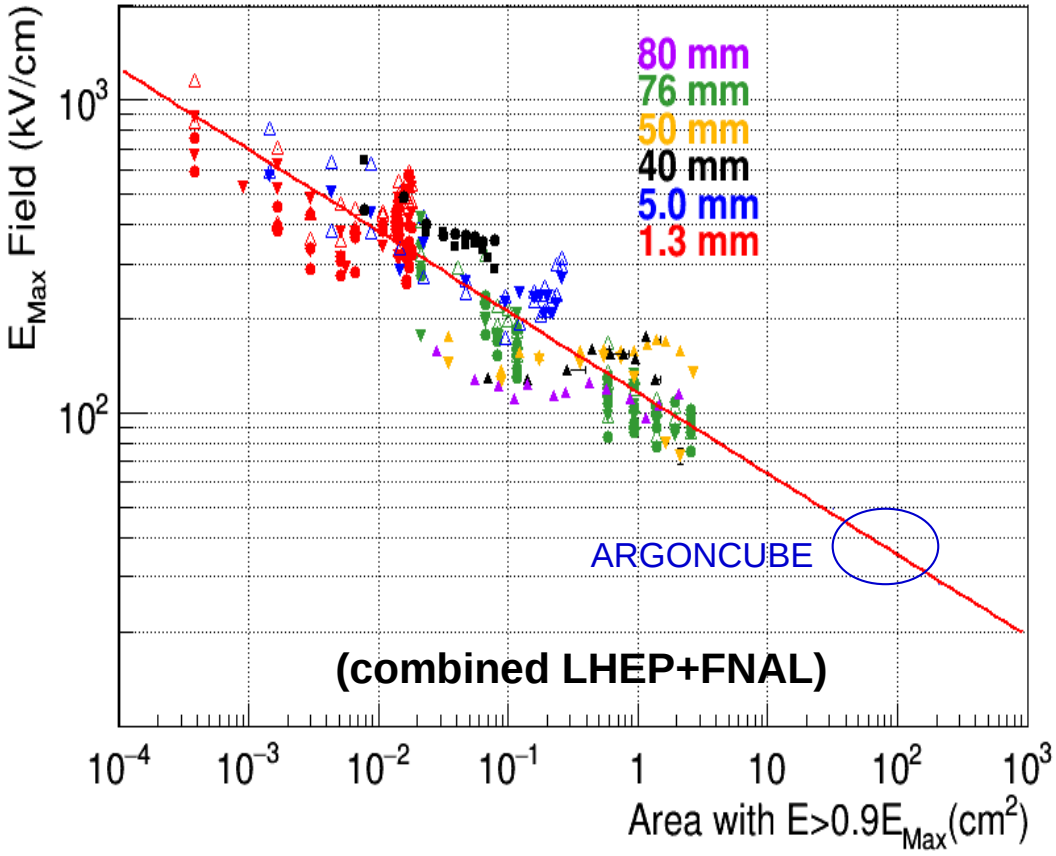
3. Studied time-resolved light emission spectra

4. Discovered slow streamers in LAr discharge

5. Measured 1st Townsend coefficient at fields O(100 kV/cm)

6. Suggested method to improve breakdown field by factor of 10

M. Auger et al., JINST 9, P07023 (2014)
A. Blatter et al., JINST 9, P04006 (2014)
M. Auger et al., JINST 11 (2016) no.03, P03017.



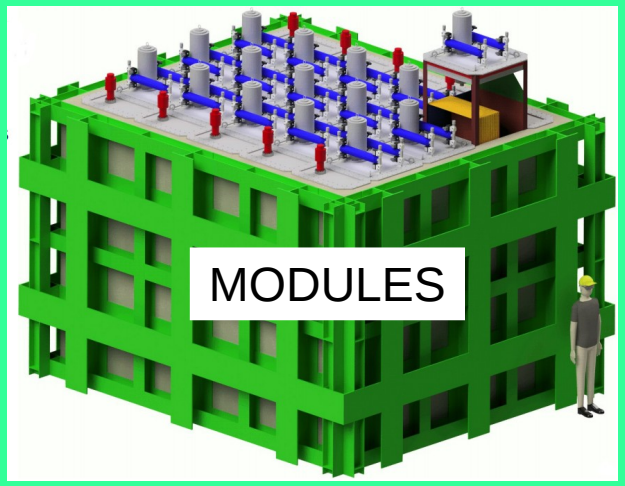
ARGONCUBE

Design motivations — mainly by DUNE ND requirements

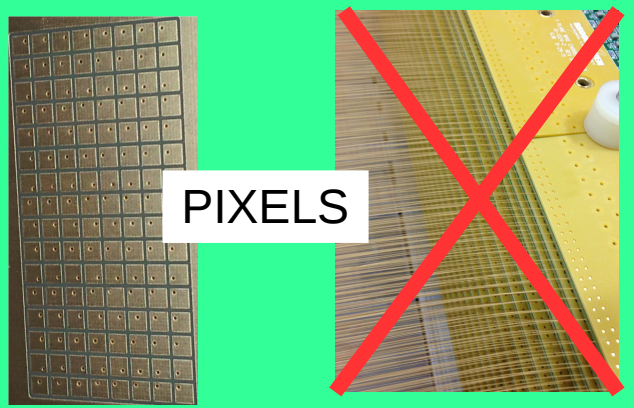
Large mass (>80t)

Space charge

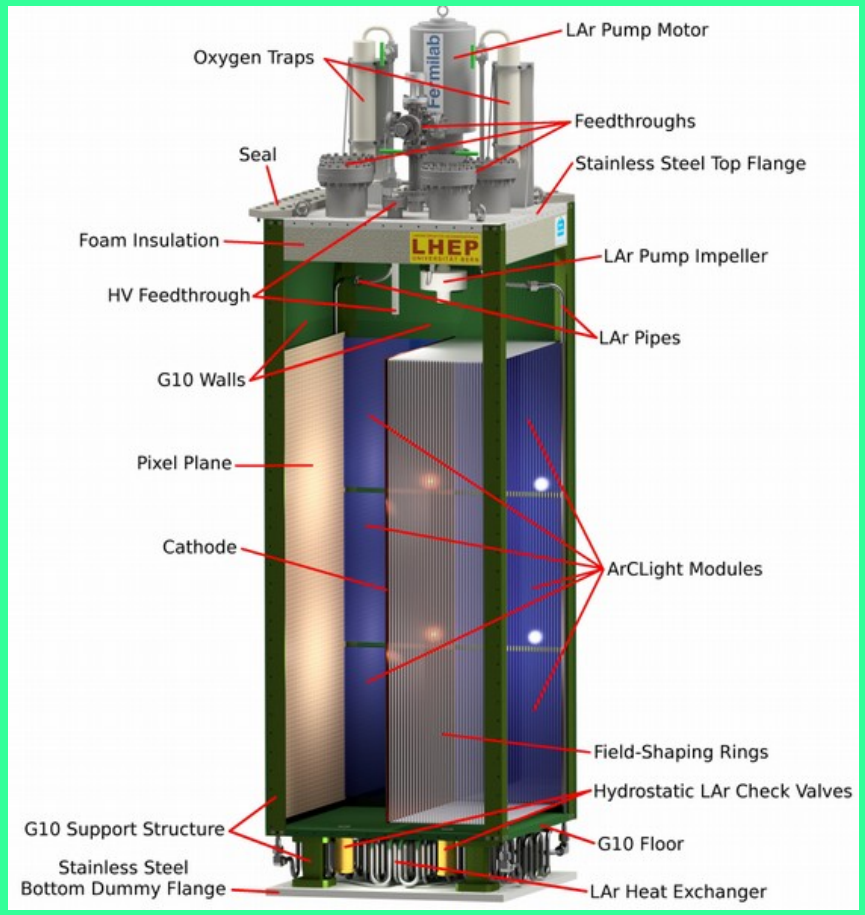
Low HV (<100 kV)



High event rate at (DUNE) ND (pileup)



ARGONCUBE
Module design features



Thin walls

Min. material budget

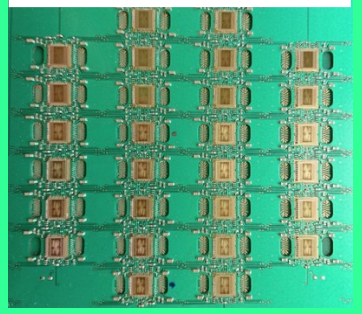
Resistive shell

Limited LAr convection

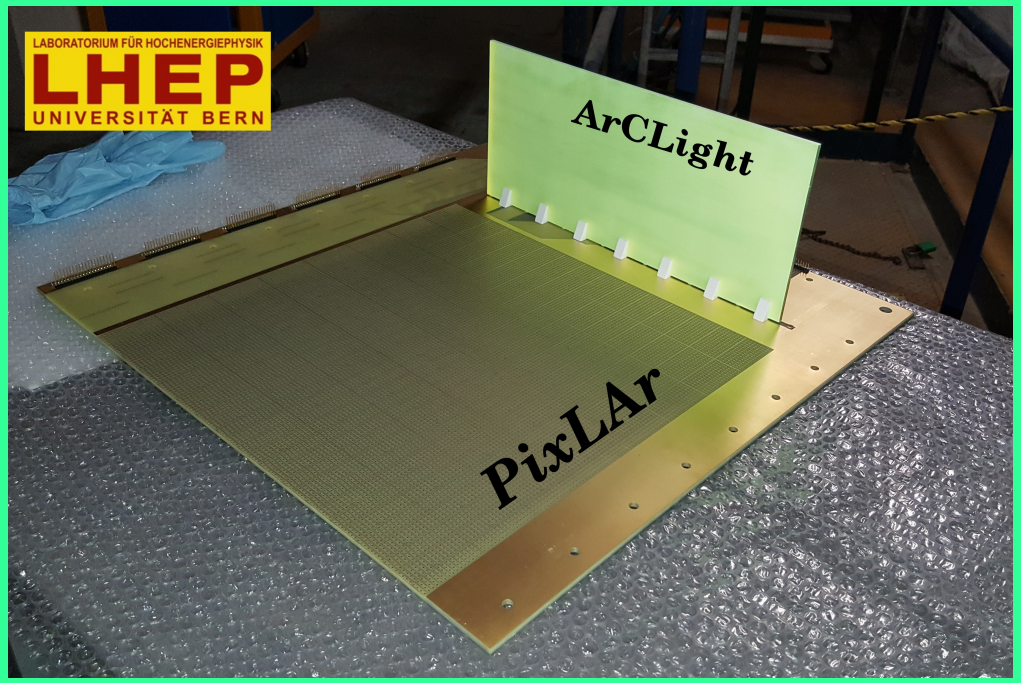
Heat management

< 100 W/module overall

LarPix ASIC



Scintillating Light Detetor ArCLight



Inspired by ARAPUCA

A.A. Machado and E. Segreto 2016 JINST 11 C02004

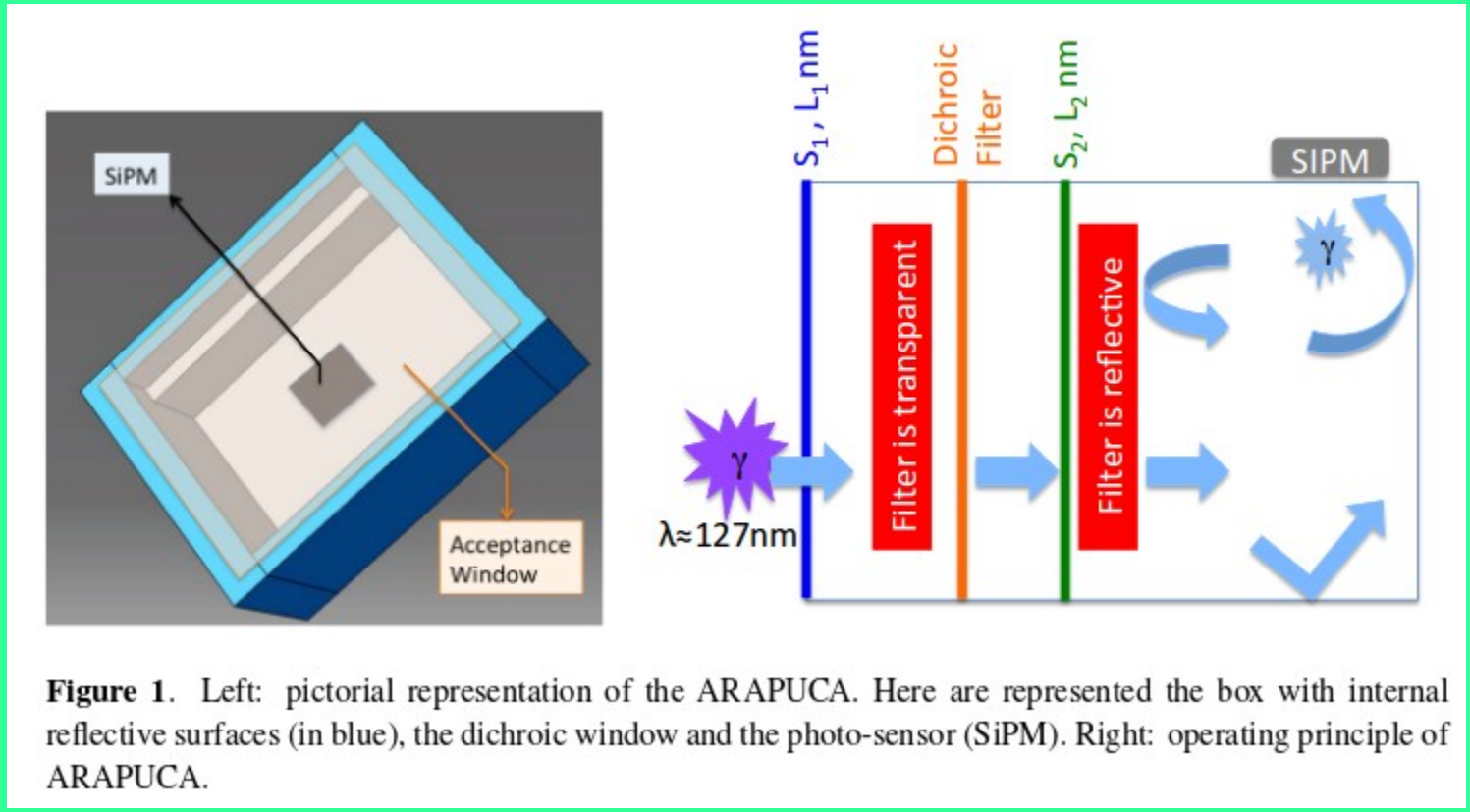
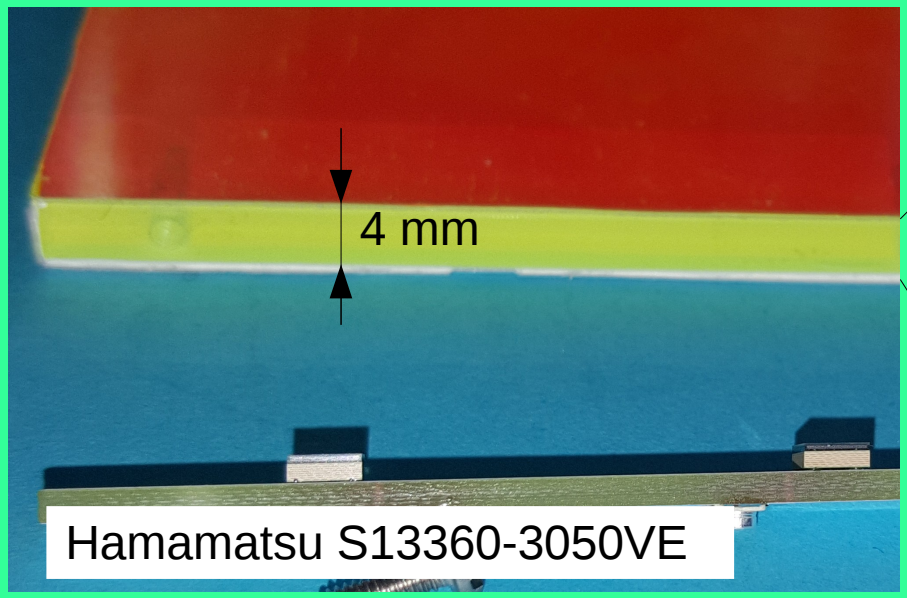


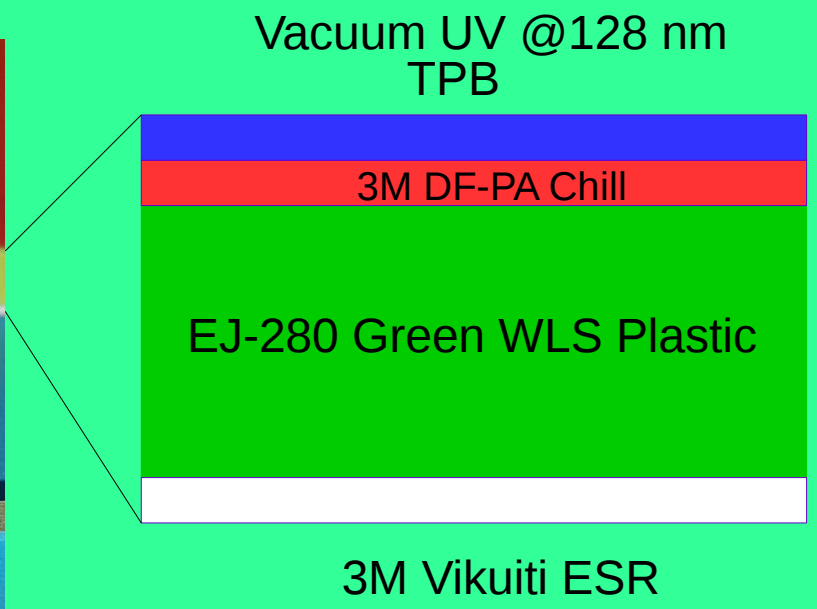
Figure 1. Left: pictorial representation of the ARAPUCA. Here are represented the box with internal reflective surfaces (in blue), the dichroic window and the photo-sensor (SiPM). Right: operating principle of ARAPUCA.

Great idea!!! but...

Fragile membrane, void inside, heavy frame, thermal deformations...

ArCLight - ArgonCube light detector

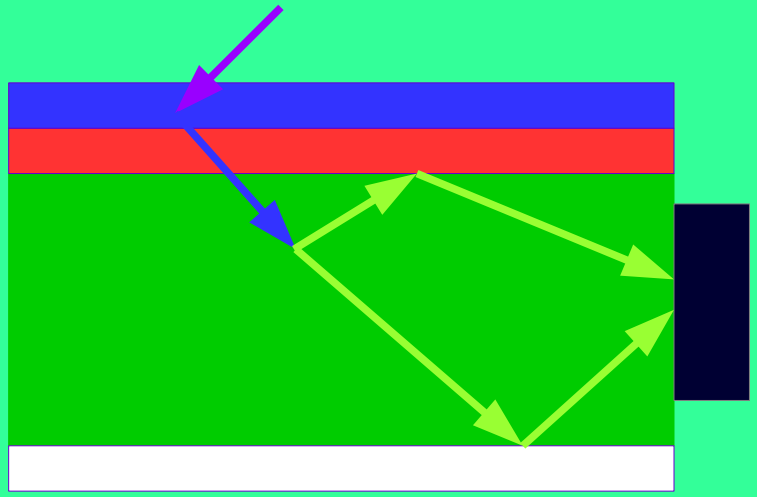




Self-supporting
SiPM can be placed at one edge only
No frame — no deformations in cold
Can be placed in high field region (parallel to the the drift)

Auger M. et al., Instruments 2 (2018) no.1, 3

Photon Detection Efficiency
Theoretical view



E. Segreto 2012 JINST 7 P05008 :

$$\epsilon_{coll} = \frac{f}{1-\langle R_{490}\rangle(1-f)} = 0.077$$

TPB conv. efficiency ε_{tpb} = 1.3/2
Dichroic transparency for blue T_{430} = 0.87
EJ-280 conv. efficiency ε_{WLS} = 0.86

Dichroic reflectance for green R_{490} = 0.98
ESR reflectance for green R_{490} = 0.98

Total surface area S_{tot} = 216 cm^2
SiPM covered S_{det} =0.36 cm^2
$f = S_{det} / S_{tot}$ = 0.0017

Absorbtion is neglected! (λ ~ meters)

Putting it all together:

$$PDE = \epsilon_{tpb} \cdot 1/2 \cdot T_{430} \cdot \epsilon_{WLS} \cdot \epsilon_{SA} \cdot \epsilon_{SiPM} = 0.01$$

ArCLight 43x15 cm with TPB coating
Installed in PixLAr detector (Fermilab)

Tile 43x15cm:

total surface area S_{tot} = 1336 cm^2 SiPM covered S_{det} = 0.72 cm^2
$f = S_{det} / S_{tot} =$ 0.0005 **PDE=0.34%**

From 1 m away: solid angle Ω= 0.06 (worst case)

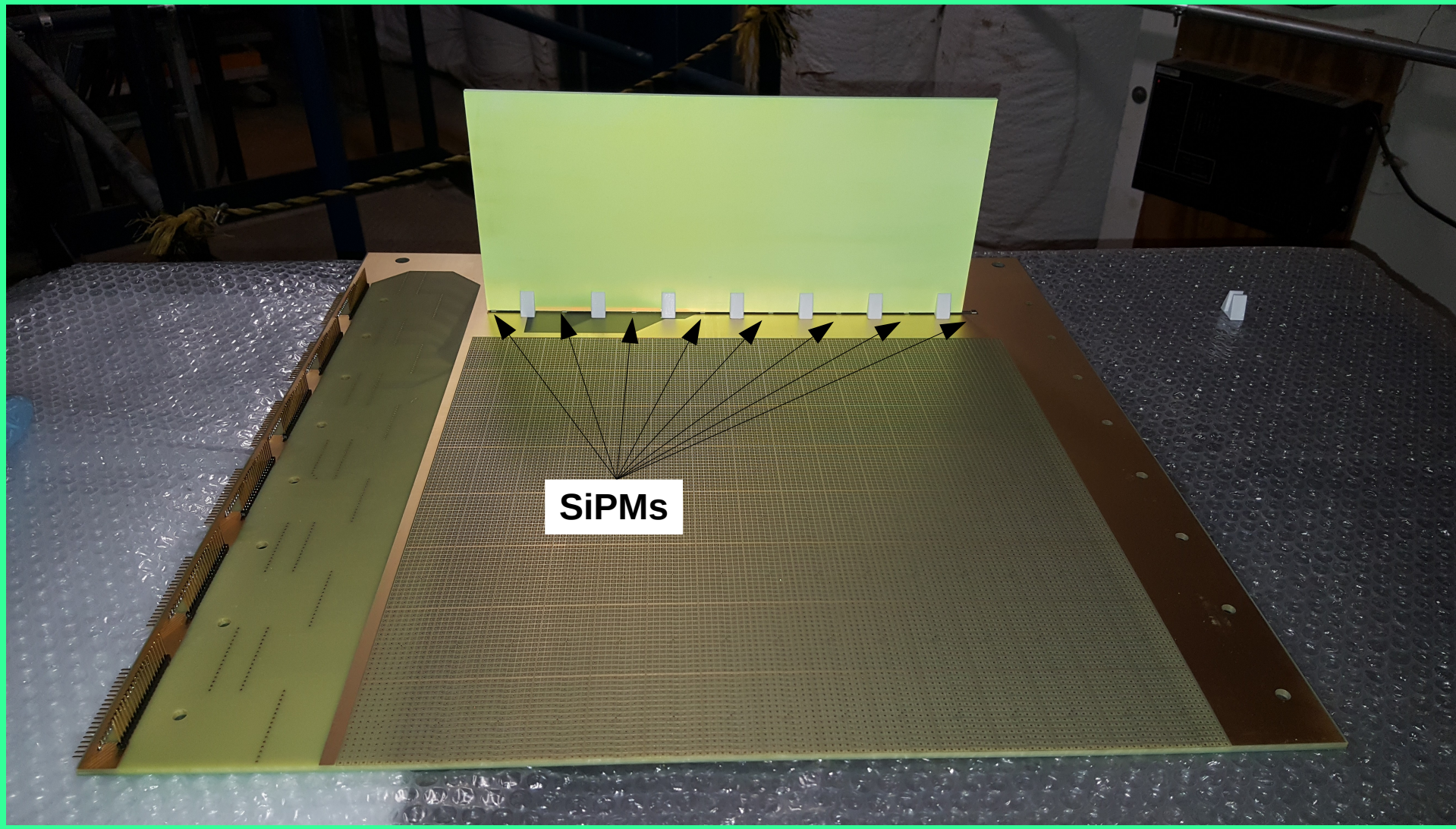
LAr scintillation produces ~26000 photons/MeV @1kV/cm

1560 photons/tyle → ~ 5.3 pe/MeV detected. For MIP 1 MeV=> 5mm,

So we have **1 p.e. per mm of MIP track**.

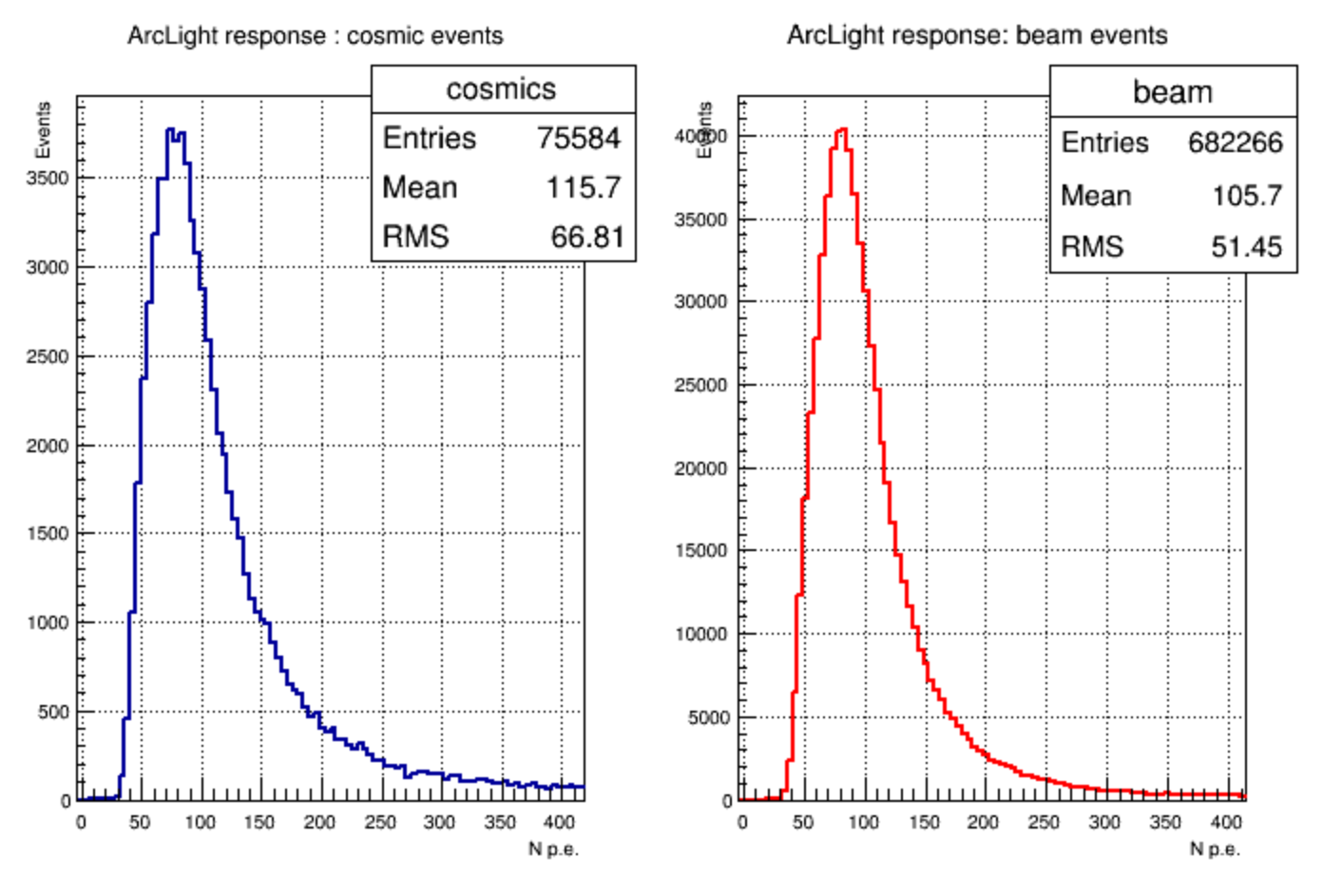
ArgonCube

ArCLight 43x15 cm with TPB coating
Installed in PixLAr detector (Fermilab)



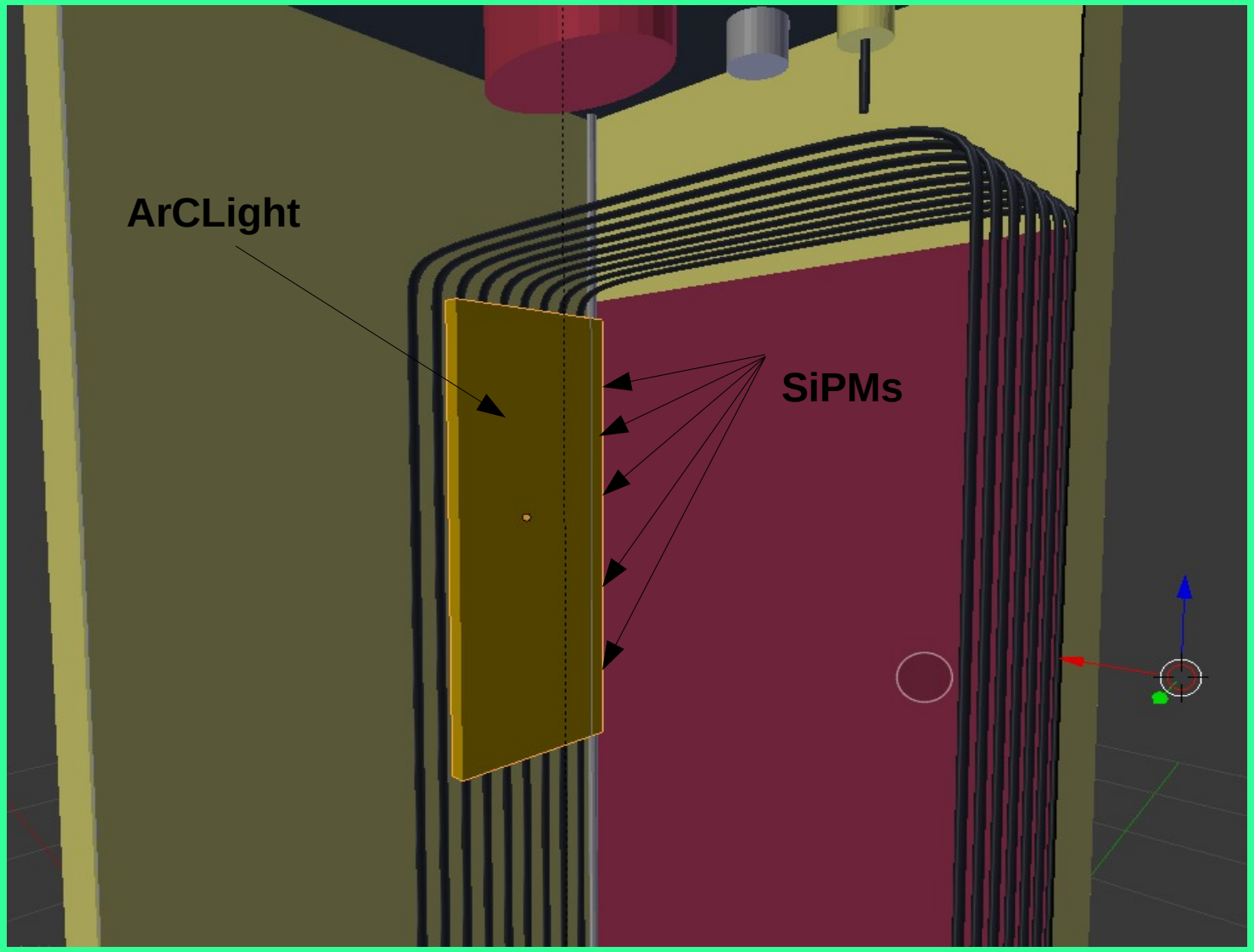
Scintillation light in PixLAr (Fermilab)

Vacuum UV @128 nm



Estimated measured PDE 0.24%

ArCLight in ArgonCUBE



Resitive Shell TPC

Resistive carbon-loaded polymer films

Desired surface resistance ~ 10 G/sq

A number of materials tested.

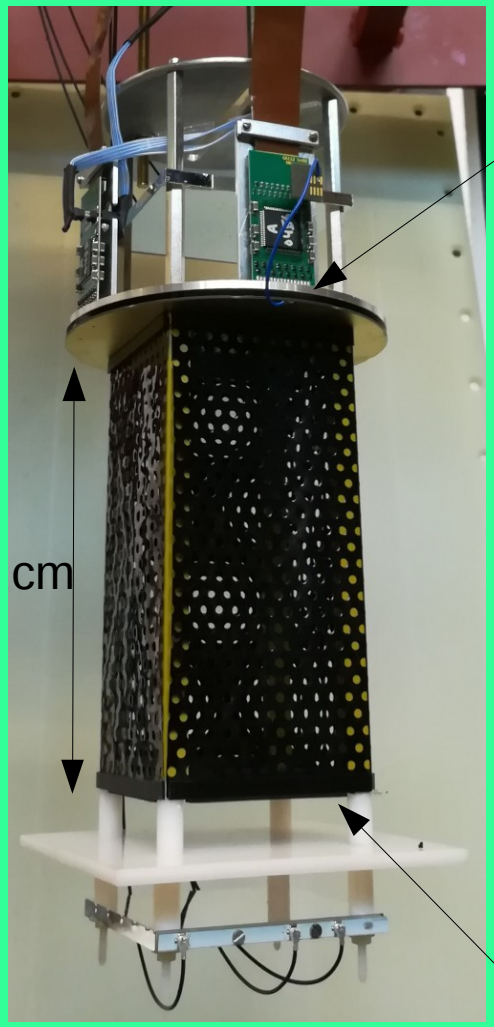
A subsample of results:

Sample #	T=290K	T=77K
1	1.3 M/sq	1.6 M/sq
2	0.5 M/sq	5.2 M/sq
3	350 M/sq	16 G/sq
4	2.6 G/sq	120 G/sq

Testing resistive film strip at LHEP, Uni-Bern, 2018

Thanks to Fermilab team for providing this component!

First Resistive Shell LArTPC (RSTPC)

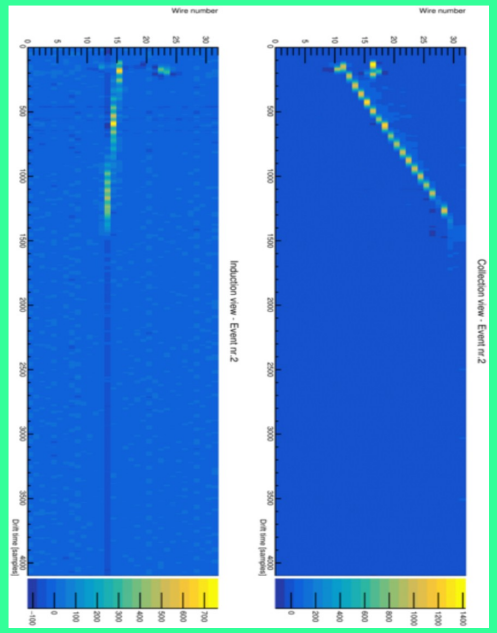


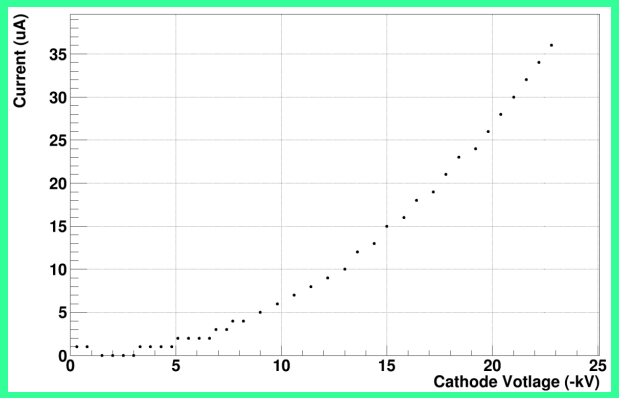
15 cm

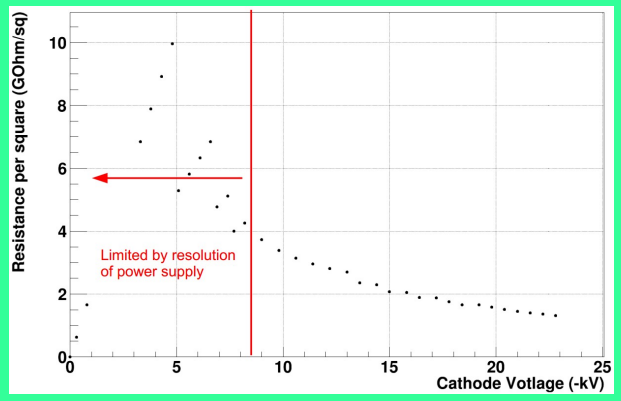
Anode at GND

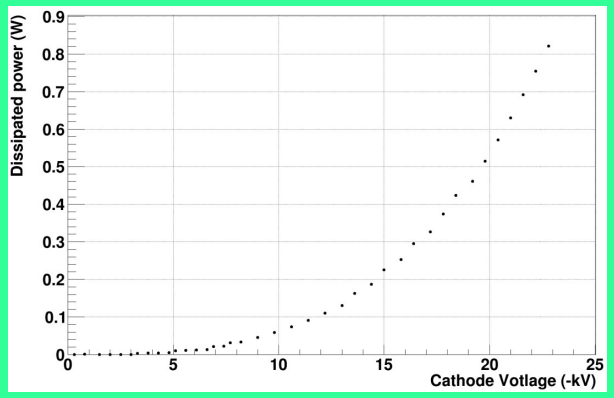
Cathode at -HV(up to 25 kV)

Field uniformity test is conducted, data analysis in progress.

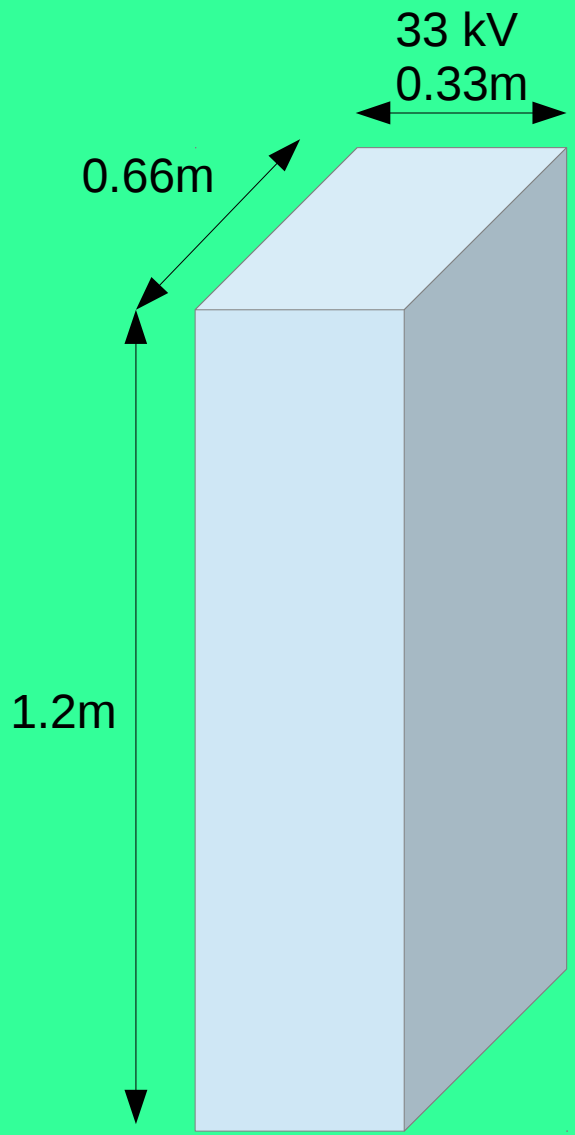


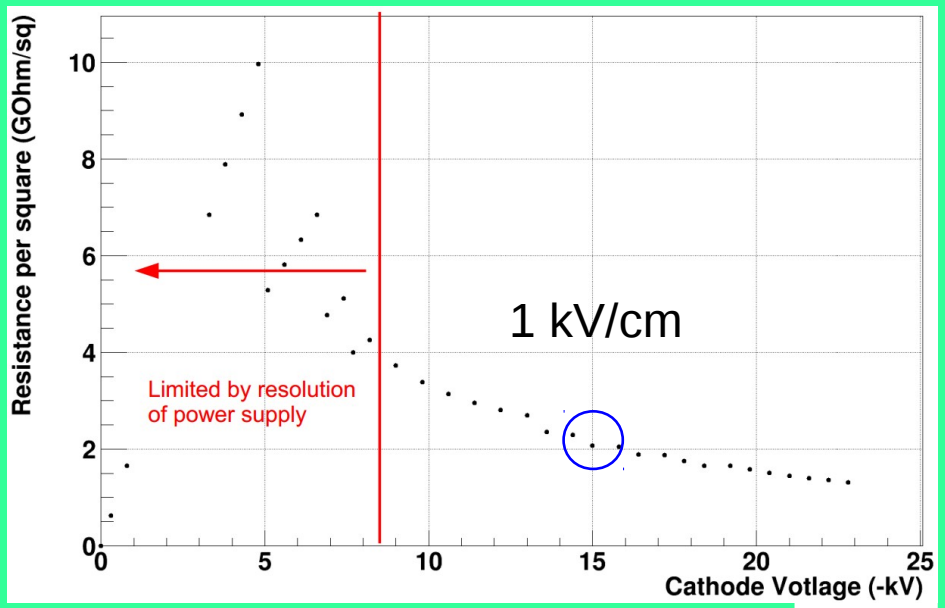






AROGONCUBE 2x2 module with RS





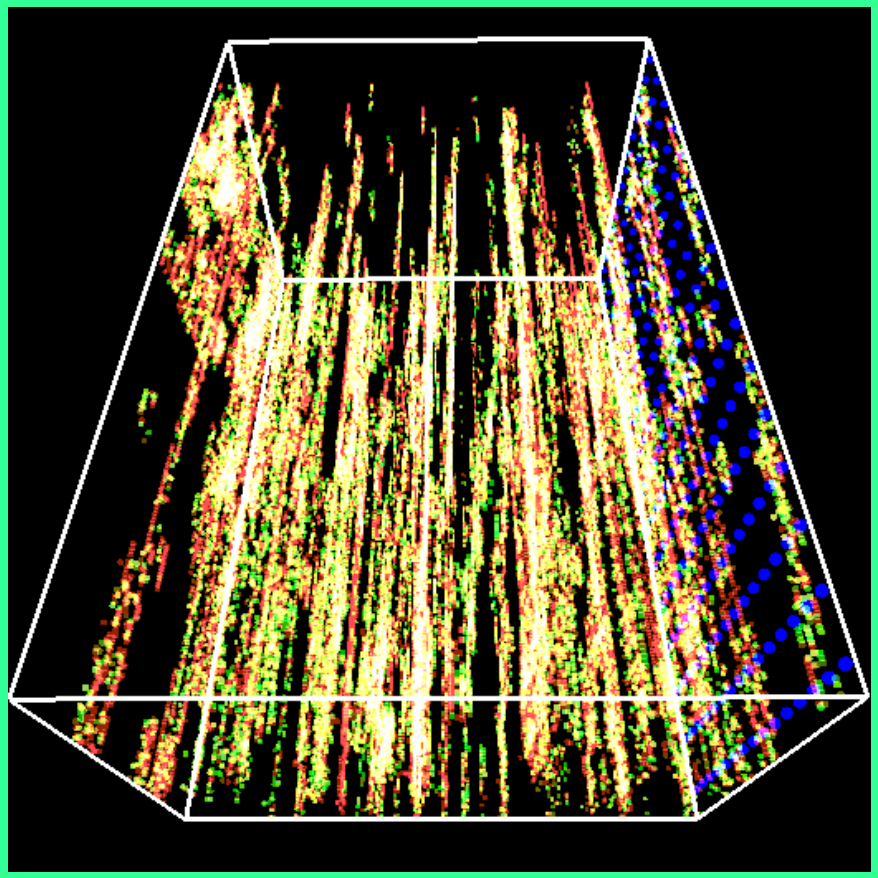
2 G/sq, L=0.33cm, W=3.72m,

Q=0.9 sq, R=0.2 G, U=33kV : P=5.4W

S=1.2 m^2 → 4.5 W/m^2

~10 W/module — acceptable.

Pixelated charge readout



First approach to pixels: LHEP 2016-2017

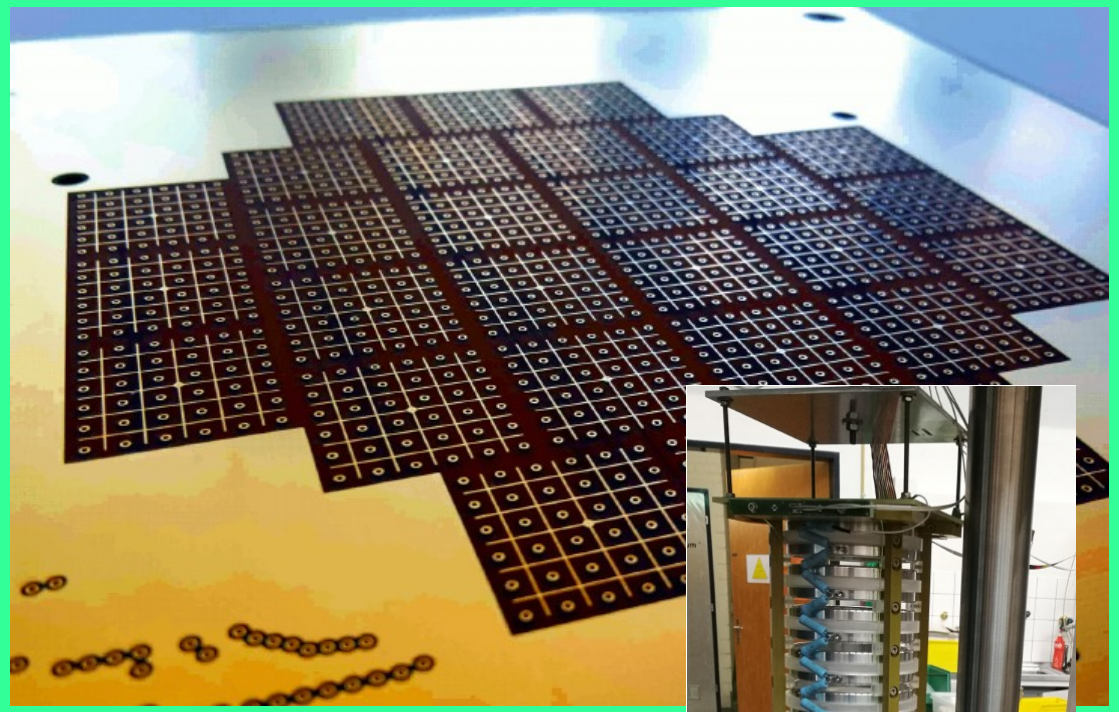
Compromise: multiplexed R/O

6x6 ROI with induction grid

BNL LARASIC4 as cold preamp

60 cm drift test LArTPC

2 runs: 2016 & 2017



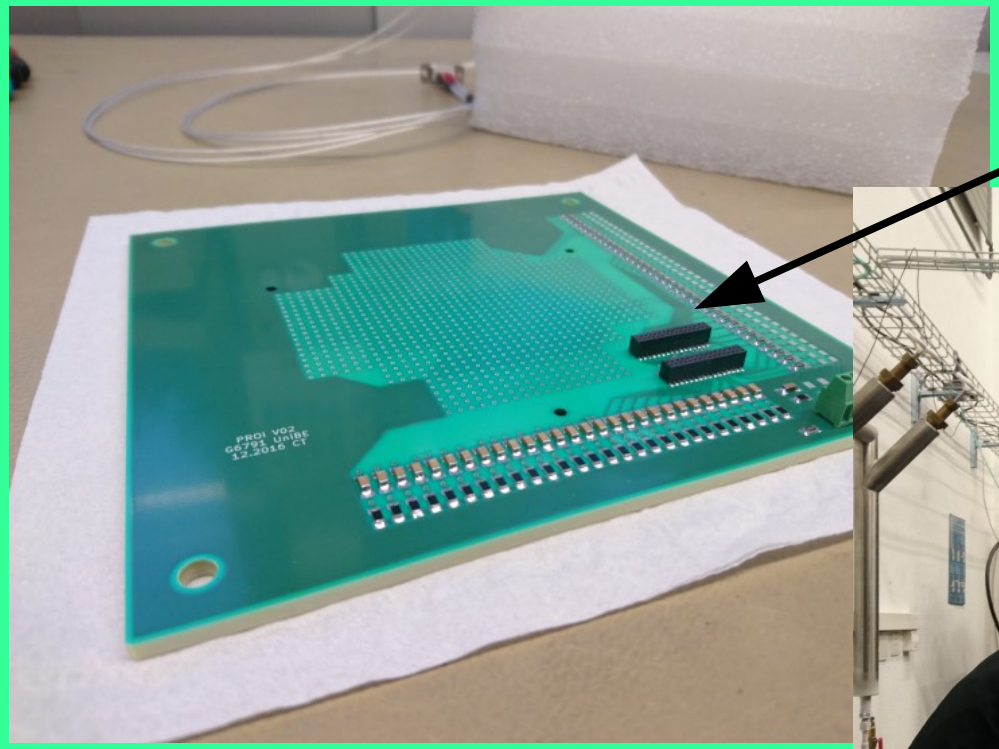
Number of R/O channels: nROI + nPixel

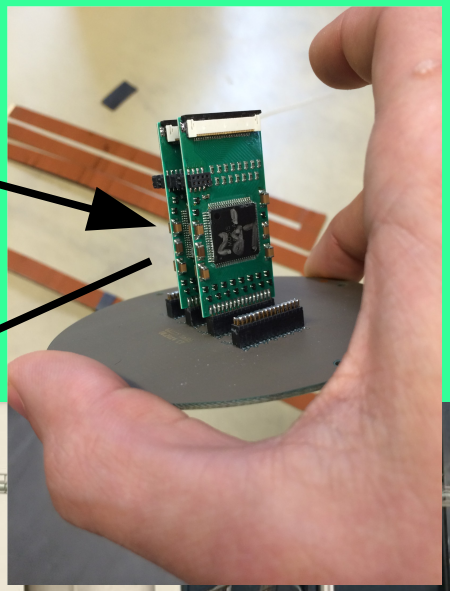
28 ROIs, each 6 × 6 pixels ⇒ **1008** pixels total @ 2.48 mm pitch

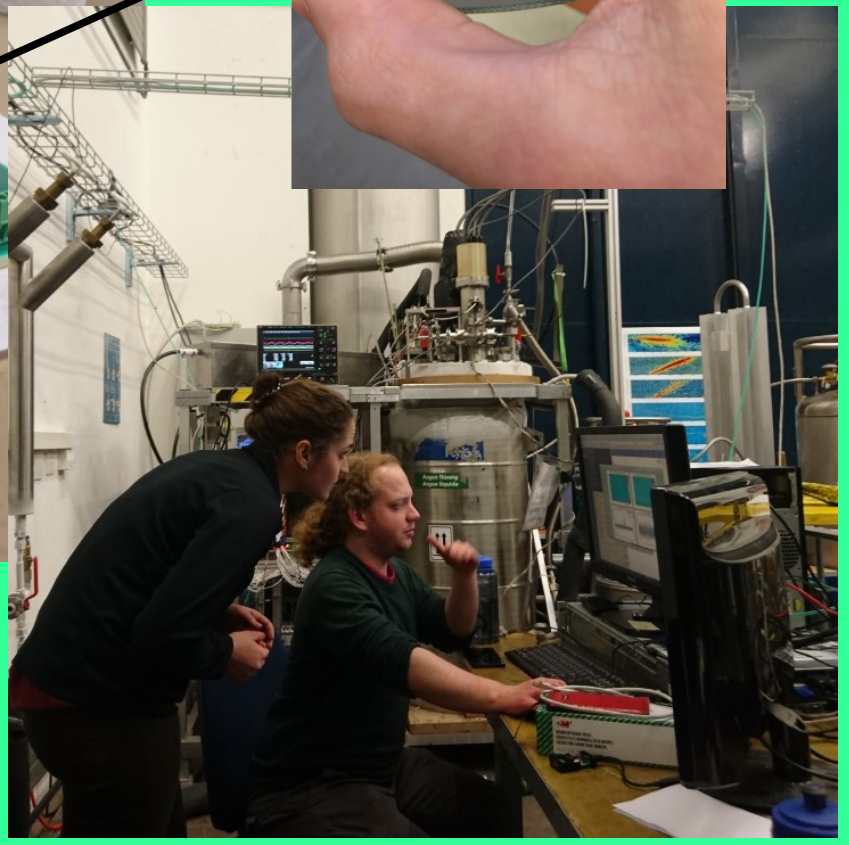
28 + 36 = **64** R/O channels

First approach to pixels: LHEP 2016-2017

4x LARASIC4 on very compact PCB



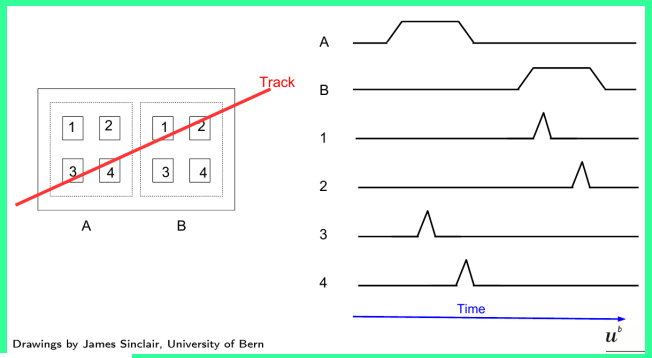


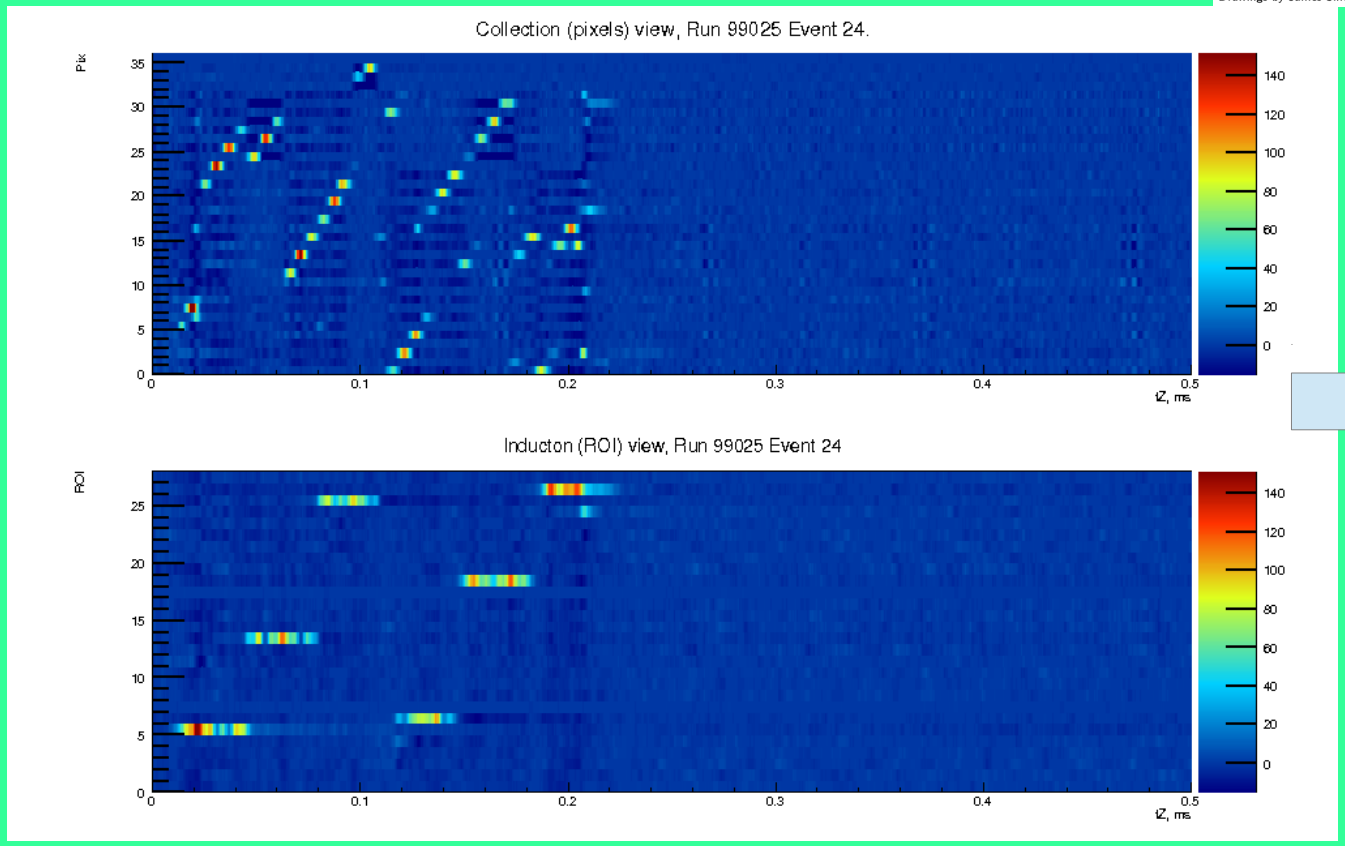


Two data taking runs conducted.

First approach to pixels: LHEP 2016-2017

Reconstruction: simple «enable» by Induction signal

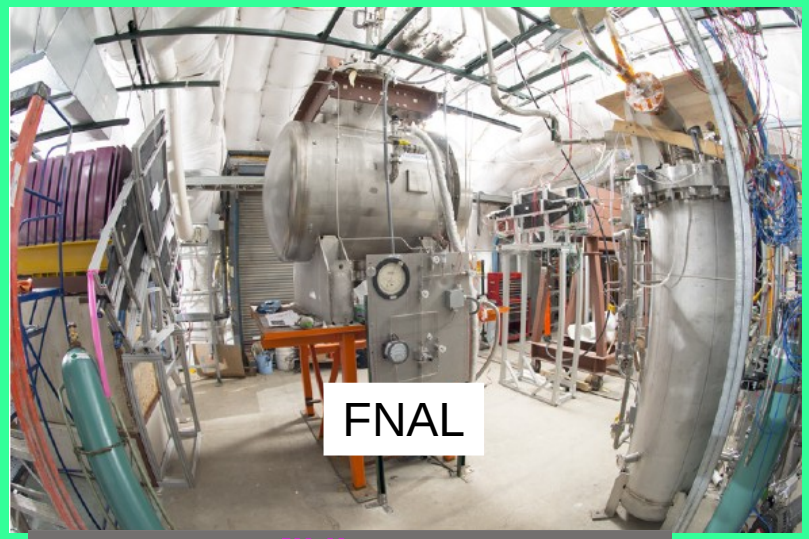


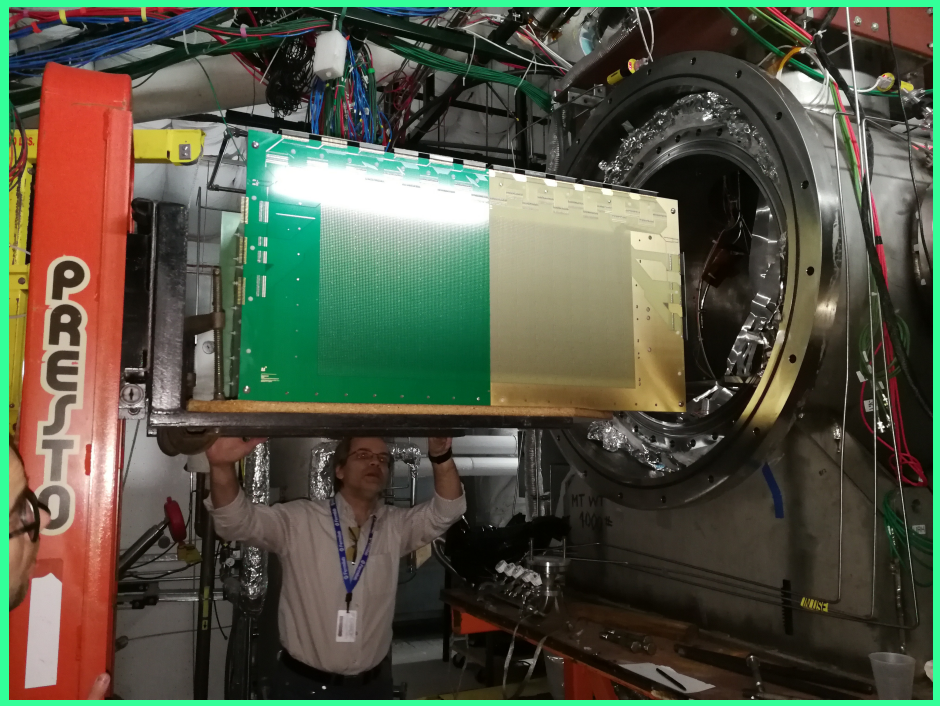


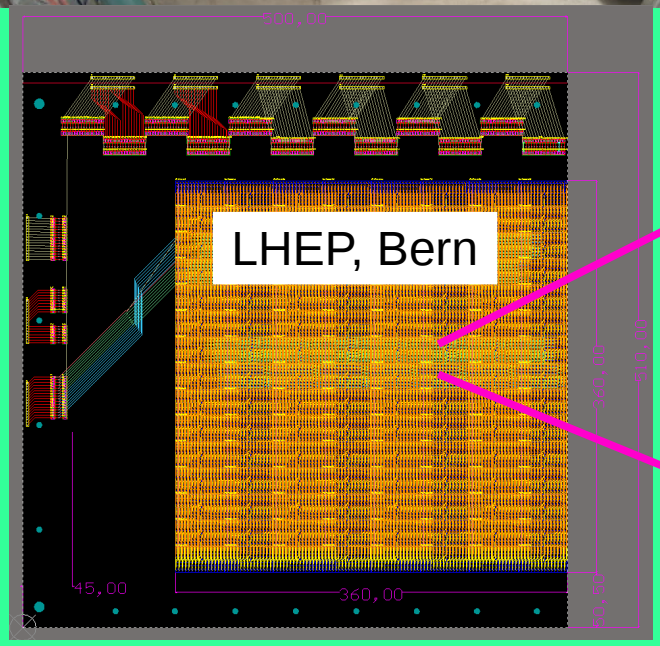
SNR for MIP in worst orientation: **~15**

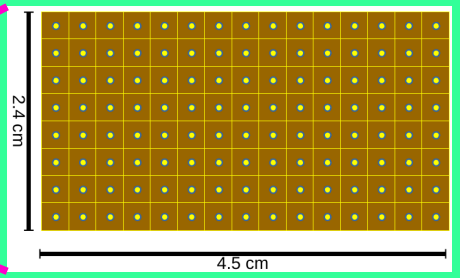
ArgonCube

Test of our Pixel plane in LArIAT: PixLAr TPC
Run: end of 2017 — beginning of 2018





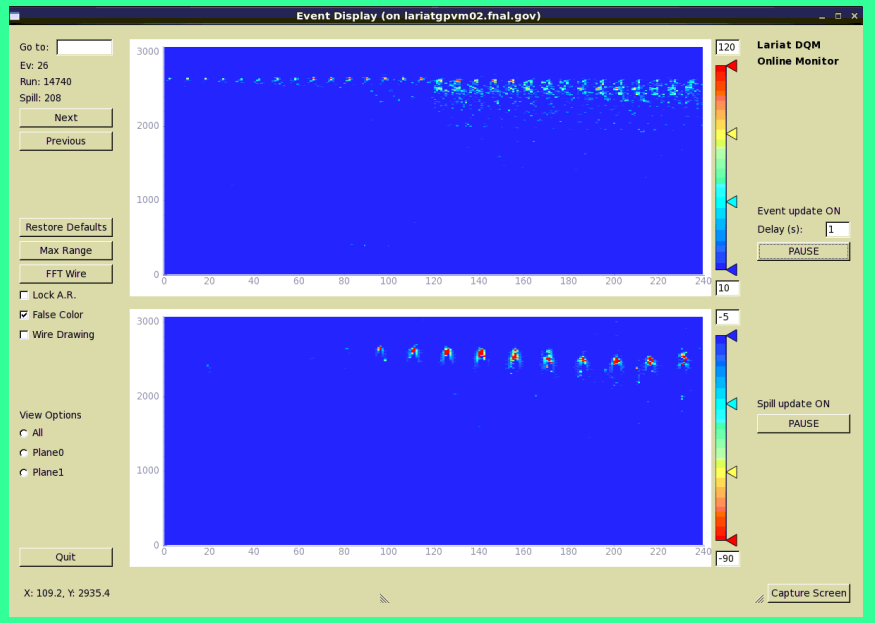


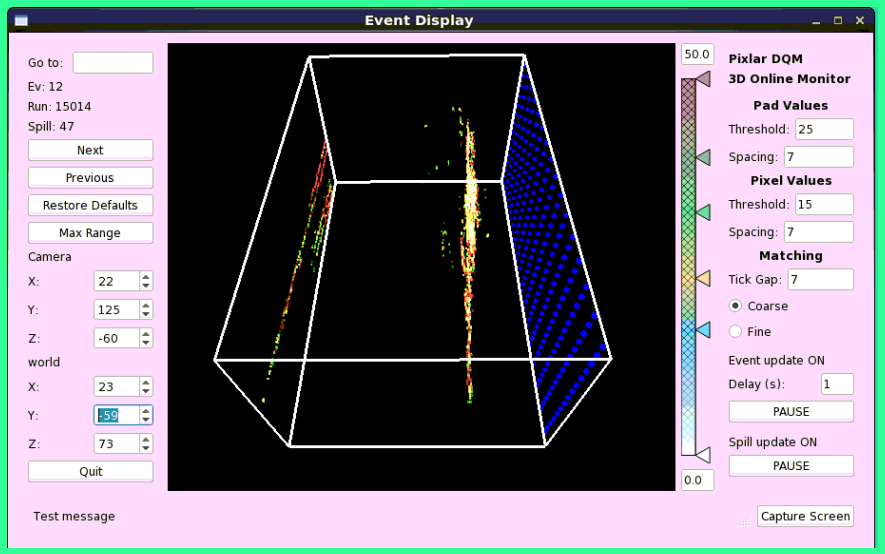


8x15=120 pix/RoI
240 RoI, 72 cm^2
28800 pixels
480 R/O channels

Medium-sized pixel readout test

Test of our Pixel plane in LArIAT: PixLAr TPC
Run: end of 2017 — beginning of 2018





11 Dec 2017 — 1 Feb 2018

426 runs are taken

Several hundred thousands events

Simple reco → 3D event display

Analysis is in progress…

May expect:

- Pion reco efficiency

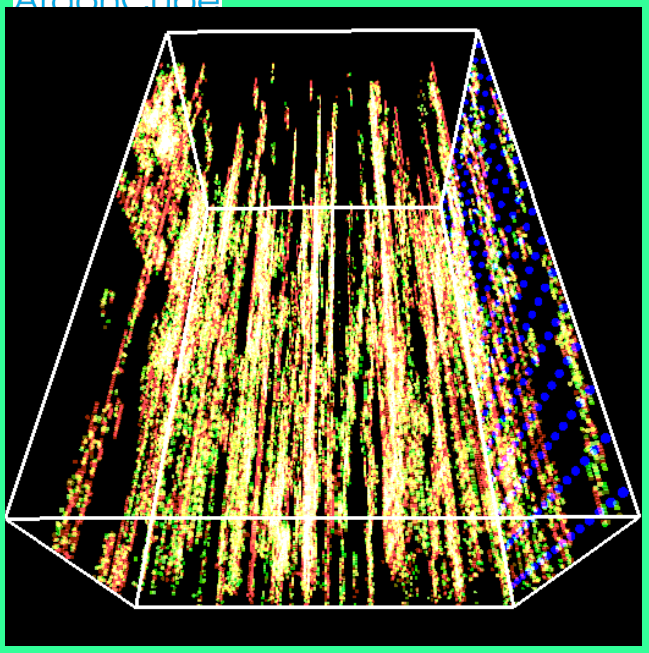
- dE/dx uncertainty (vs angle)

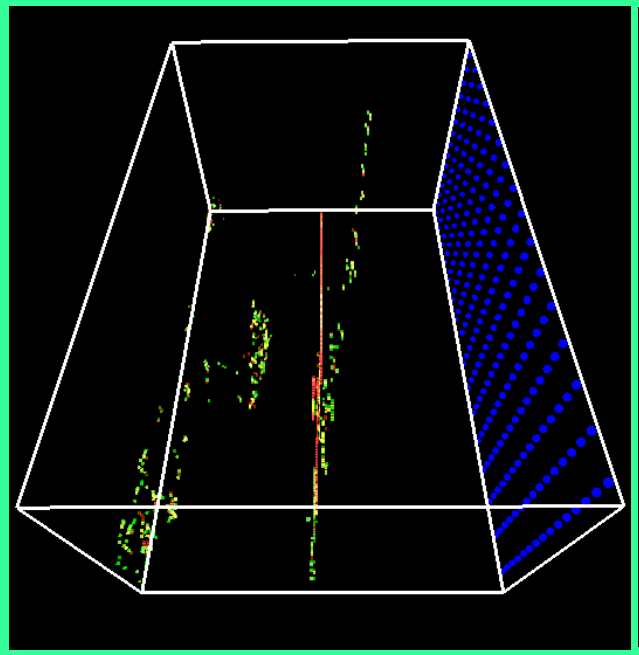
- EM shower reco, energy uncertainty

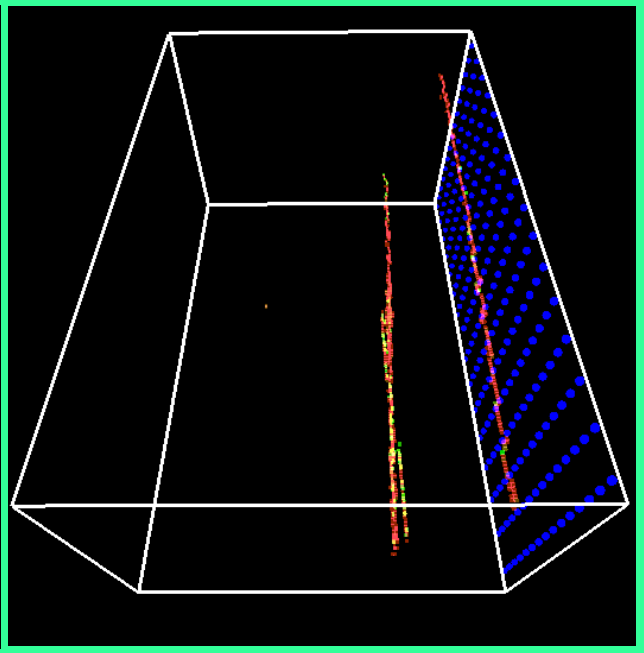
- Pileup limit, two event separation efficiency

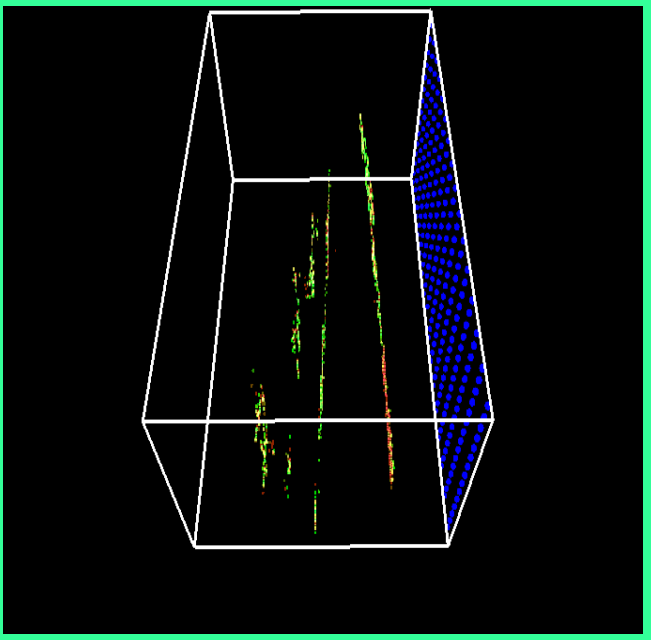
Pixels are good! Precious data in hands!

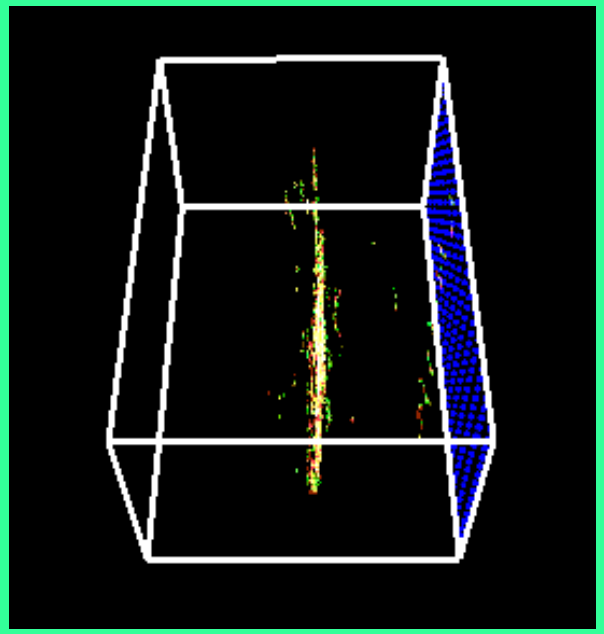
PixLAr Event Gallery

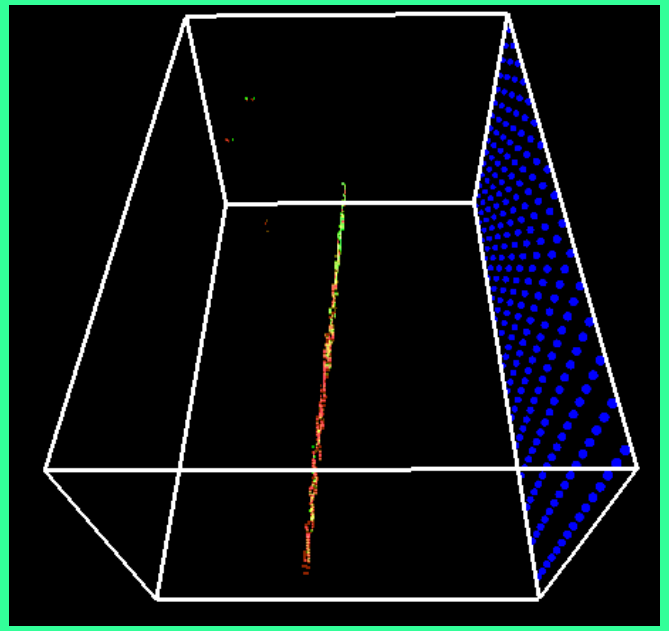




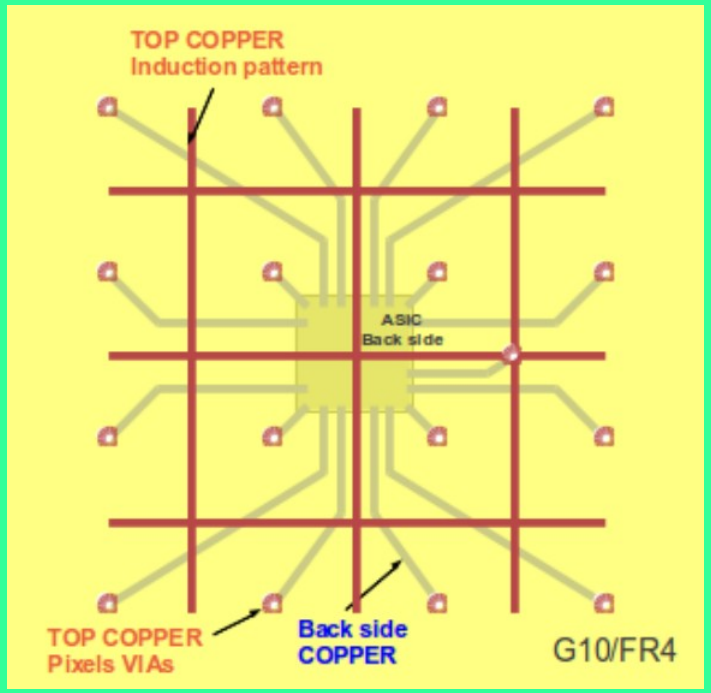








Unambiguous readout: requirements for pixel R/O ASIC



Number of physical pixels: nROI ∗ nPixel

Can use ROIs induction signal to wake up ASIC to save power.

For ND module: 2planes x 1m x 3.5m, ~5 tons of LAr per module
3x3 mm pixels → ~800000 pixels/module
If we reach 50 μW/pixel we are at 40 W/module and 8 W/ton — safe!

Need to keep heat low at very high number of channels

Requirements for pixel R/O ASIC

SNR of >10 for MIP (signal is ~19000 electrons ~3 fC for 3x3 pixel)

Noise ENC<1900 electrons

Heat dissipation < 50 μW/pixel

≥16 channels/ASIC

≥10 bits ADC

Time slice ≤ 1 us

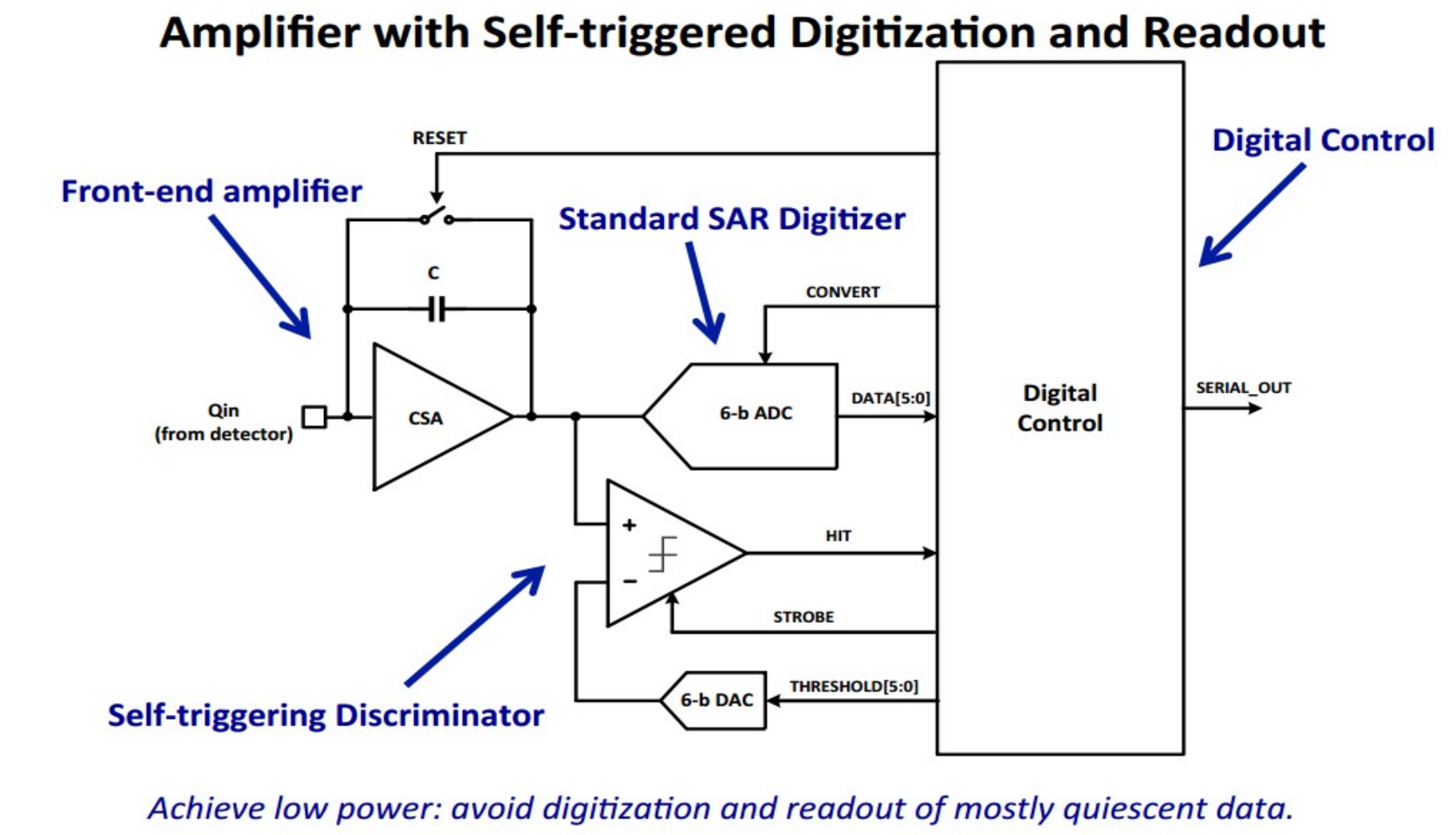
Smart zero suppression

Multiplexing at the data output lines

Concept for pixel R/O ASIC

(courtesy of Dan Dwyer, LBNL)

Process: TSMC 180nm



ArgonCube

Concept for pixel R/O ASIC

(courtesy of Dan Dwyer, LBNL)

Target 1: Demonstrate low-noise low-power cryogenic amplifier (CSA)

Design goal: Power use (heat generation) less than heat flux through cryostat walls

→ Total pixel electronics power consumption ~< 10 W/m^2

Pixel Pitch	Pixels/m^2	Power/m^2
3 mm	111.1k	11.1 W
4 mm	62.5k	6.3 W
5 mm	40.0k	4.0 W

(assuming 100 µW/channel)

Analog Power:

- ASIC Simulation: 24 µW/channel
- Bench Measurement: 24 µW/channel

Unexpected surprise: Digital power also very low!

Mode:	Core Voltage	I/O Voltage	Power (Dig.) [µW/ch]	Power (Ana.+Dig.) [µW/ch]
Default	1.8 V	3.3 V	233	257
Low-power	1.1 V	2.0 V	37	61

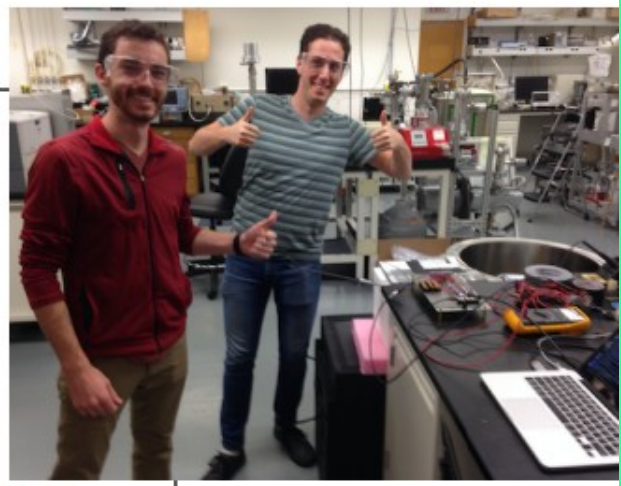
→ *Still some room for tuning I/O voltage to bring power down further.*

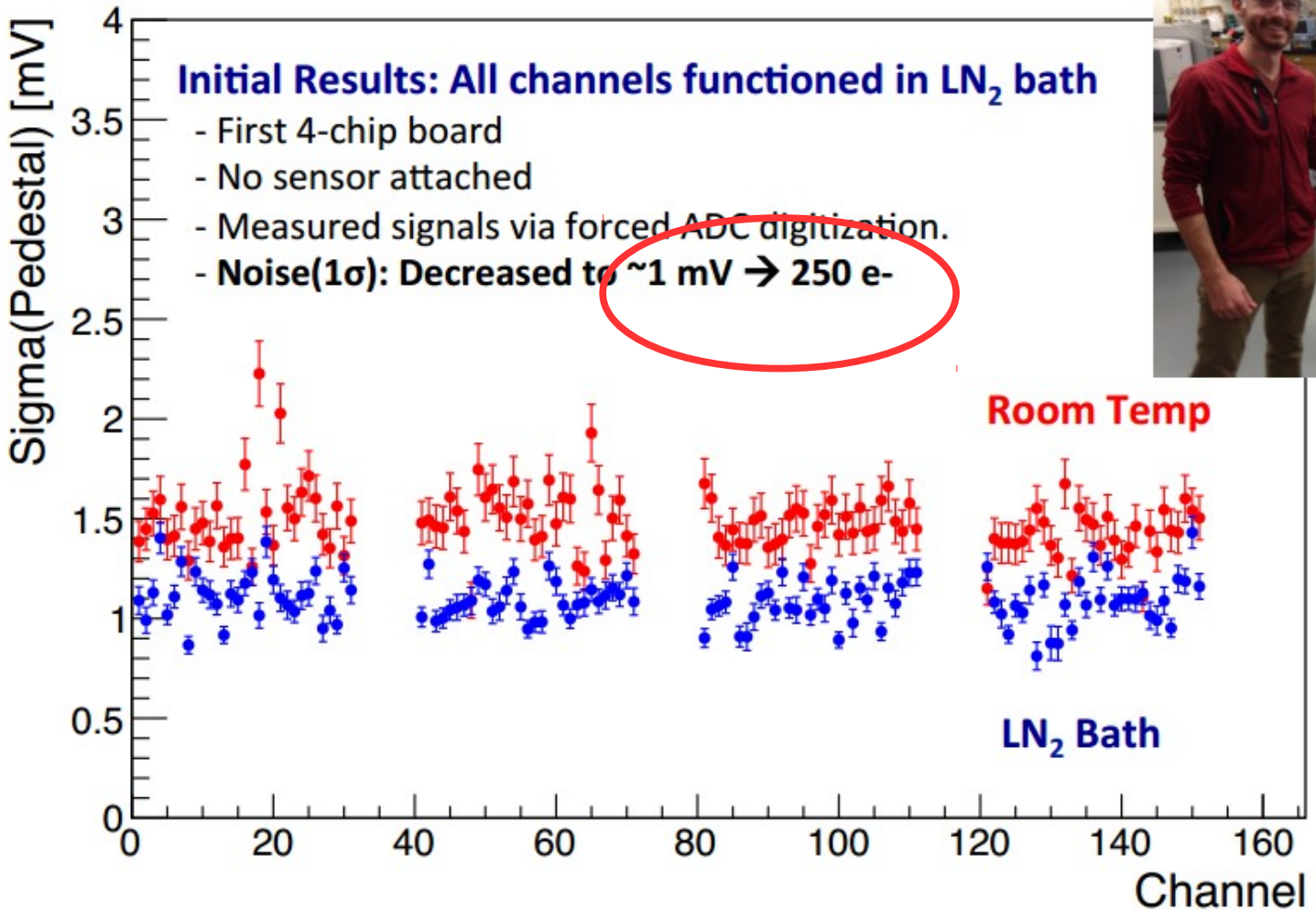
Concept for pixel R/O ASIC

(courtesy of Dan Dwyer, LBNL)

Target 1: Demonstrate low-noise low-power cryogenic amplifier (CSA)

Design goal: Operate at liquid argon temperature





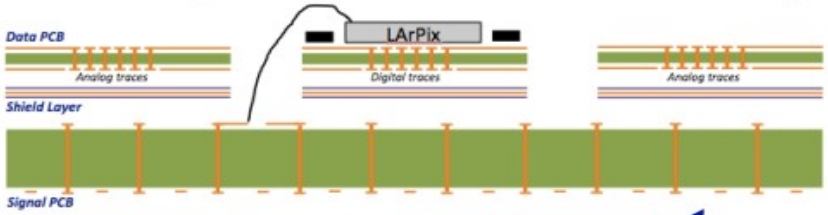
Concept for pixel R/O ASIC

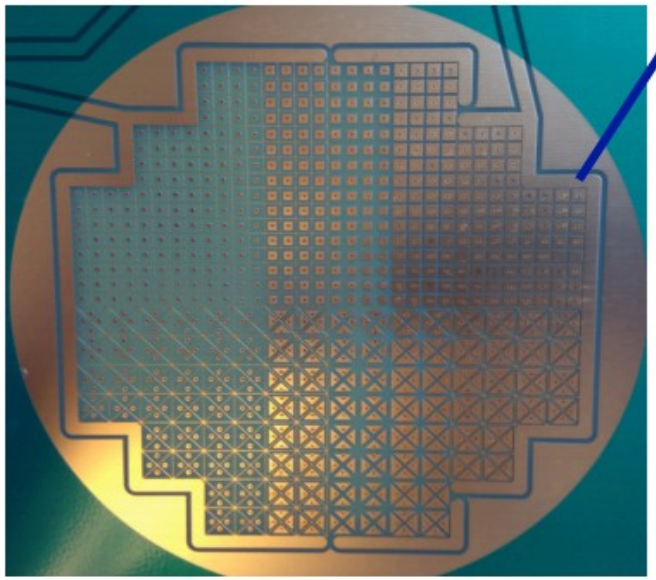
(courtesy of Dan Dwyer, LBNL)

Prototype Scalable Sensor

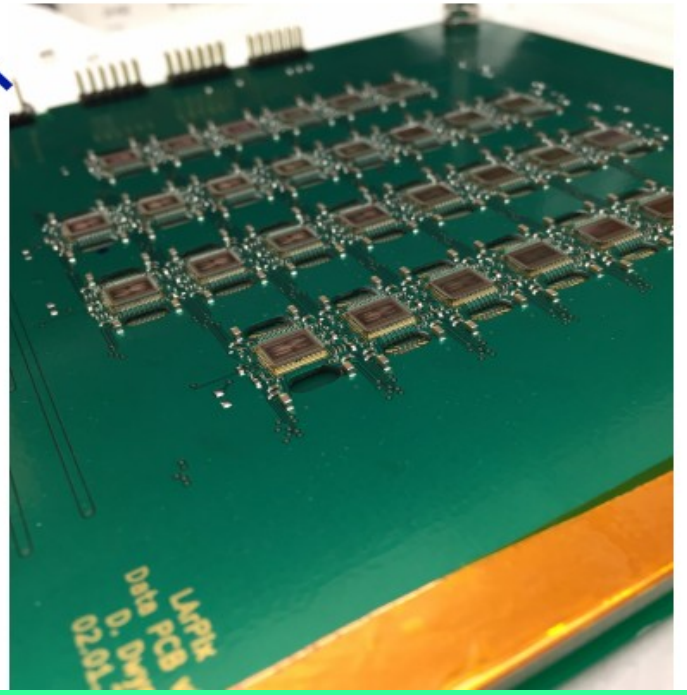
New Sensor:

- Uses new digital data board to provide scalable sensor (dense pixel packing)
- Coupled to 10-cm diameter pixel sensor board
  → Designed to fit both 10-cm-drift TPC (@LBNL) and 60-cm drift TPC (@Bern).

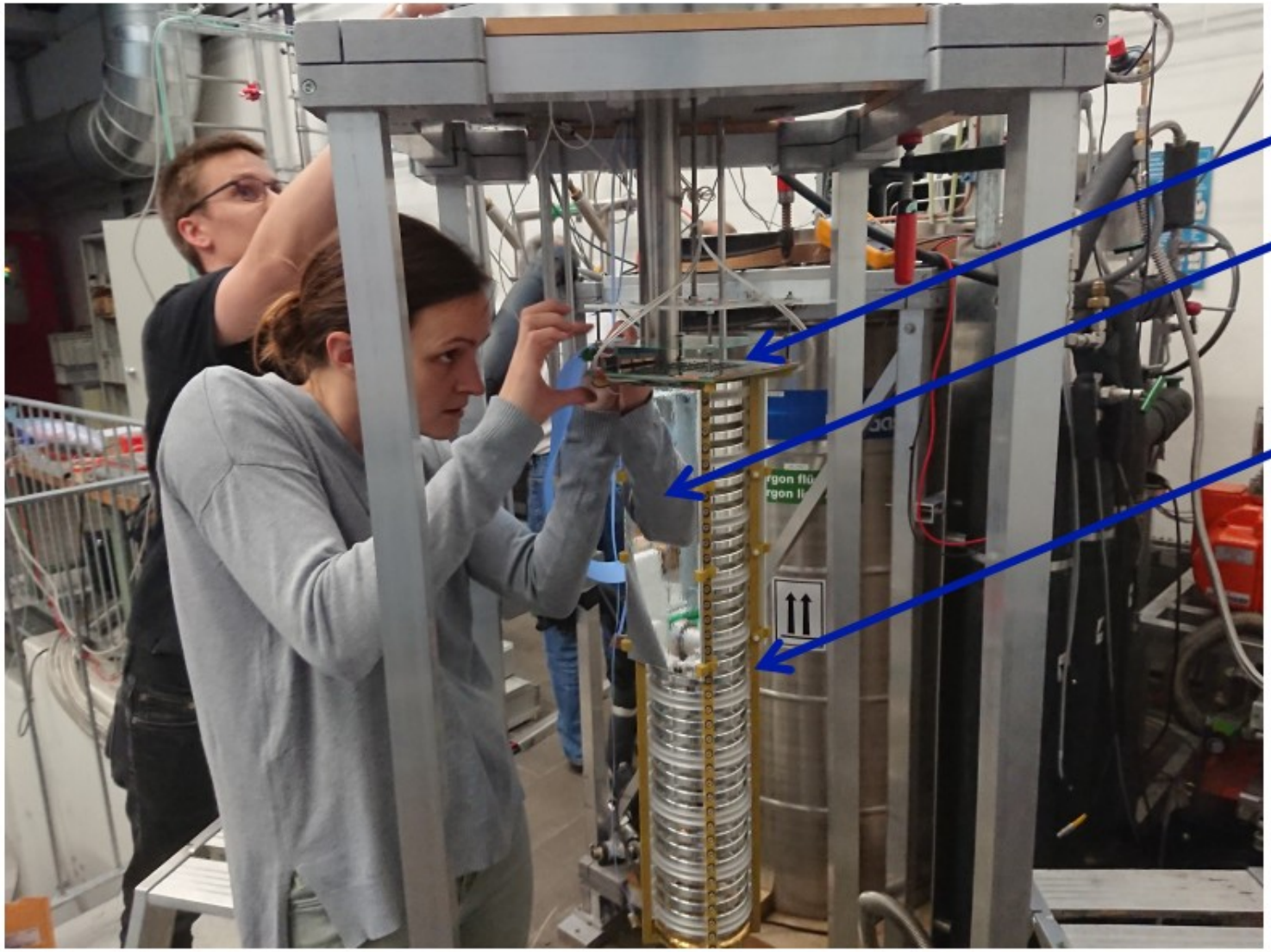




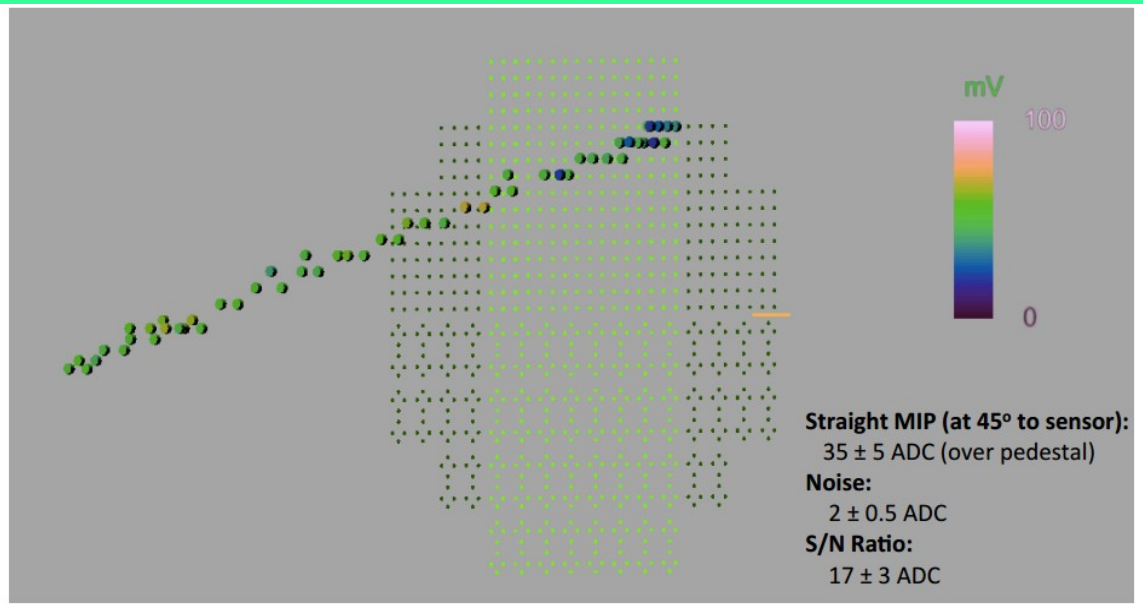
- 832 pixels
- 28 Chips

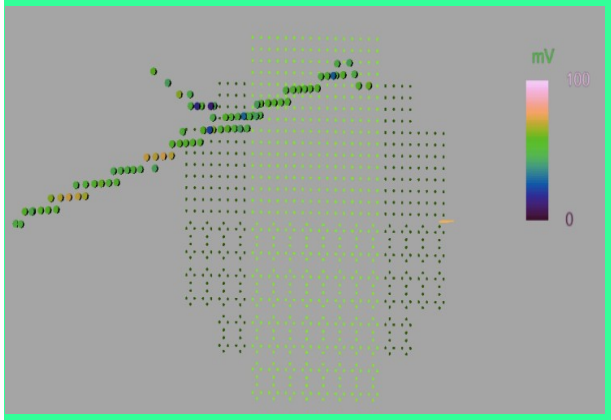


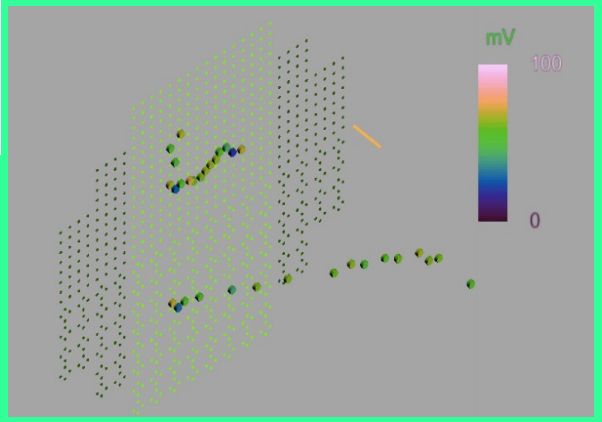
First test in a Lar TPC at Bern



First test in a Lar TPC at Bern

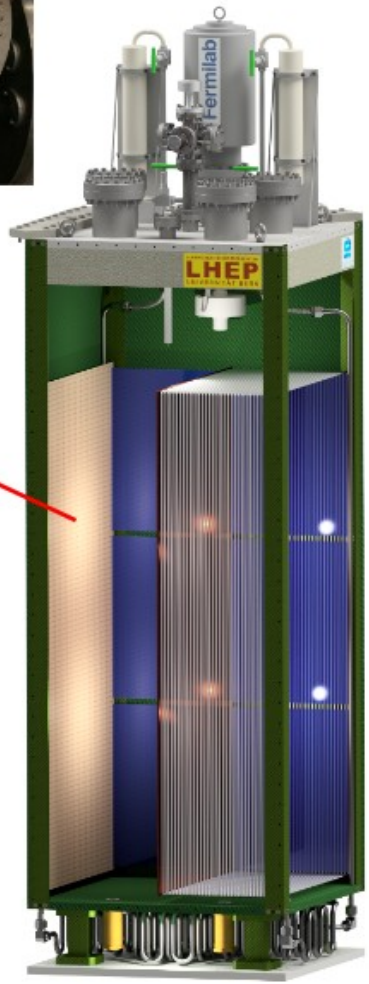




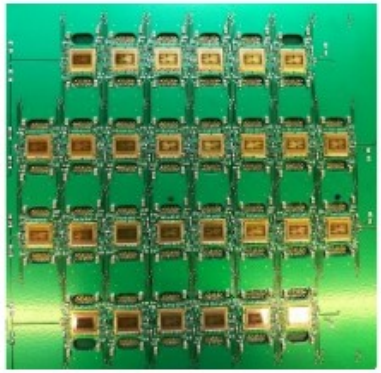


TPC operating at 60 kV, 1kV/cm drift field

2x2 ArgonCube proto in Bern



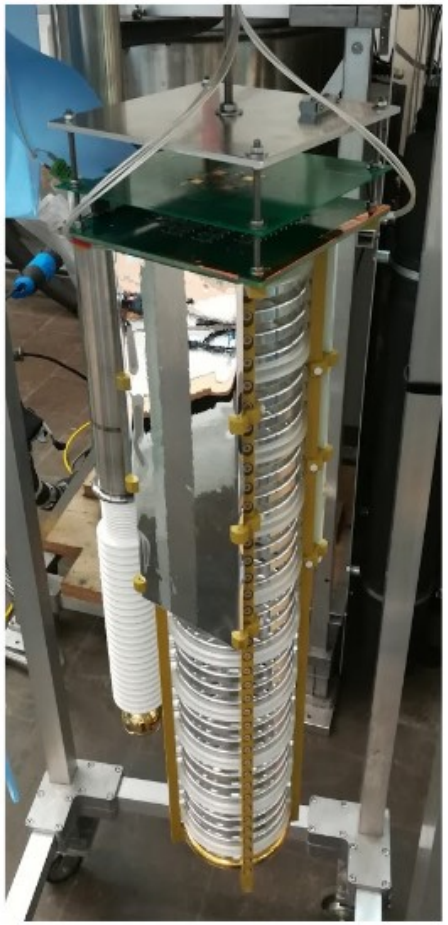
Pixel Plane

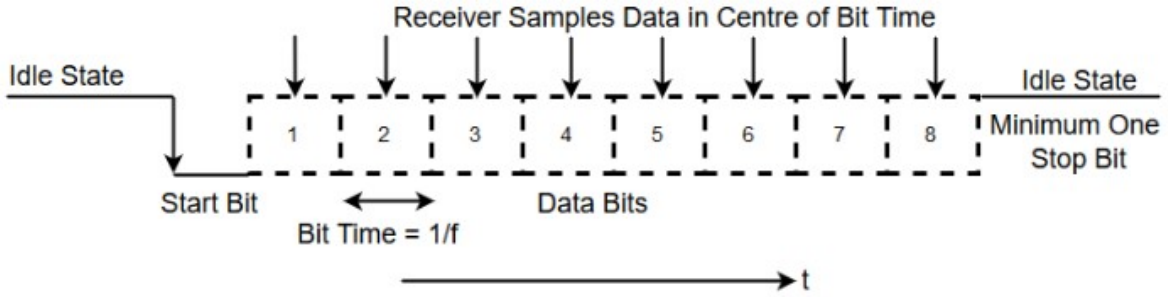


- 2 readout areas: 60cm * 120cm
- Read out with LArPix
- Pixel pitch: 3mm

- 1 pixel board:
  - 80'000 pixels
  - 32 pixel/chip -> 2500 chips
  - 100 chips/line -> 25 lines

- 1 module: **160'000 pixel**
  5'000 chips
  50 lines

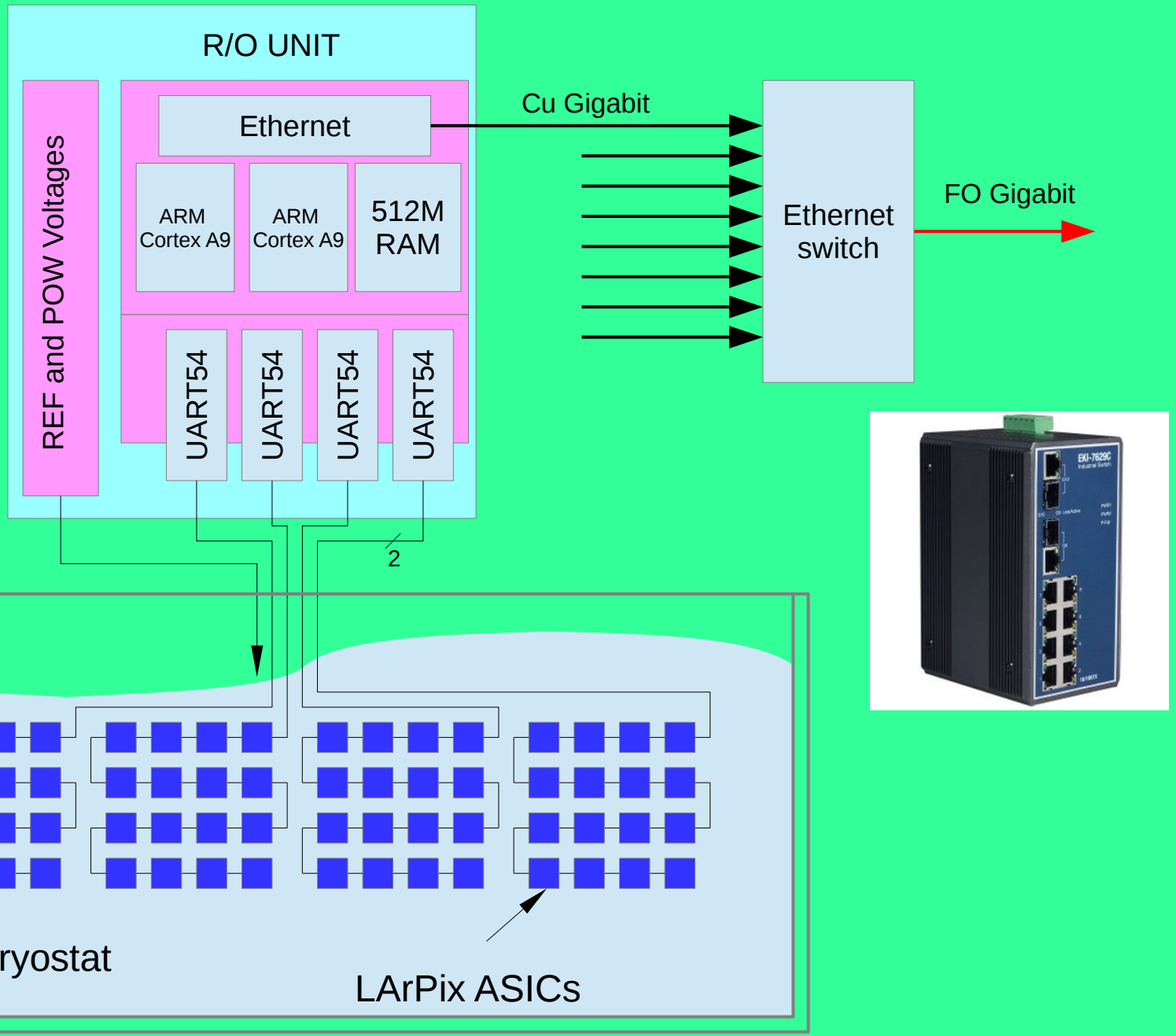




UART-like communication with a 54 bit data word

300Hz	54 bit, 16 chips, 60cm drift
~10Hz	54 bit, 1 chips, 30cm drift
1 chip	540 bit/s
5000 chip	2,7 Mbit/s

Warm F/E electronics



Near Detector Recommendations Approved by EB

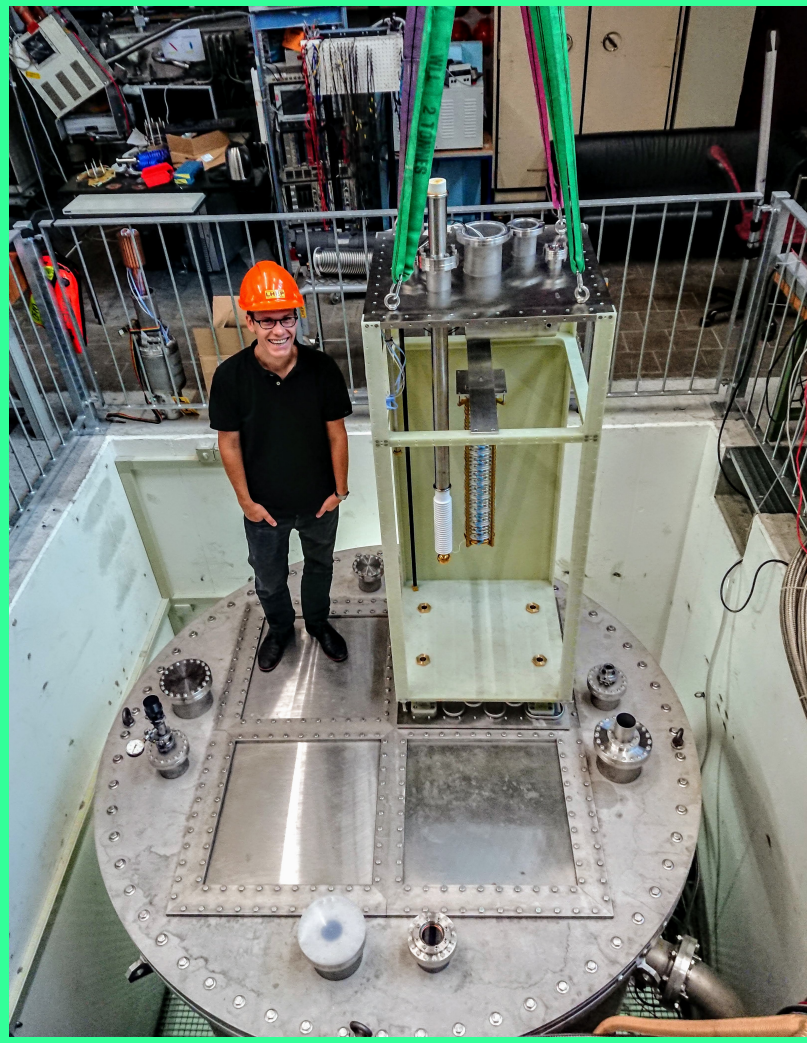
1. The LArTPC at the near site should be optically segmented, with a short drift space and 2-dimensional pixelated readout, similar to the concept being studied by the ArgonCube collaboration.
2. The design of a mobile LAr detector that can make measurements at one or more off-axis positions should go forward (DUNE-PRISM)

Quick review of recommended ND components

- LAr (ArgonCube concept)
- HPgTPC (+ECAL)
- 3DST
- Magnetic Volume
- DUNE-PRISM

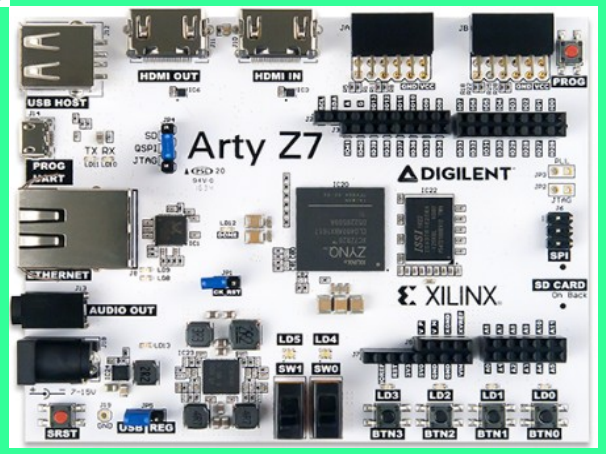
For up-to-date details see: Near Detector Session I (Tuesday 09:00) and Near Detector Session II (Tuesday 14:00)

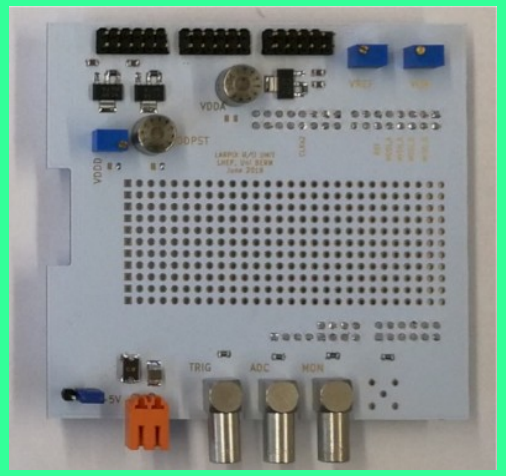
Thank you !

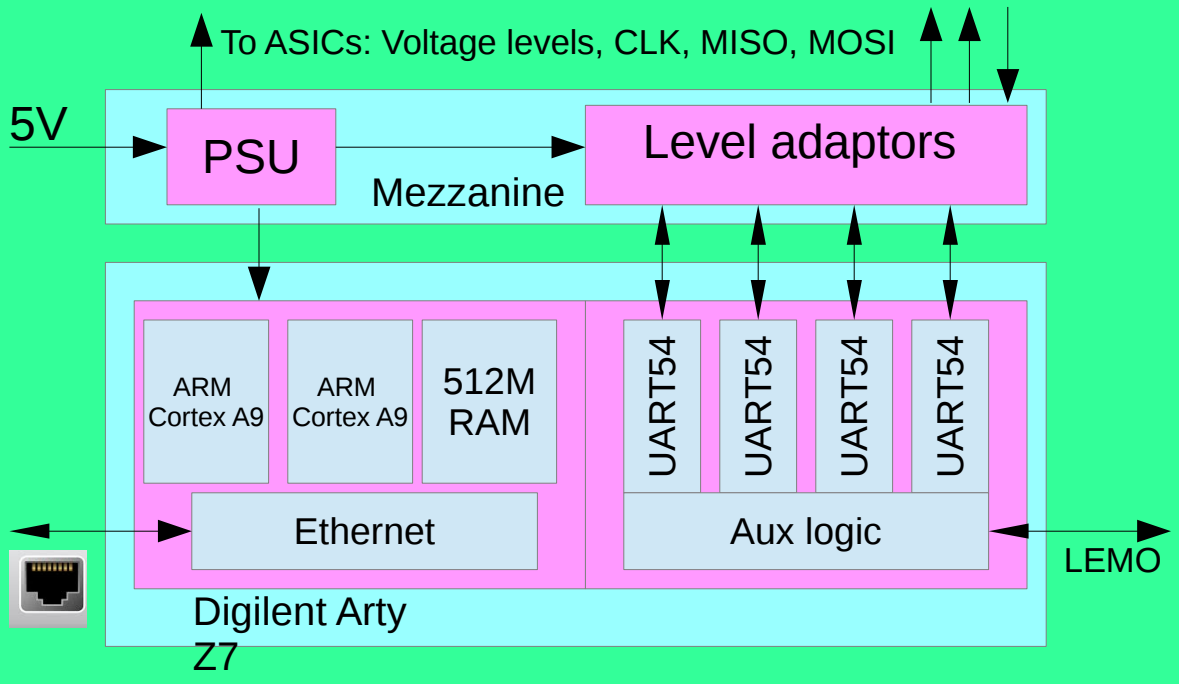


Backup Slides

Warm F/E electronics







Cathode potential

Single-volume TPC	ARGONCUBE
1-2 MV: - Feedthrough is a challenge - Drift time > 10 ms	100 kV - Feedthrough home-made or commercial - Wide choice of PS units - Drift time ~ 1ms

Charge attenuation → calorimetry constant term

LAR Purity ~ 0.01 ppb	Purity ~0.1 ppb (reached in ARGONTUBE)

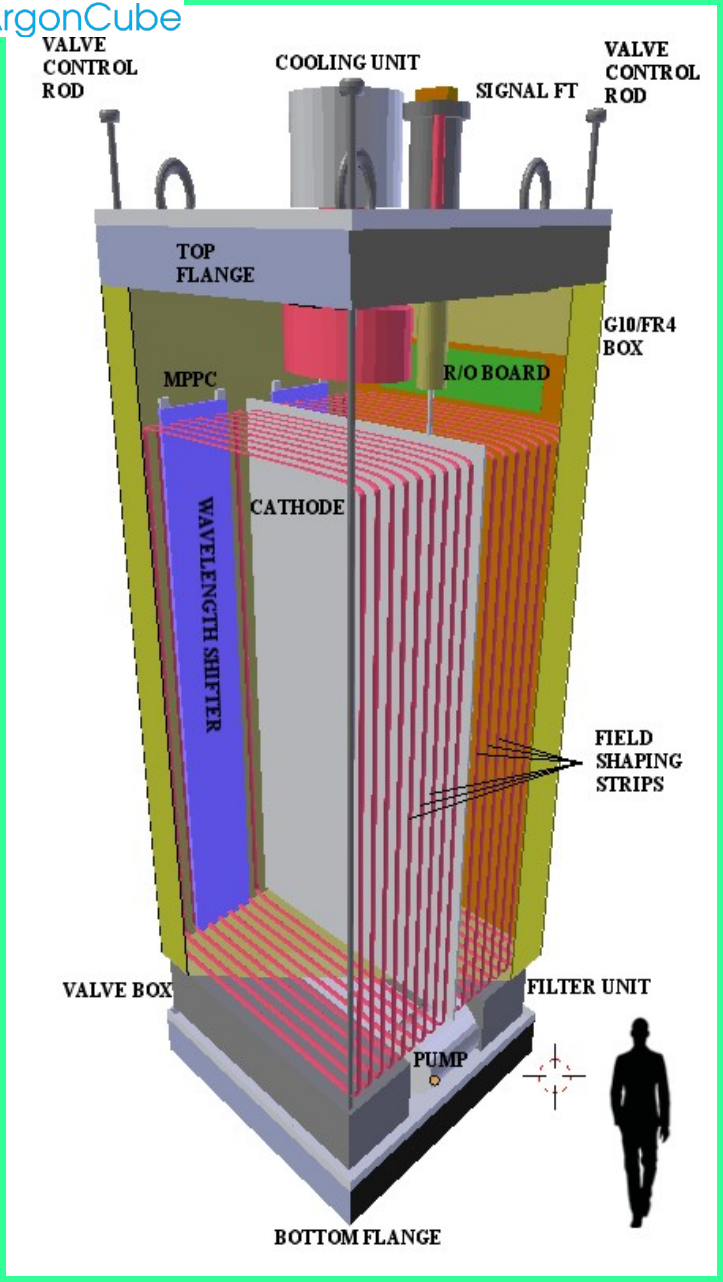
Accumulation of volume charge

Low distortions (~3%, in MicroBooNE 10%)

Risk of breakdowns (arcing)

Stored charge ~ 1nF x 1 MV = 1 mC	~ 1nF x 100 kV = 0.1 mC / module
Stored energy 1 mC x 1 MV = **1 kJ**	0.1 mC x 100 kV = **10 J / module**

ArgonCube



Module: an independent TPC

- LAr purification: recirculation through Oxygen-traps
- Temperature: individual cryo-cooler unit
(removes heat input from electronics and heat leaks)

- Cathode bias (-100 kV) supplied via HV feed-through
- Resistive divider for field shaper
- Relatively low voltage => breakdown-free setup
- Electrically transparent container => low dead volume

- PCB-technology for R/O plane manufacturing
- Pad arrays for charge readout, 4x4 mm^2 pads
- 8x8 pads ROI served by one R/O ASIC at the PCB back
- Mechanically robust production technology
- Low failure cost

- Light collection via WLS light guides
- Light readout with SiPMs in coincidence

Reliable/repairable self-contained unit

LarPix V2:
64 channels/chip

4 mm pitch:
3.2x3.2cm/chip

10x10 ASICs for a 32cm by 32cm tile

8 tyles/side, 16 tyles/module (102400 pix), 1600 chips/module, 16 lines/module, 4 (8) R/O units/module

Feedthrough: 32 pins data, 32 pins gnd, clock and power.

Typical rate: 0.1Hz/pix, => overal 10 kHz, 2.5 (1.25) kHz / R/O Unit

Data rate 640 kbps/module, 2.6 Mbps overal for 2x2 TPC