The MEG II Cylindrical Drift CHamber (CDCH)

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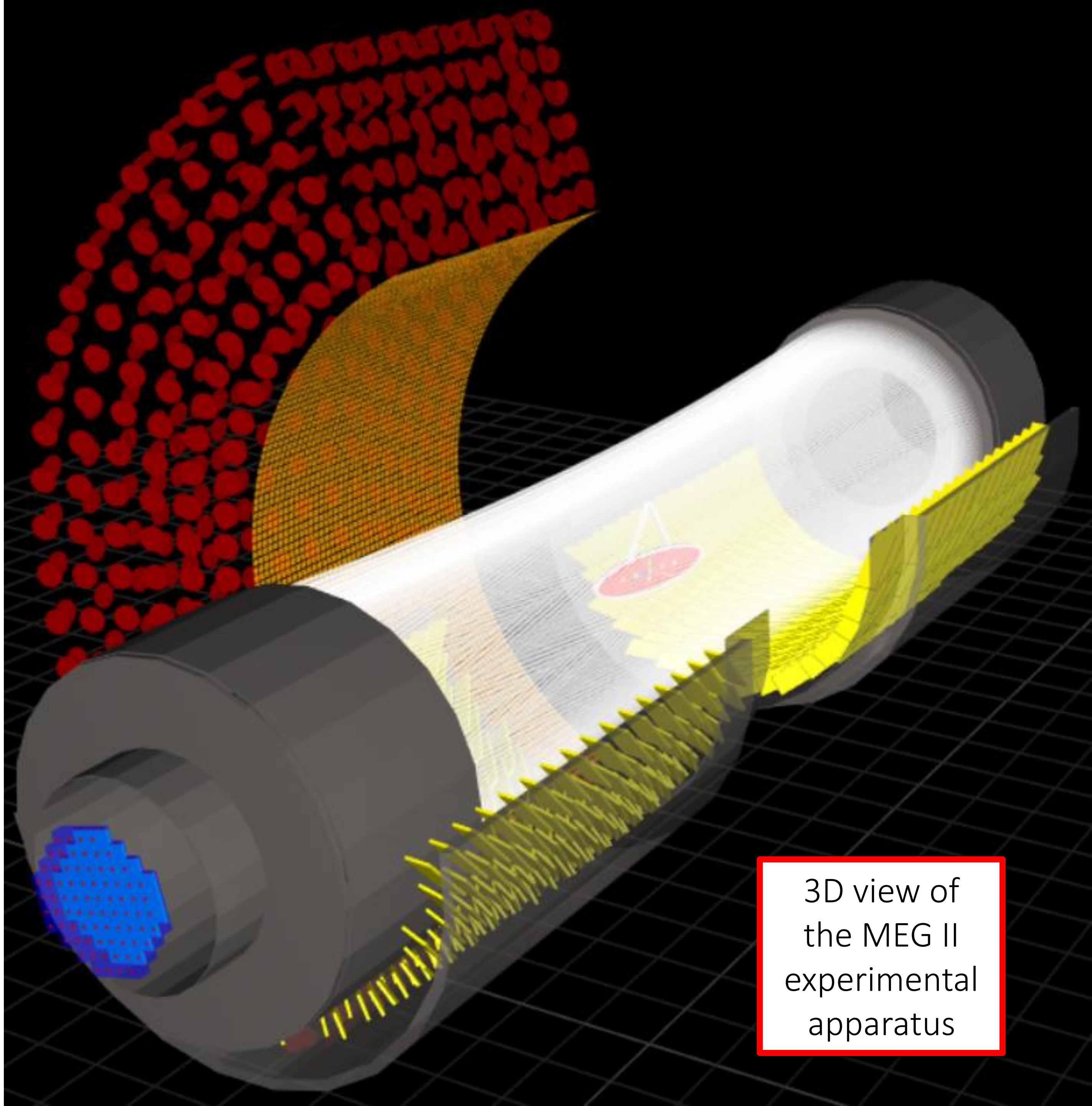
Outline

- ➢ Introduction to MEG II experiment
- ➢ Construction and Commissioning of the MEG II Cylindrical Drift CHamber (CDCH)
  - Performance and new design concept
  - Mechanics and electronics
  - Final working point
  - Integration into the experimental apparatus
  - Investigations on wire breakages
  - Investigations on anomalous currents
  - Conditioning with beam
- ➢ Physics data taking and measured performance
- ➢ Conclusions and prospects



3D view of the MEG II experimental apparatus

Introduction to the MEG II experiment

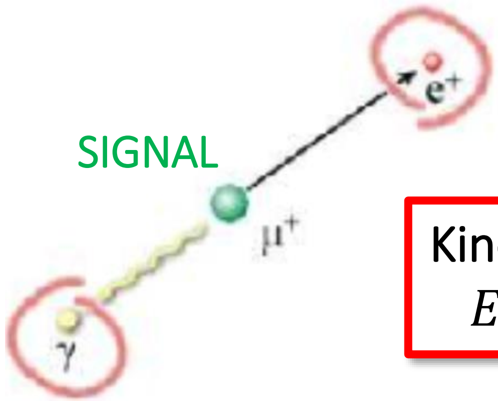
The $\mu^+ \rightarrow e^+\gamma$ decay

[European Physics Journal C (2016) 76:434]

- Lepton Flavour Violation (LFV) processes experimentally observed for neutral leptons
  - Neutrino oscillations $\nu_l \rightarrow \nu_{l'}$
- LFV for charged leptons (CLFV): $l \rightarrow l'$???
- If found → definitive evidence of New Physics

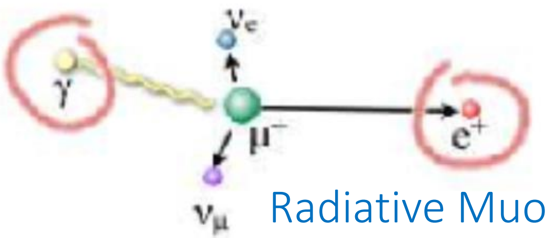
- In this context the MEG experiment represents the state of the art in the search for the CLFV $\mu^+ \rightarrow e^+\gamma$ decay
  - **Final results** exploiting the **full statistics** collected during the 2009-2013 data taking period at **Paul Scherrer Institut** (PSI, Switzerland)
  - $BR(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$ (90% C. L.) **world best upper limit**

SIGNAL



Kinematic variables
$E_e, E_\gamma, t_{e\gamma}, \theta_{e\gamma}$

- 28 MeV/c μ^+ continuous beam stopped in a 174 μm-thick BC400 target (15° slant angle)
- Most intense DC muon beam in the world at PSI: $R_\mu \approx 10^8$ Hz
- μ^+ decay at rest: 2-body kinematics
- $E_\gamma = E_e = 52.8$ MeV
- $\theta_{e\gamma} = 180°$
- $t_{e\gamma} = 0$ s



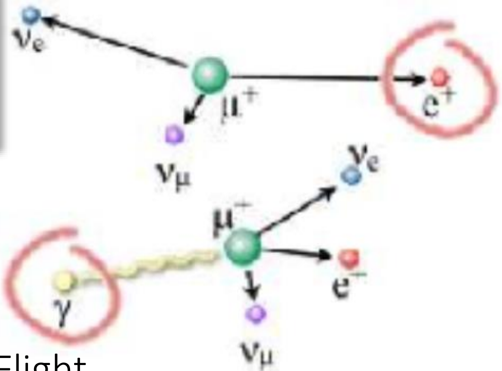
Radiative Muon Decay (RMD)

- $E_\gamma < 52.8$ MeV
- $E_e < 52.8$ MeV
- $\theta_{e\gamma} < 180°$
- $t_{e\gamma} = 0$ s

Standard μ decay
≡
[Michel decay]

BACKGROUNDS

From RMD, Annihilation-In-Flight or bremsstrahlung



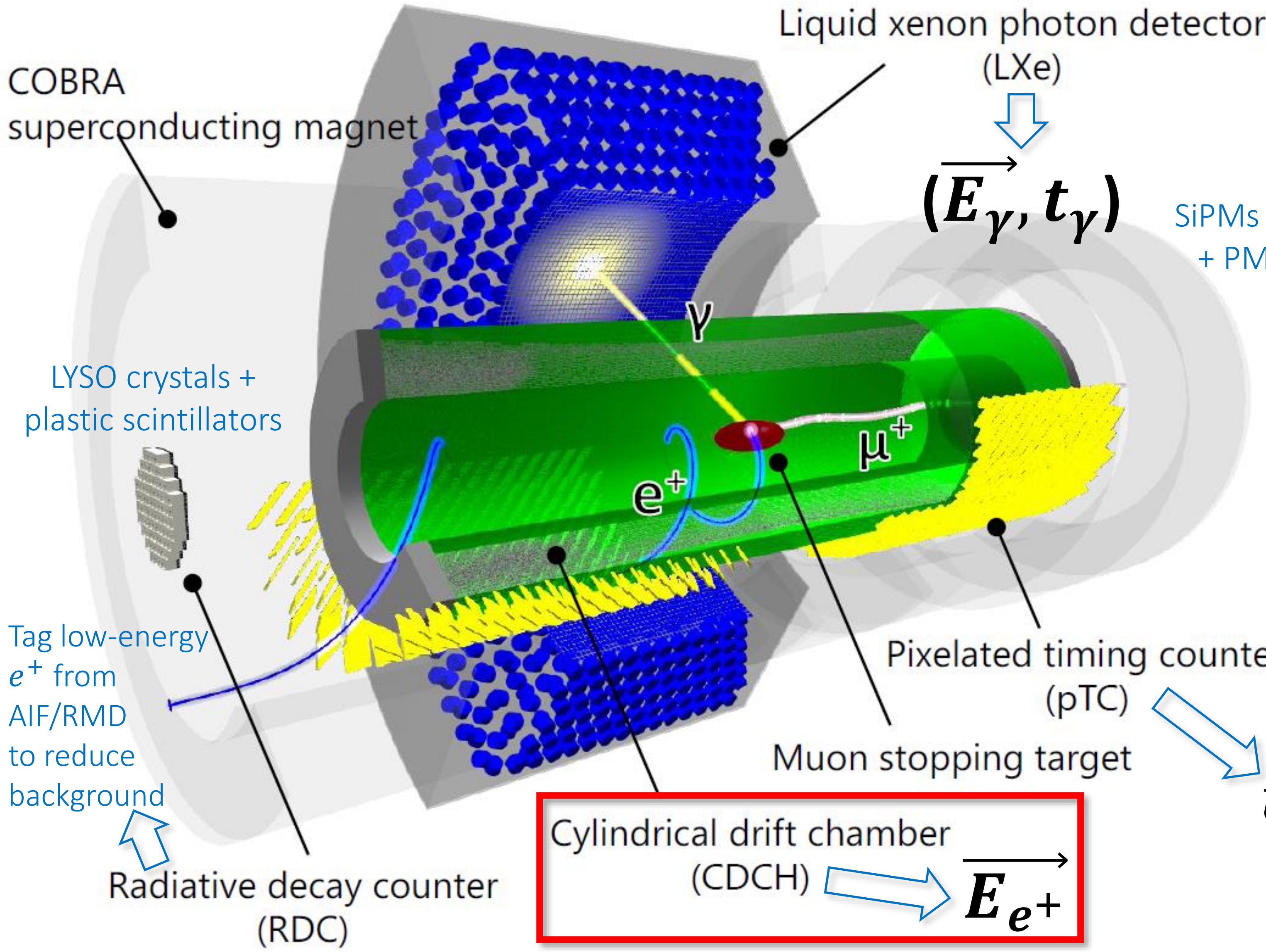
Accidental

- $E_\gamma < 52.8$ MeV
- $E_e < 52.8$ MeV
- $\theta_{e\gamma} < 180°$
- $t_{e\gamma}$ = flat

- $BKG_{ACC} \propto R_\mu \Delta E_e \Delta t_{e\gamma} \Delta E_\gamma^2 \Delta\theta_{e\gamma}^2$ ➜ DOMINANT in high-rate environments
- $BKG_{RMD} \approx 10\% \times BKG_{ACC}$

The MEG II experiment

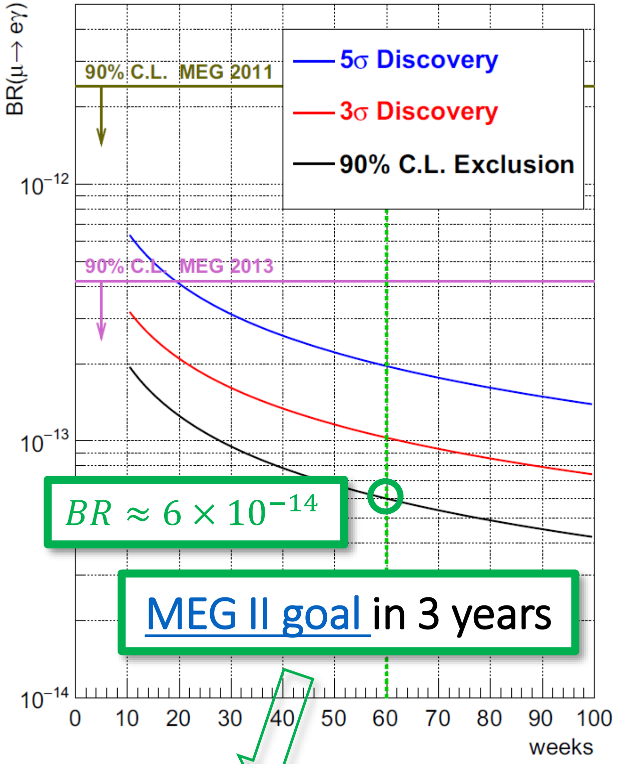
- Full design paper
- Full commissioning paper
- Full operation paper



Cylindrical drift chamber
(CDCH) $\overrightarrow{E_{e^+}}$

t_{e^+}

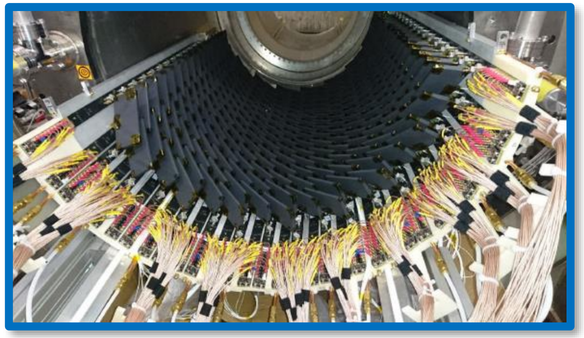
SiPMs on the γ entrance face
+ PMTs on the other faces



$BR \approx 6 \times 10^{-14}$

MEG II goal in 3 years

- Increasing the μ^+ stopping rate
- Improving the detectors figures of merit
  - $\times$ 2 factor than MEG

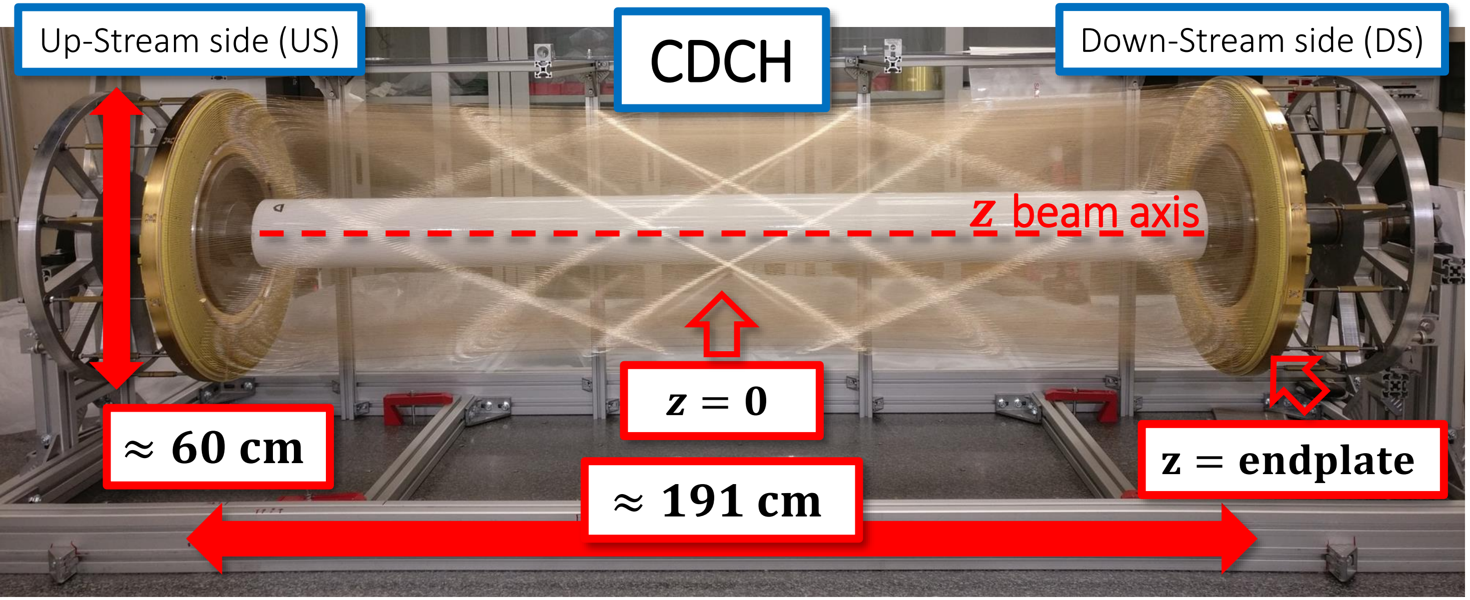


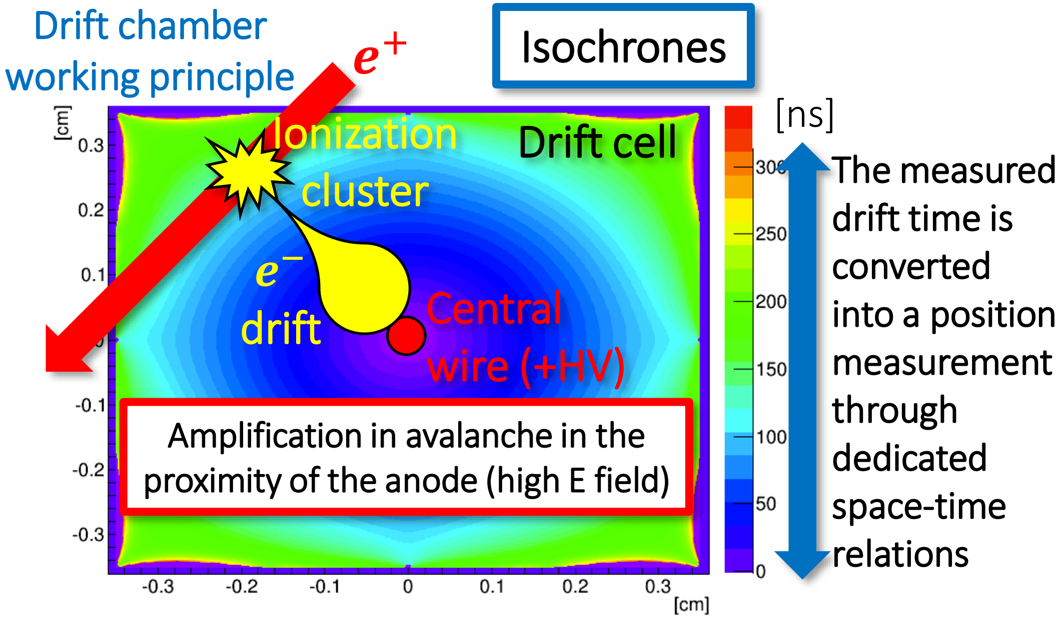
Plastic scintillators tiles read out by SiPMs

The MEG II Cylindrical Drift CHamber (CDCH)

- Design and assembly
- Commissioning

Detector performance



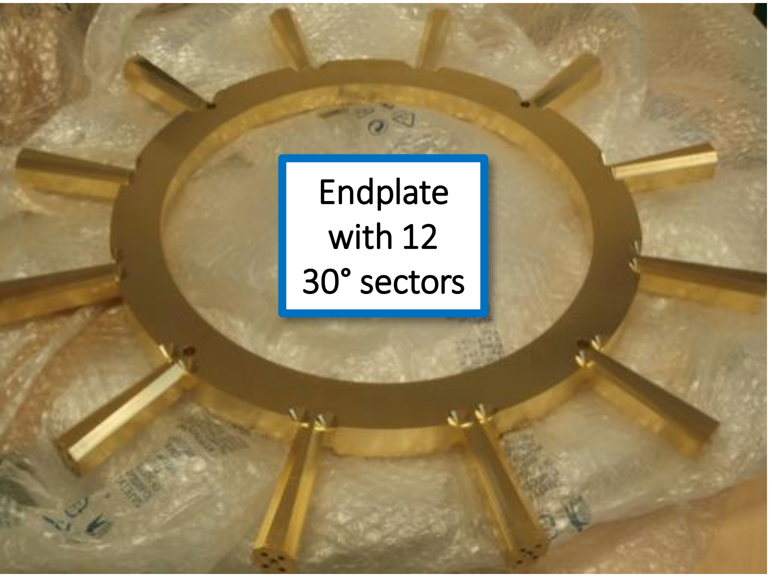


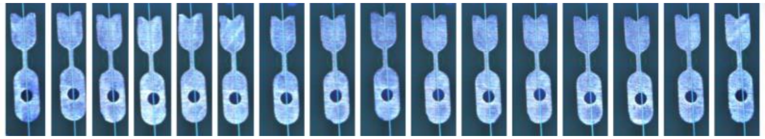
e^+ variable	MEG	MEG II
ΔE_e (keV)	380	91
$\Delta\theta_e, \Delta\varphi_e$ (mrad)	9.4, 8.7	7.2, 4.1
$\Delta Z, \Delta Y$ (at target, mm)	2.4, 1.2	2.0, 0.7
$\varepsilon_{tracking} \times \varepsilon_{TC-match}$ (%)	65 × 45	74 × 91

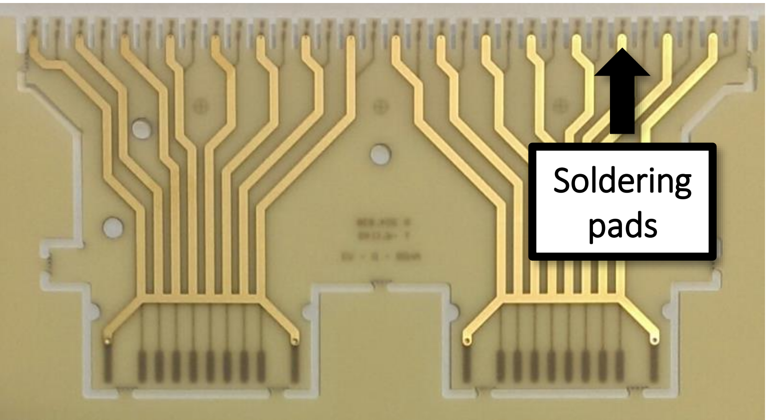
- Currently most updated reconstruction algorithms on real data
- Practically at the MC level

- Low-mass single volume detector with high granularity filled with He:iC_4H_{10} 90:10 gas mixture
  - + additives to improve the operational stability: 1.5% isopropyl alcohol + 0.5% Oxygen
  - 9 concentric layers of 192 drift cells defined by 11904 wires
  - Small cells few mm wide: occupancy of ≈1.5 MHz/cell (center) near the stopping target
  - High density of sensitive elements: ×4 hits more than MEG drift chamber (DCH)
- Total radiation length 1.5×10^{-3} X_0: less than 2×10^{-3} X_0 of MEG DCH or ≈150 μm of Silicon
  - MCS minimization and γ background reduction (bremsstrahlung and Annihilation-In-Flight)
- Single-hit resolution (measured on prototypes): $\sigma_{hit} < 120$ μm
- Extremely high wires density (12 wires/cm²) → the classical technique with wires anchored to endplates with feedthroughs is hard to implement
  - CDCH is the first drift chamber ever designed and built in a modular way

Design and wiring

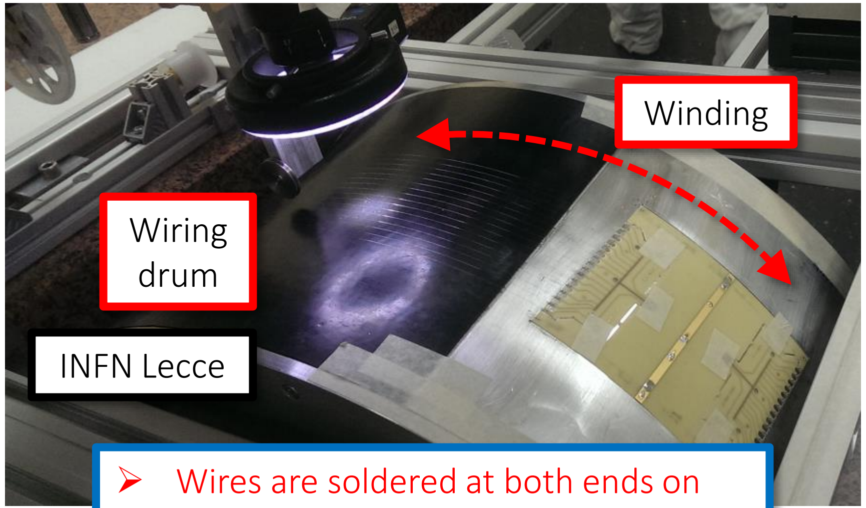




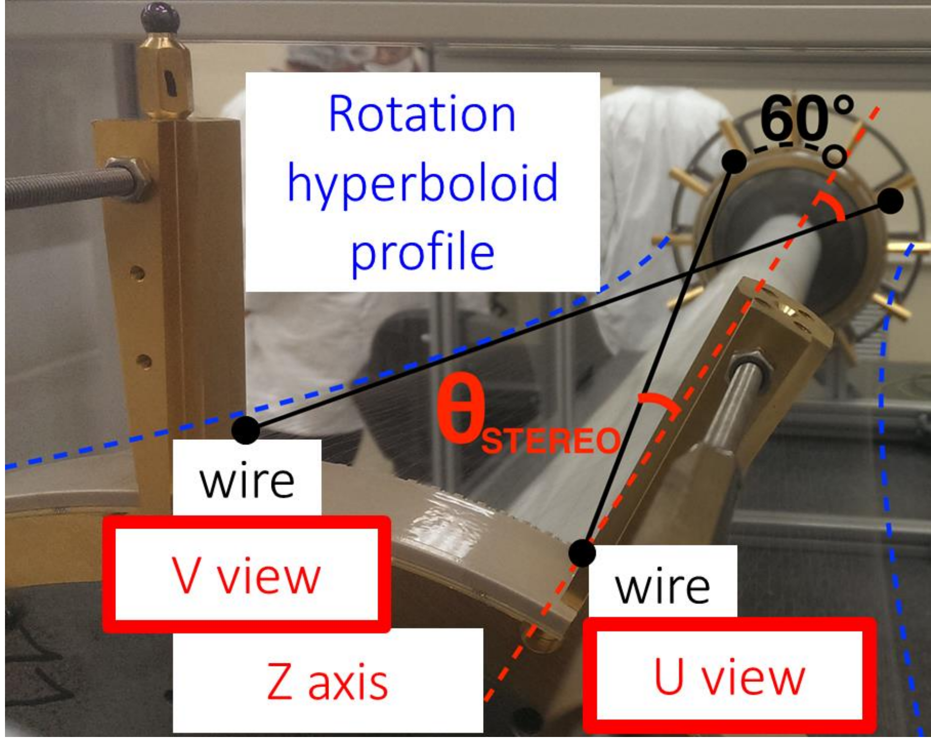


Stereo wires geometry for longitudinal hit localization

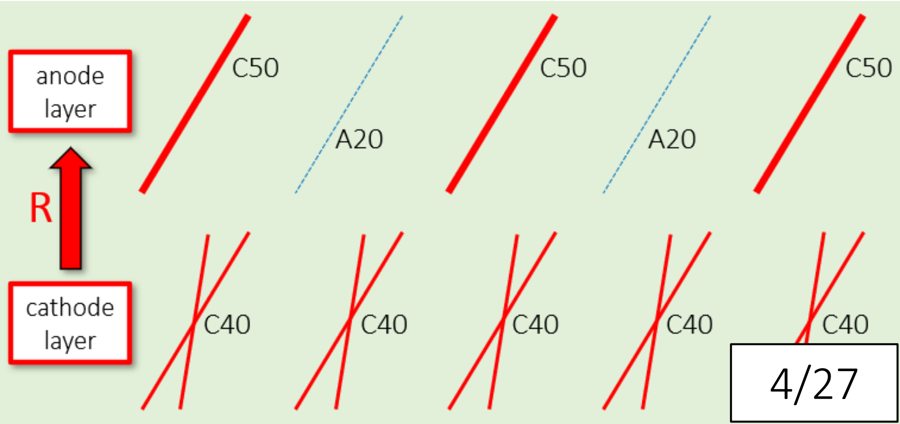
- $\theta_{stereo} \approx 6° \div 8.5°$ as R increases



- Wires are soldered at both ends on the pads of 2 PCBs (wire-PCBs) which are then mounted on CDCH endplates
- Wiring inside a cleanroom

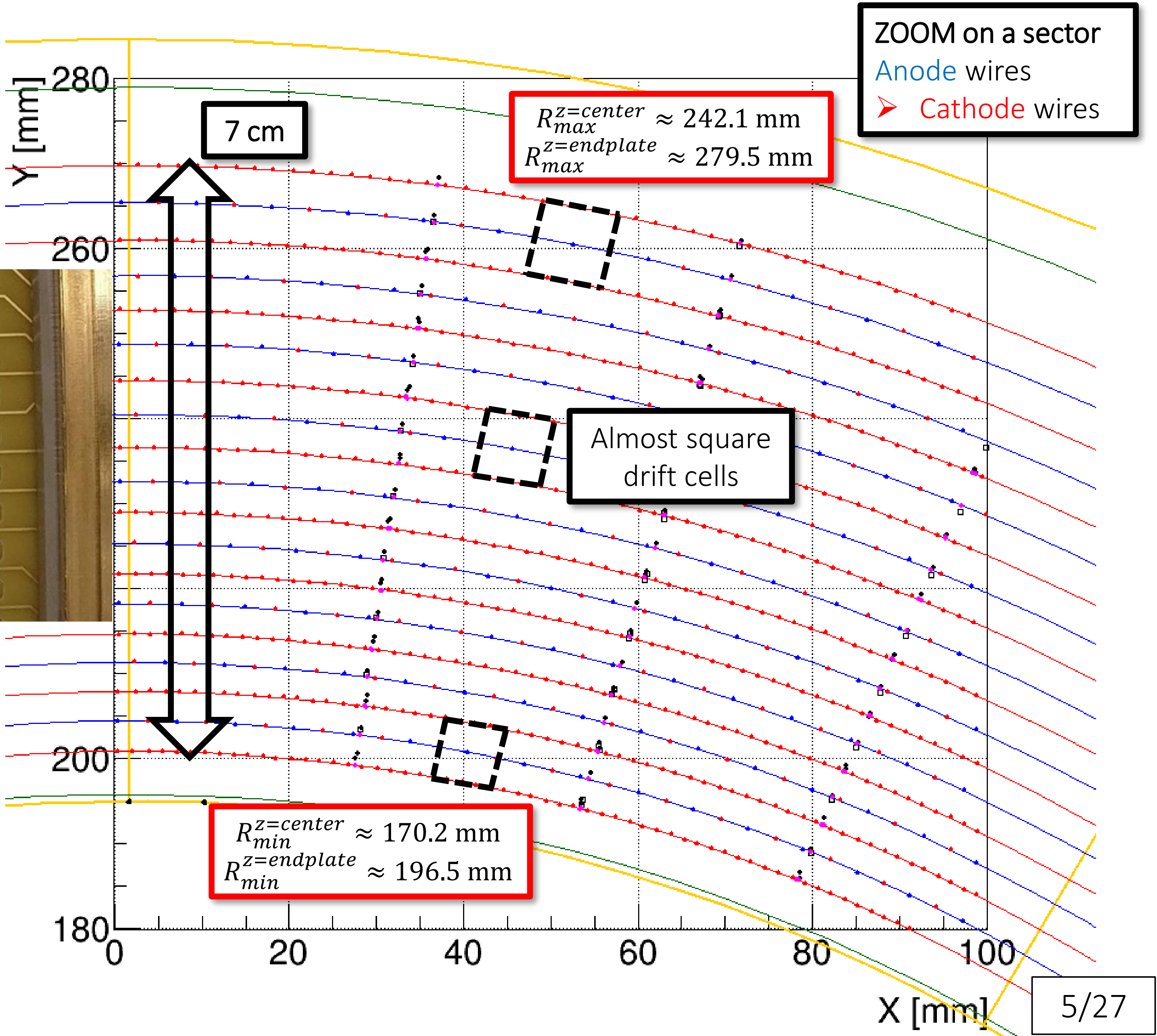


- Anode wires: 20 μm Au-plated W
- Cathode wires: 40/50 μm Ag-plated Al
  - 40 μm ground mesh between layers
- Guard wires: 50 μm Ag-plated Al
- Field-to-Sense wire ratio 5:1



Stereo geometry

Radial perspective

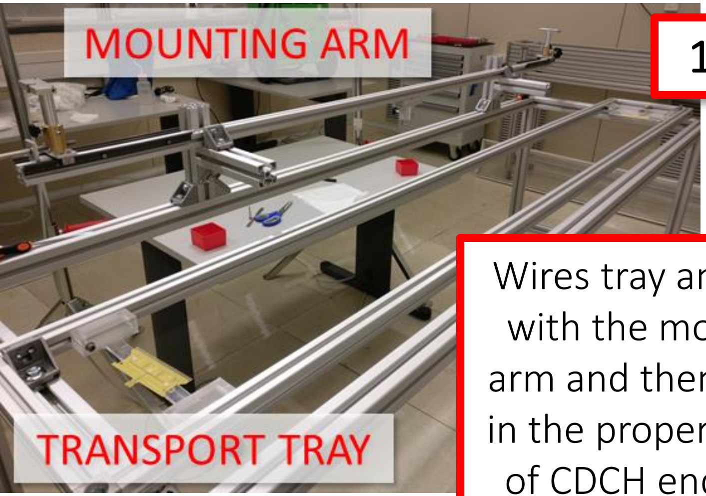


Cell width increases with R and |z|

- Cell width (z=endplate): ≈6.7÷8.7 mm
- Cell width (z=center): ≈5.8÷7.5 mm

Modular assembly

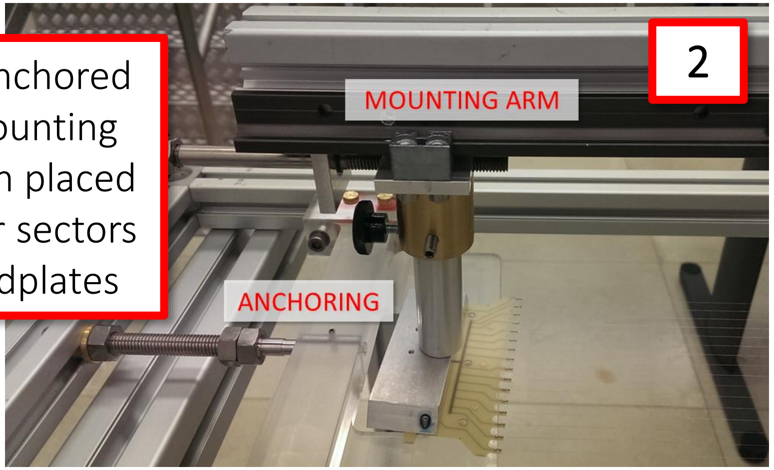
San Piero a Grado (INFN Pisa) cleanroom facility



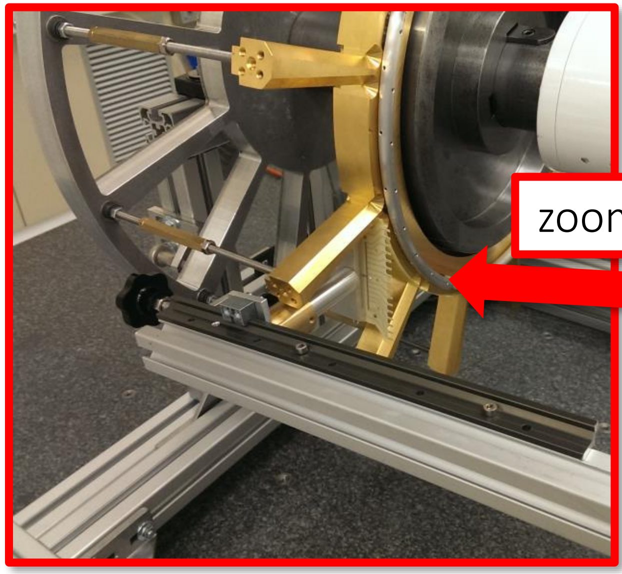
1

This operation is repeated for the 12 sectors in one layer and for all the wires layer

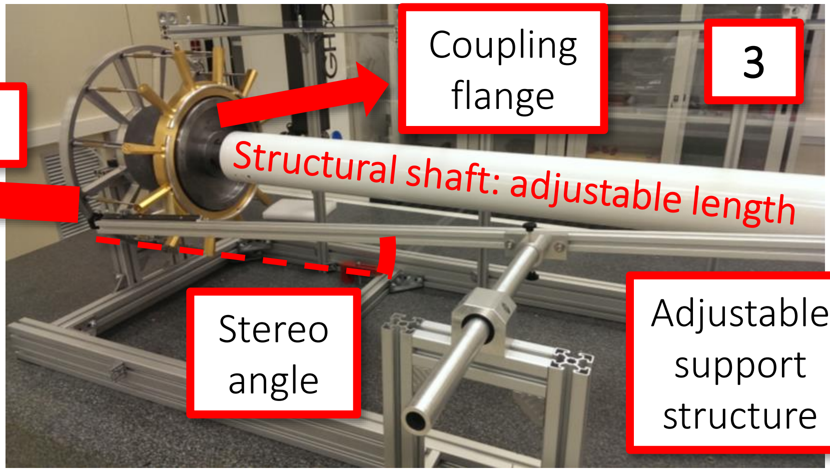
Wires tray anchored with the mounting arm and then placed in the proper sectors of CDCH endplates



2



zoom



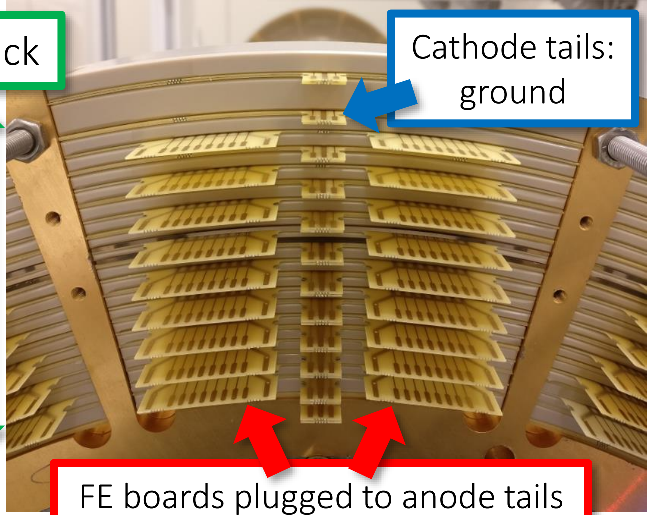
Coupling flange

3

Stereo angle

Adjustable support structure

Final wire-PCBs stack



Cathode tails: ground

FE boards plugged to anode tails (HV + signals)

PEEK spacers to mount the PCB at the correct radius

- Once each wires layer is mounted a geometry survey campaign with a Coordinate Measuring Machine (CMM) is performed to record the mounting position of each wire-PCB ($\approx 20\ \mu m$ accuracy)
- **Thickness of the PEEK spacers adjusted** to minimize the discrepancy from the nominal mounting radius

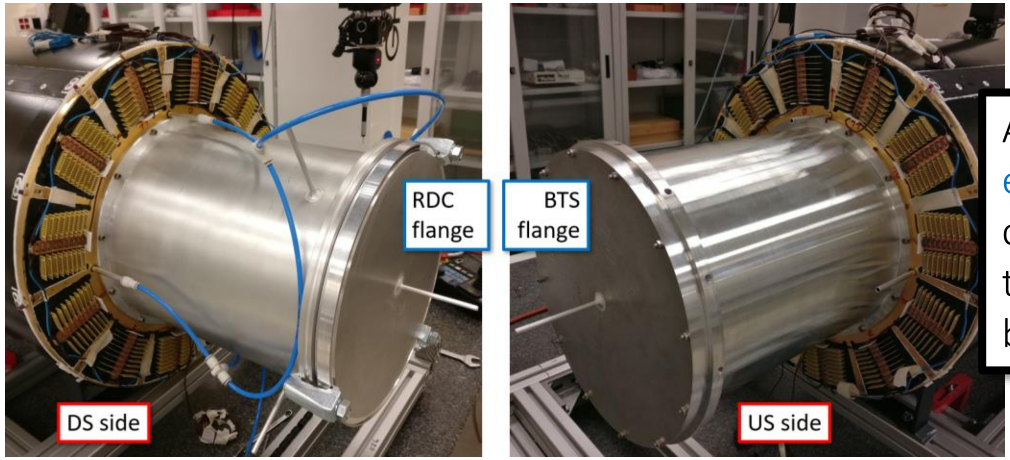
Mechanical structure

Mag (mm)
0.037
-0.010
-0.012
-0.019
-0.007
0.009
0.043
0.017
-0.020
-0.007
-0.013
-0.018

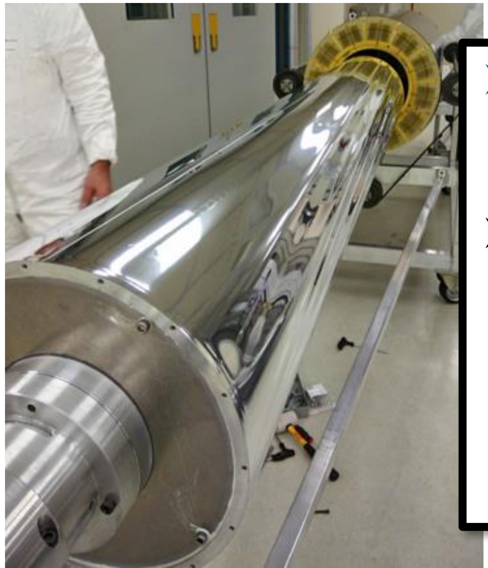
Endplate planarity check
in the DAQ configuration

US DS

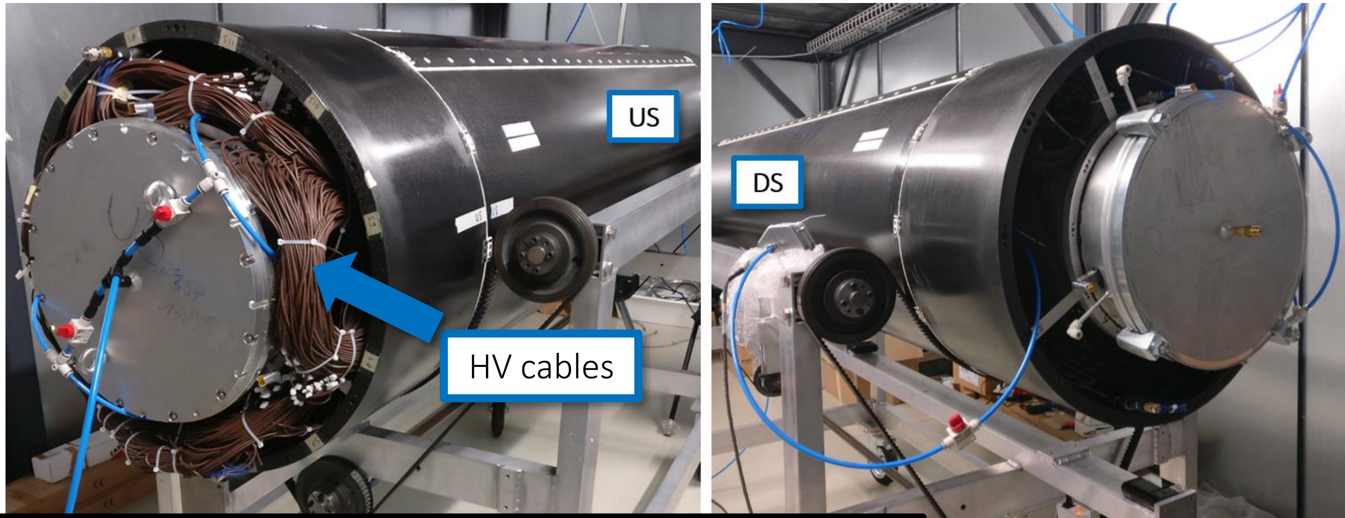
Mag (mm)
0.007
-0.000
-0.011
0.009
0.001
-0.004
-0.001
-0.003
0.005
-0.010
0.003
0.005



Aluminum inner extensions to connect CDCH to the MEG II beam line



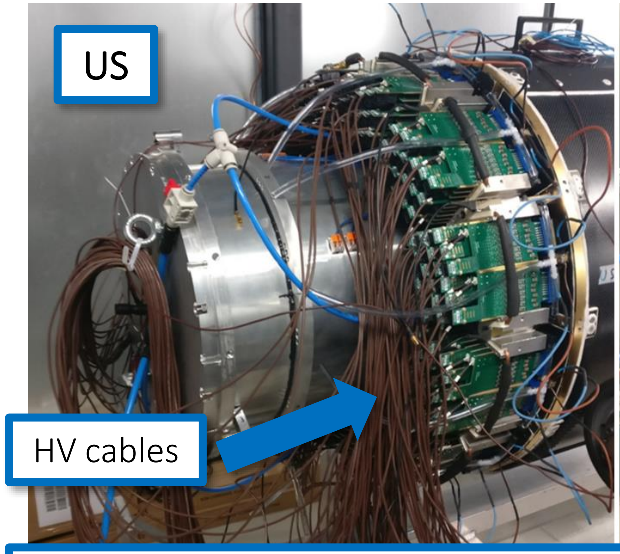
- 20 μm-thick one-side aluminized Mylar foil at inner radius
- To separate the inner beam + target volume filled with pure He from the wires volume filled with He:IsoB 90:10 mixture

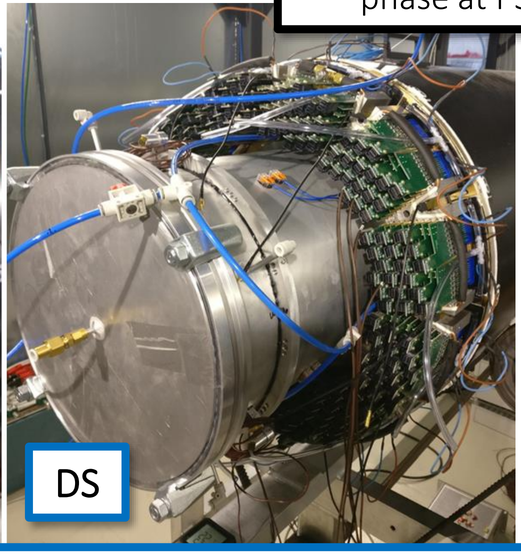


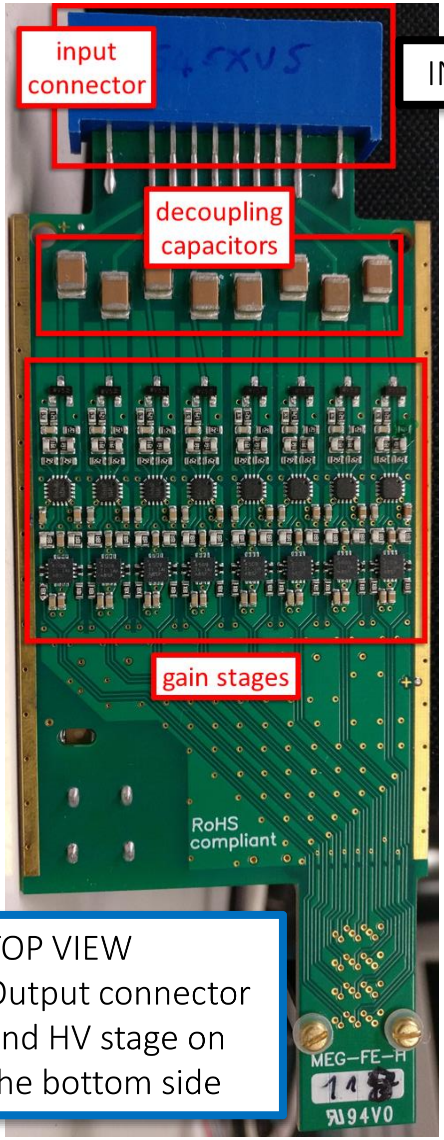
- External CF structure
    - Structural + gas tightness function
- CDCH mechanics proved to be stable (at μm level) and adequate to sustain a full MEG II run

FE electronics

Some pictures from the commissioning phase at PSI

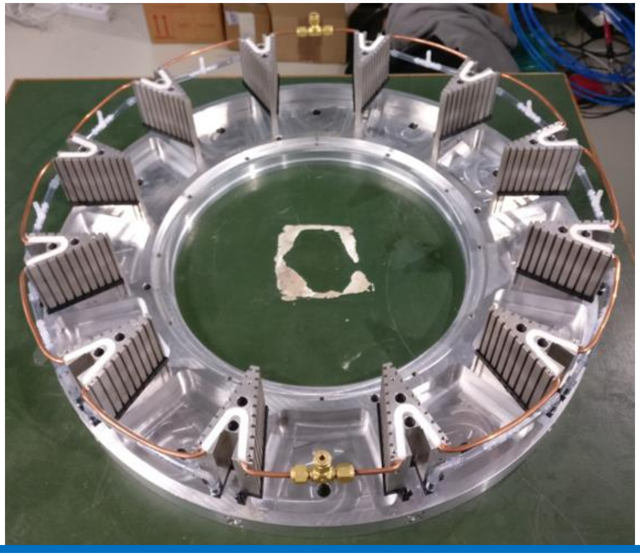




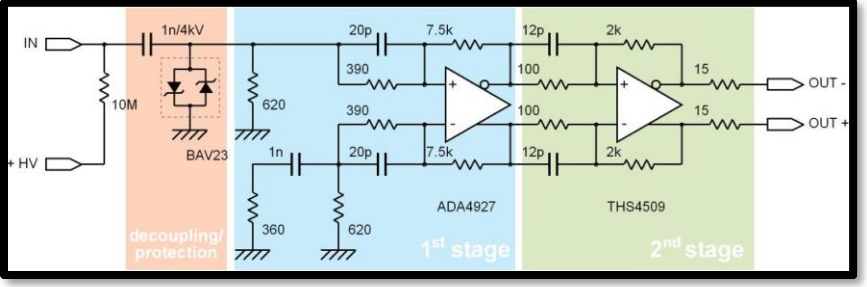


- ➢ TOP VIEW
- ➢ Output connector and HV stage on the bottom side

Several T and RH sensors are placed inside the endcaps for monitoring

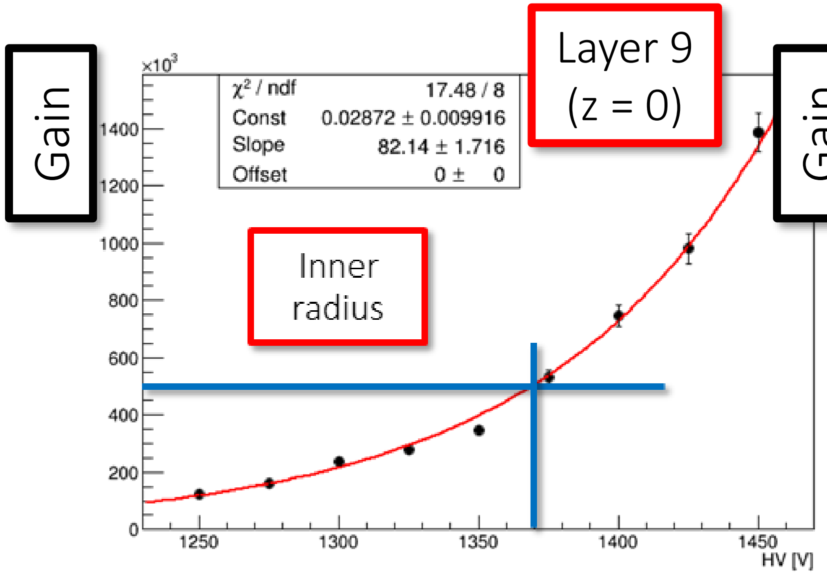


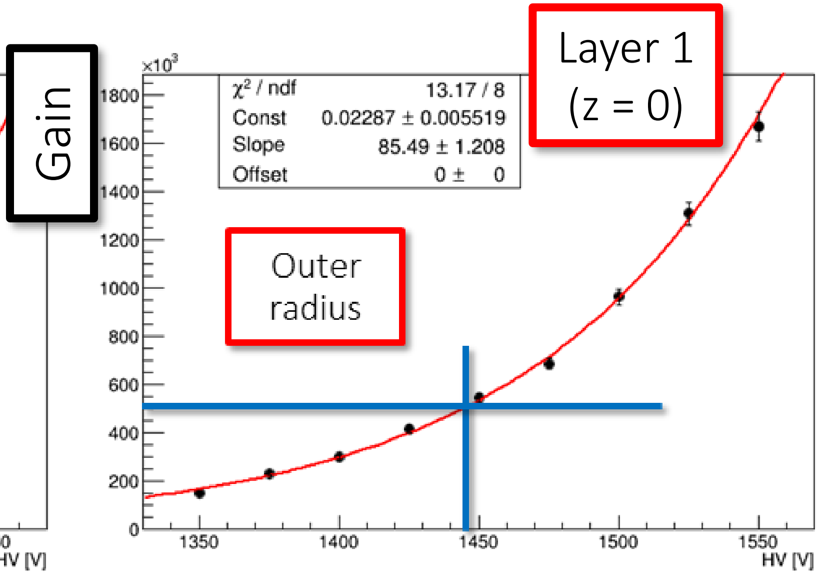
- ➢ 216 FE boards per side
  - 8 differential channels to read out signal from 8 cells
  - Double amplification stage with low noise and distortion
  - High bandwidth of nearly 400 MHz
    - o To be sensitive to the single ionization cluster and improve the drift distance measurement (cluster timing technique)
- ➢ Signal read out from both CDCH sides
- ➢ HV supplied from the US side



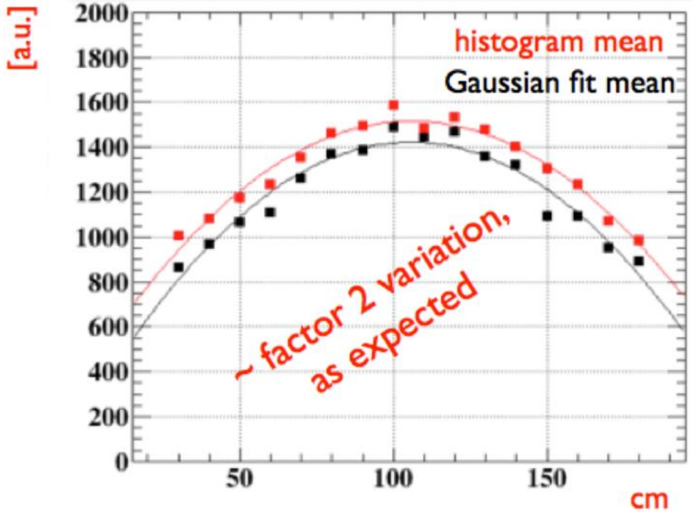
- ➢ FE electronics cooling system embedded in the board holders
  - Power consumption for each channel: 40 mA at 2.2 V
  - Heat dissipation capacity granted by a **1 kW chiller system**: 300 W/endplate
- ➢ Dry air flushing inside the endcaps to avoid water condensation on electronics and dangerous temperature gradients

HV working point





Expected **gain variation vs. longitudinal coordinate z** given the CDCH hyperbolic shape



- **Garfield simulations on single electron gain**
  - Gas mixture He:Isobutane 90:10 and P = 970 mbar (typical at PSI)
- Working point → HV for gas gain $G = 5 \times 10^5$
  - To be sensitive to the single ionization cluster

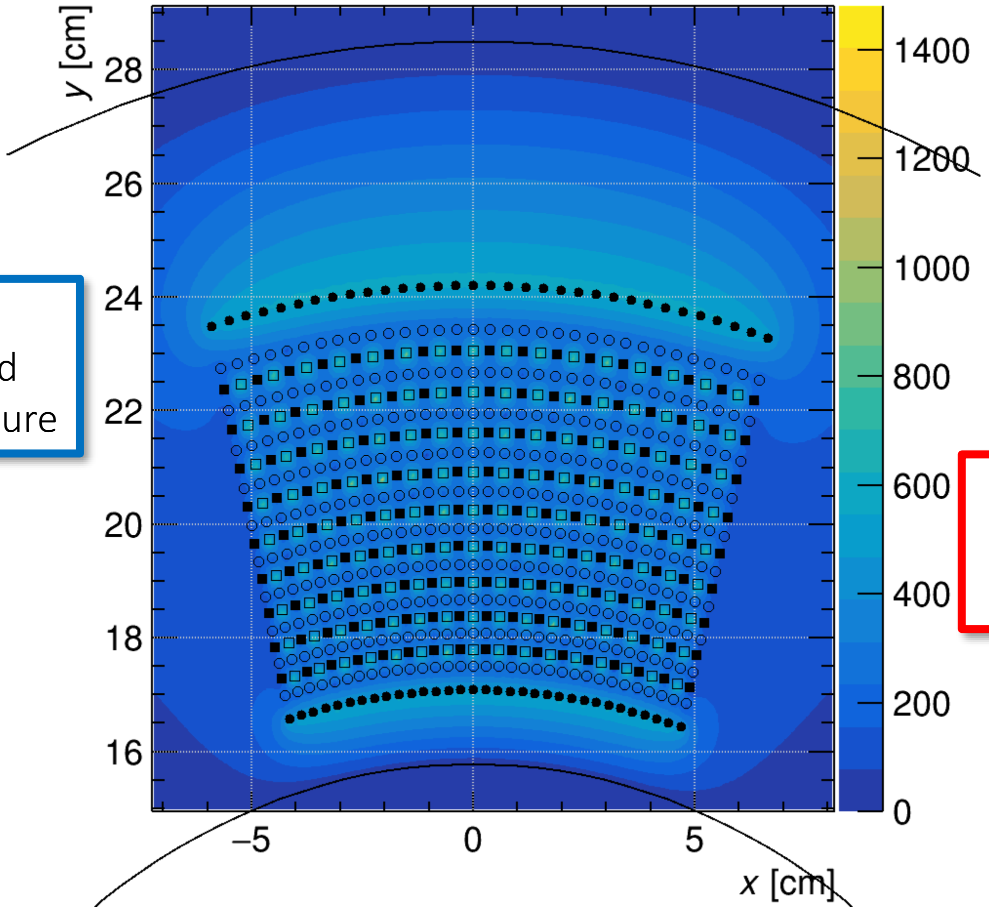
HV tuning by 10 V/layer to compensate for the variable cell dimensions with radius and z

L1	L2	L3	L4	L5	L6	L7	L8	L9
1480 V	1470 V	1460 V	1450 V	1440 V	1430 V	1420 V	1410 V	1400 V
Outer layer								Inner layer

Average HV Working Point (WP) as a function of the layer

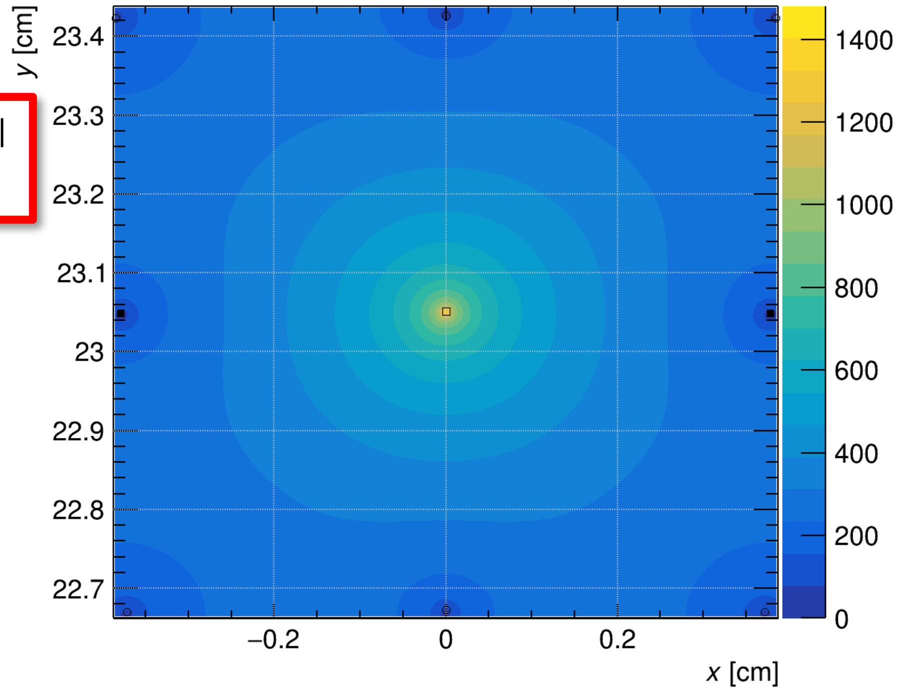
100 V safety margin above the HV WP to recover the gain drop with time

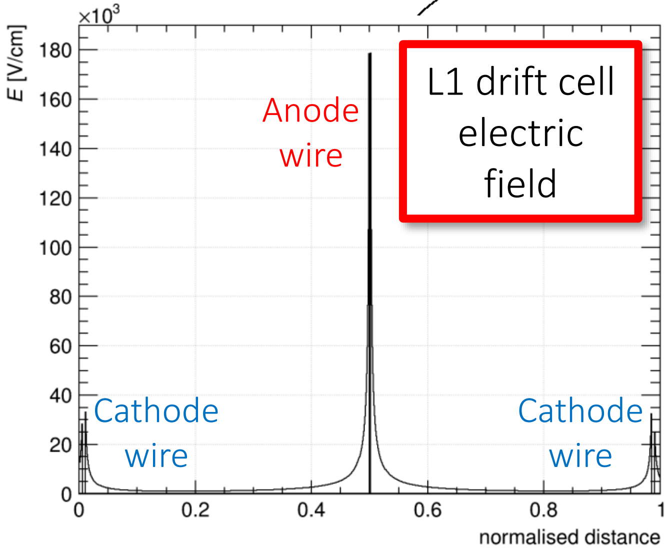
Garfield++
with HV WP and
standard gas mixture

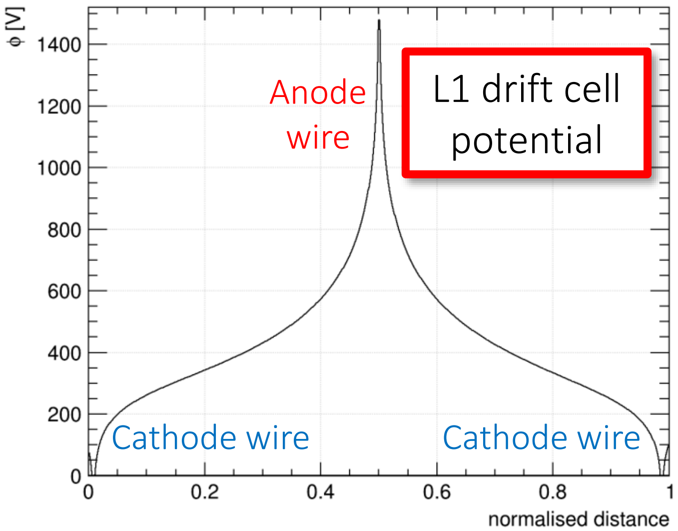


One 30°
sector potential

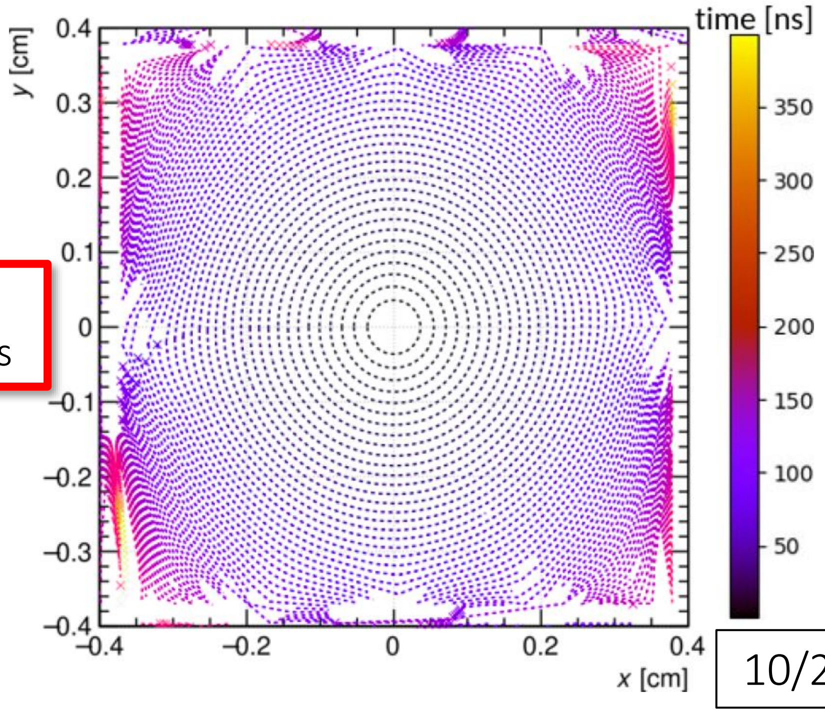
L1 drift cell
potential



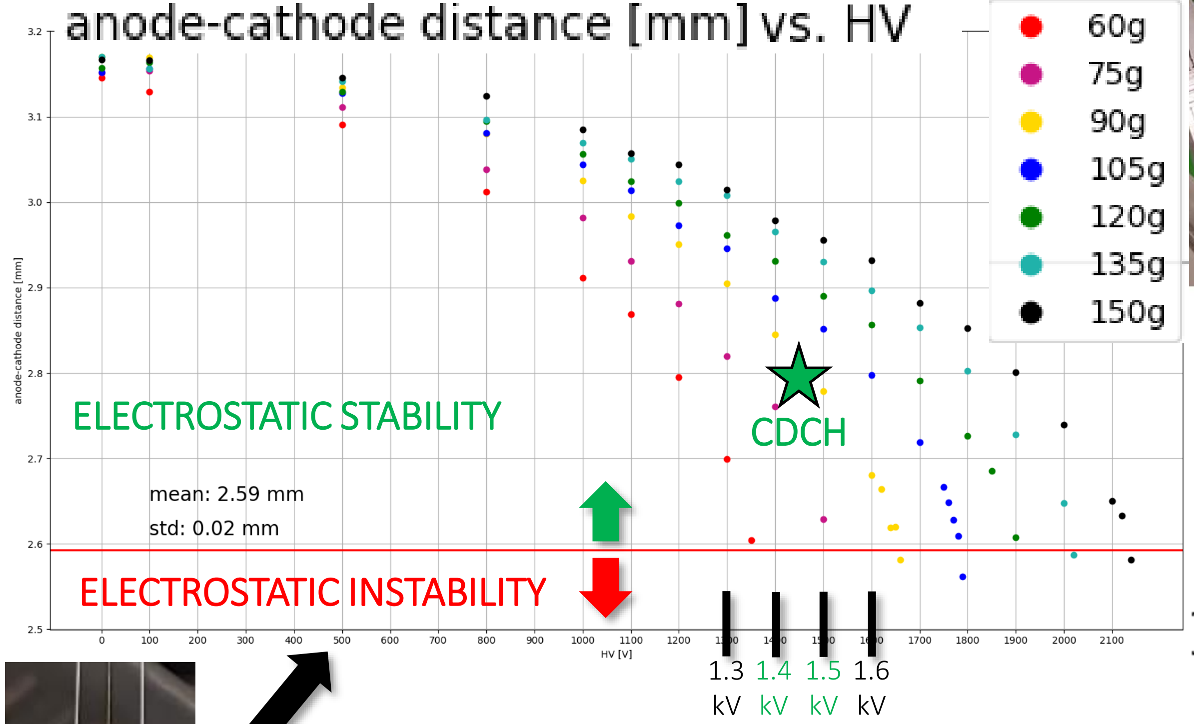


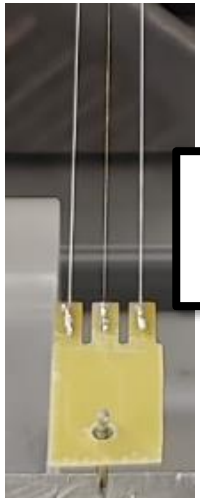


Example
isochrones

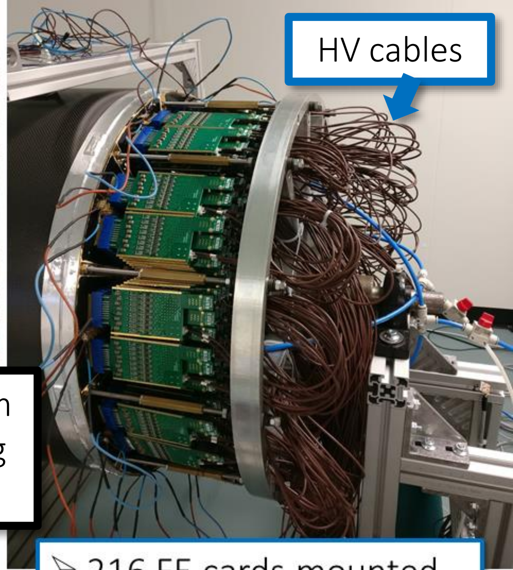


Working length





2 m-long 3-wires prototype in the MEG lab at INFN Pisa

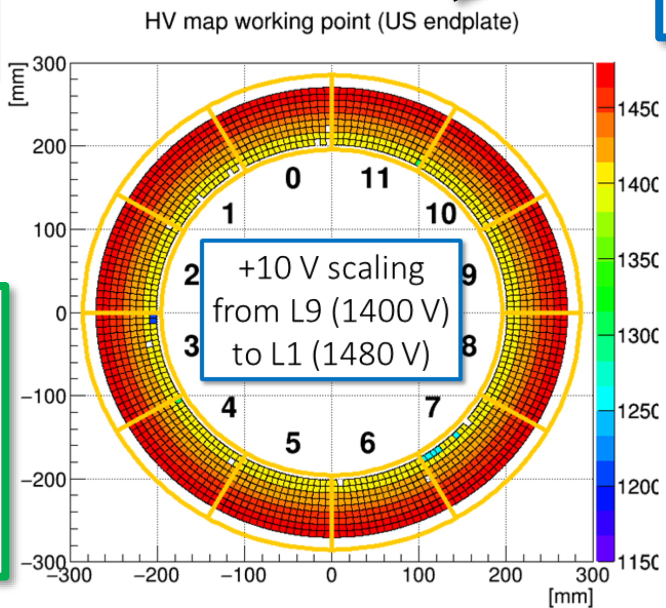


Some pictures from the commissioning phase at PSI

- CDCH temporarily sealed with CF + Al tape
- Nitrogen flux

- 216 FE cards mounted on the US side

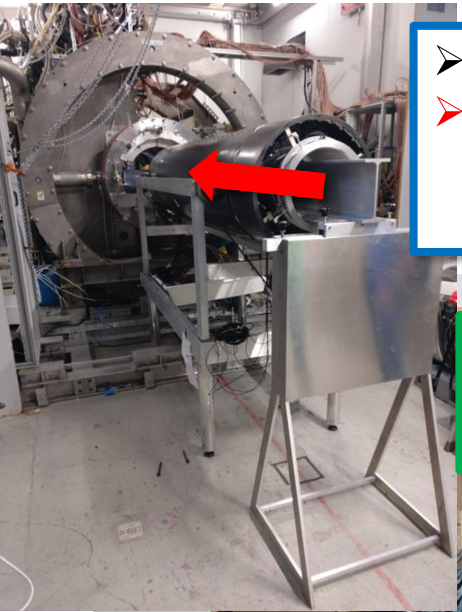
Final CDCH length experimentally found through systematic HV tests at different lengths/wires elongations



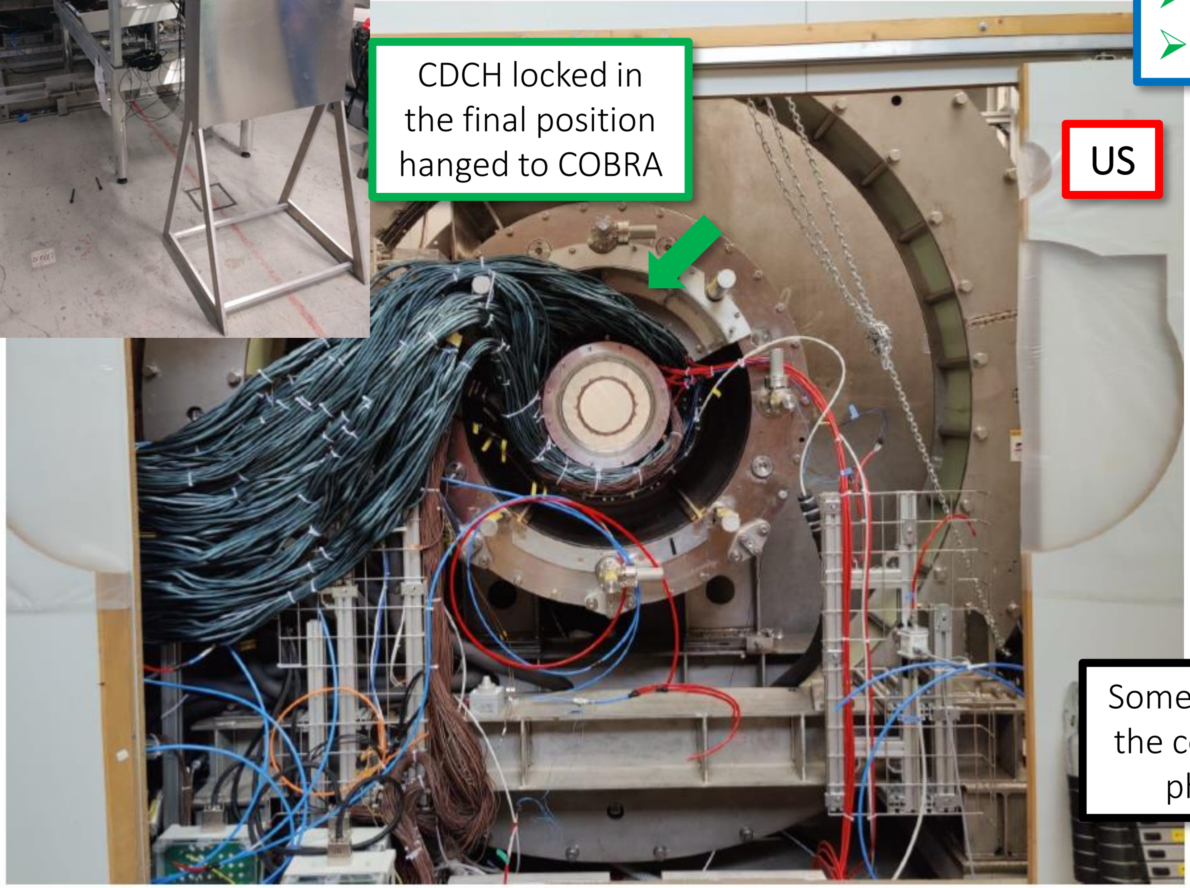
Cell inefficiency experimentally measured
- Negligible in e^+ reconstruction
  - 0.5% worsening in resolutions

- Tests performed in 2019 and 2020 at PSI inside a cleanroom
- CDCH length adjusted through geometry survey campaigns with a laser tracker (20 μm accuracy)
- **Final length set to +5.2 mm of wires elongation**
  - **65% of the elastic limit**

Integration into the MEG II apparatus

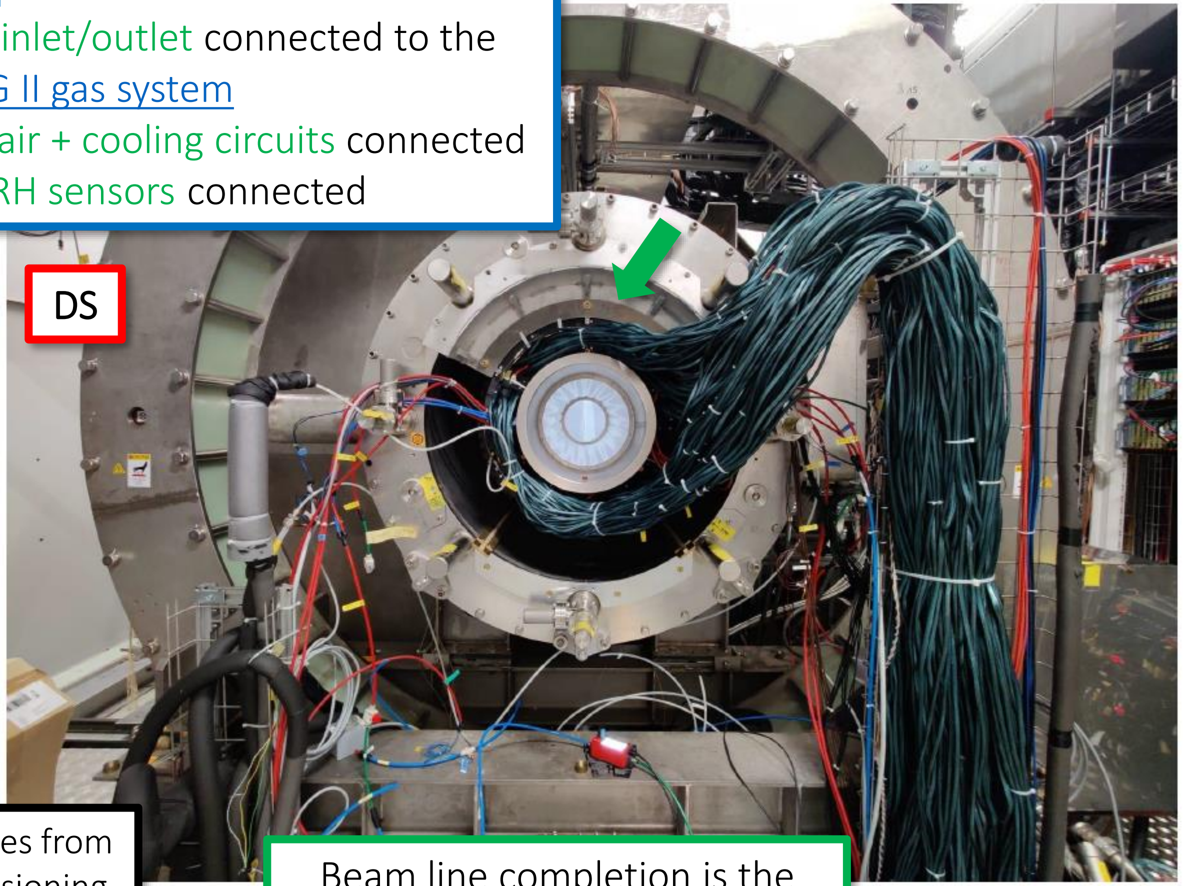


- CDCH inside the experimental area
- Insertion rail through the inner volume to slide CDCH inside the COBRA magnet



CDCH locked in the final position hanged to COBRA

- HV + signal cabling completed for the possible 2π read out
- Gas inlet/outlet connected to the MEG II gas system
- Dry air + cooling circuits connected
- T + RH sensors connected



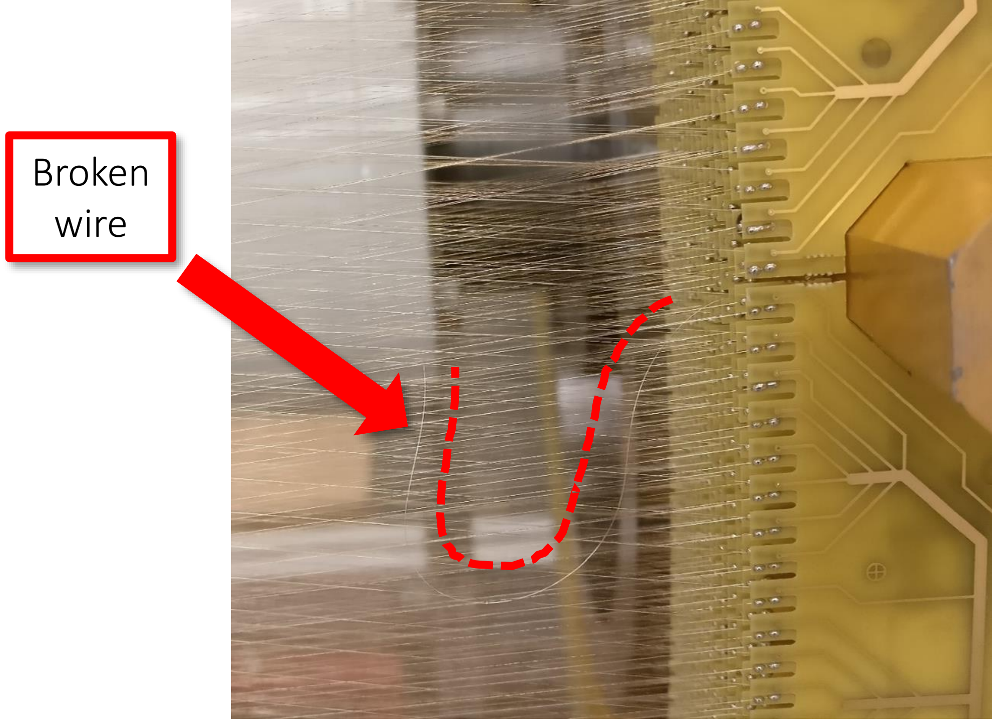
Some pictures from the commissioning phase at PSI

Beam line completion is the last operation (not shown here)

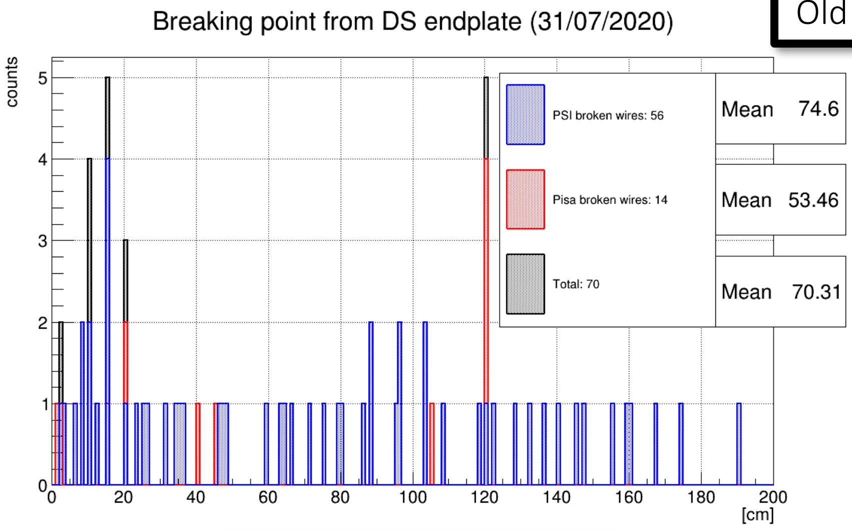
Investigations on wire breakages

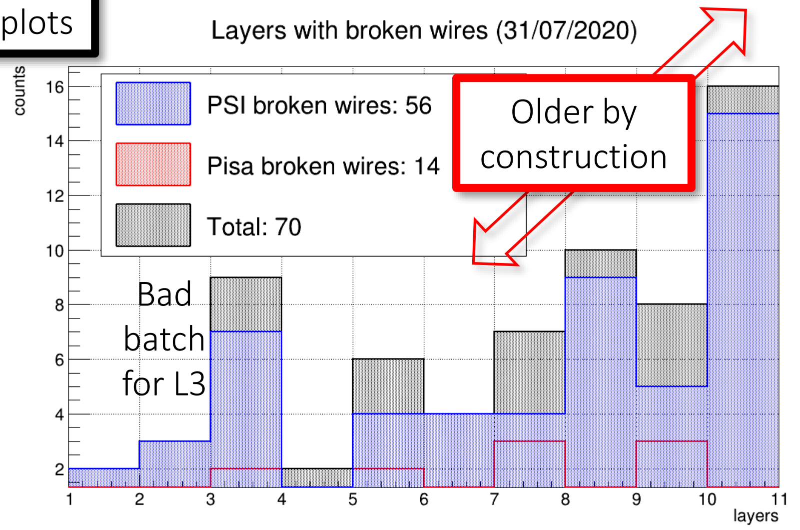
Wire breakages

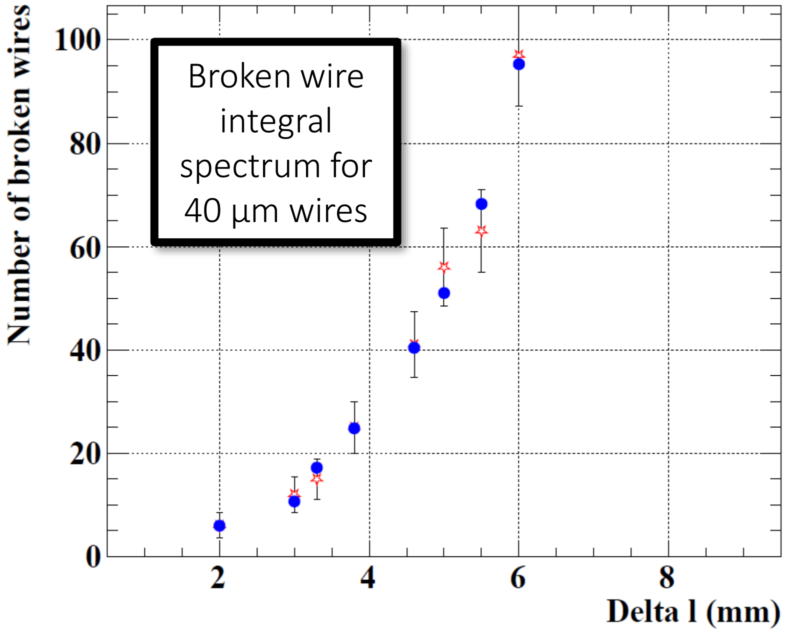
- During assembly at Pisa and the final lengthening operations at PSI we experienced the breaking of aluminum wires in the chamber
  - Mainly the 40 μm cathodes were affected
  - A few 50 μm cathodes and guards
- **107 broken wires in total during CDCH life** (14 at Pisa)
  - 97 broken 40 μm cathodes (90%)
- **Consequent delay in construction and commissioning**
- Studies of the effect of a missing cathode on isochrones returned a negligible impact on e^+ reconstruction (cathode wires redundancy)



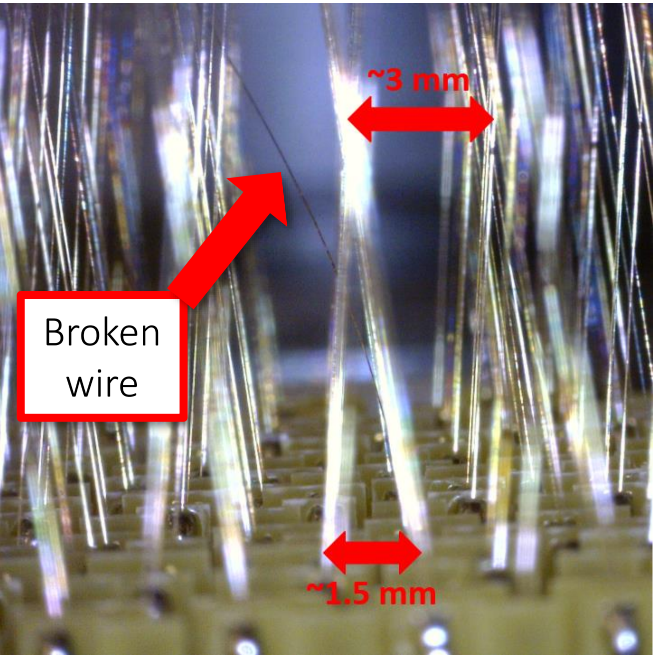
Old plots







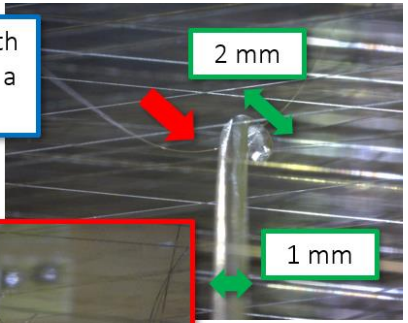
Broken wires extraction



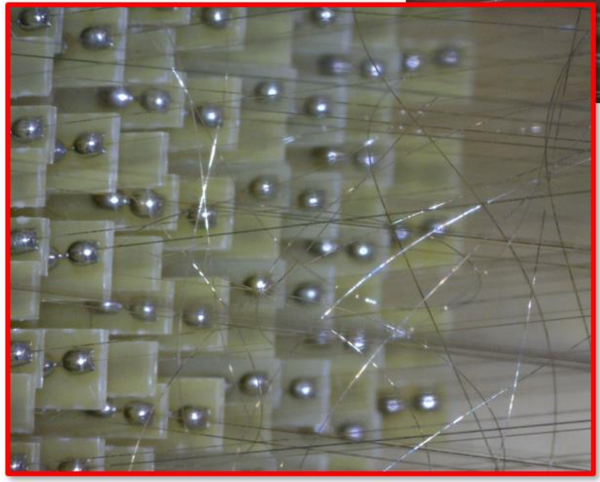
- Each broken wire piece can randomly put to ground big portion of the chamber
- They must be removed from the chamber
  - Very delicate and time-consuming operation
- We developed a safe procedure to extract the broken wires from inside CDCH
  - Exploiting the radial projective geometry given by the stereo wire configuration

Commercial camera mount with precision movements for all axes

Example of extraction with a broken wire hooked by a stainless steel rod

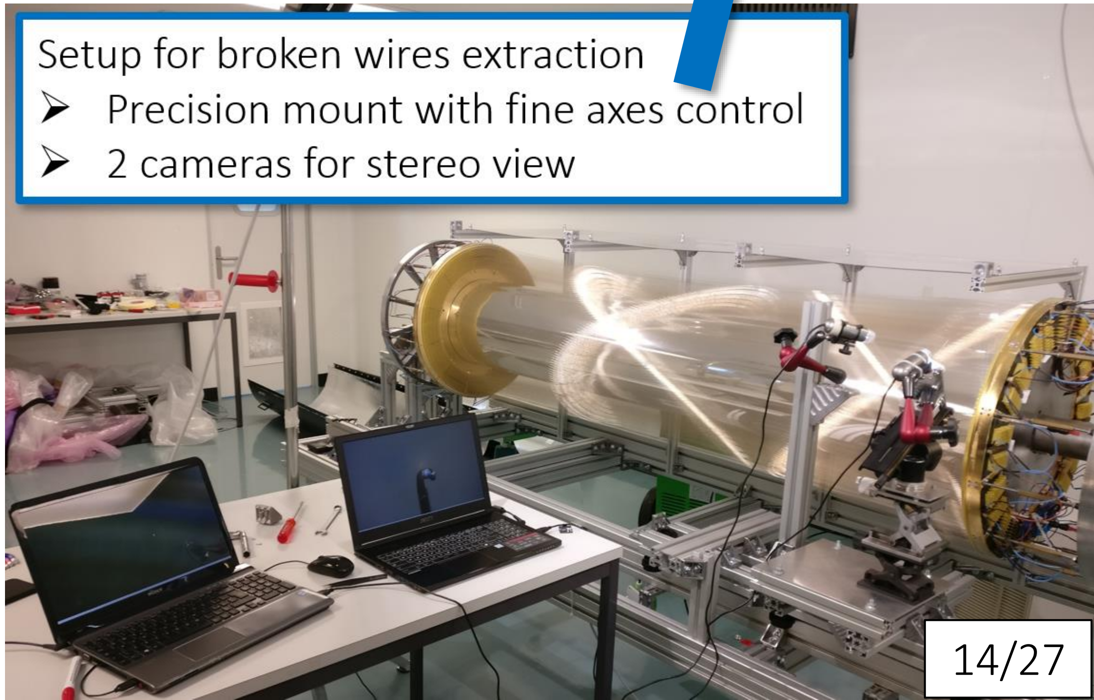


1. Enter with a small tool inside the chamber (few mm space)
2. Hook the wire piece as close as possible to the wire-PCB
3. Extract the wire segment
4. Pull it perpendicularly in the radial direction to break it at the soldering pad

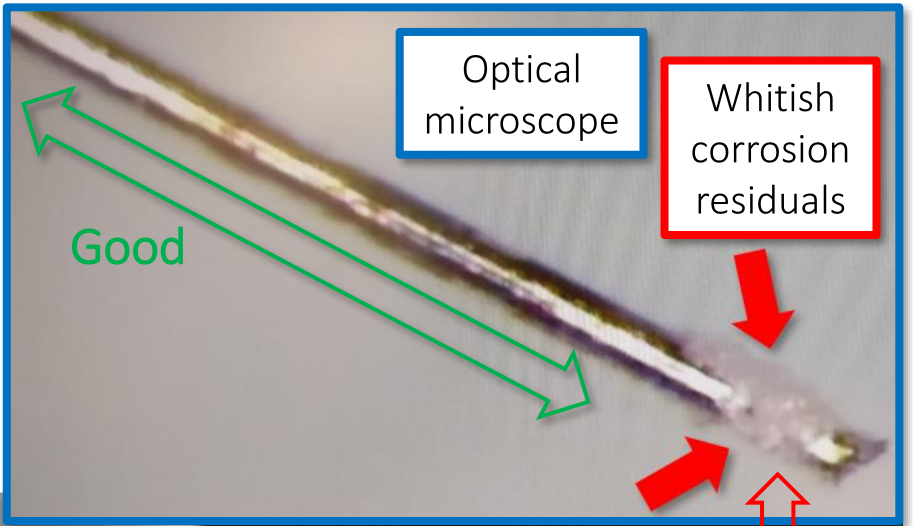


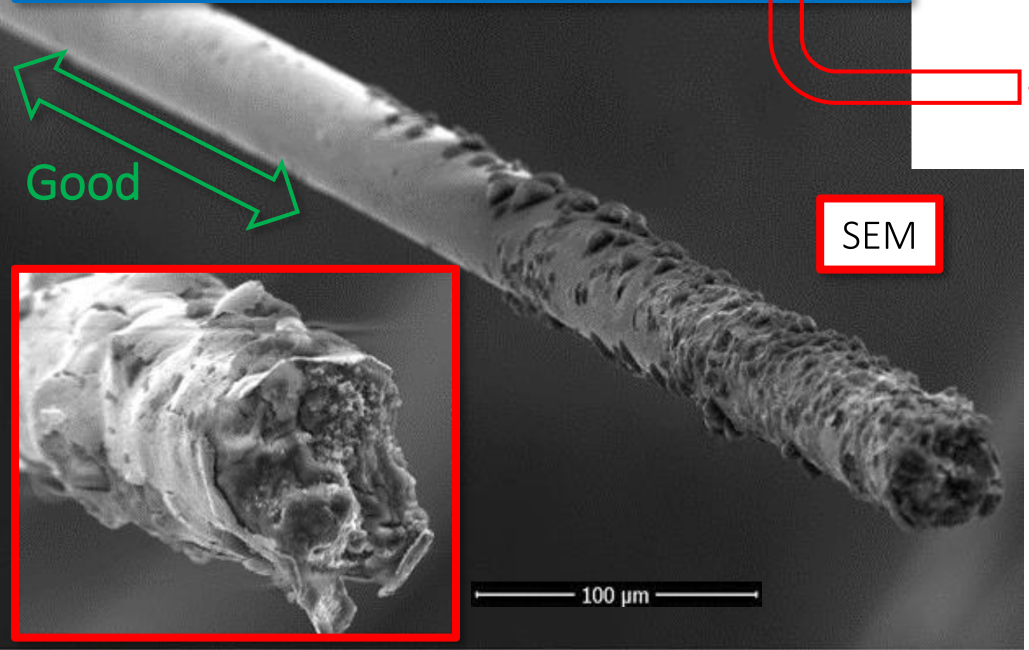
One of the worst case...

Setup for broken wires extraction
- Precision mount with fine axes control
- 2 cameras for stereo view

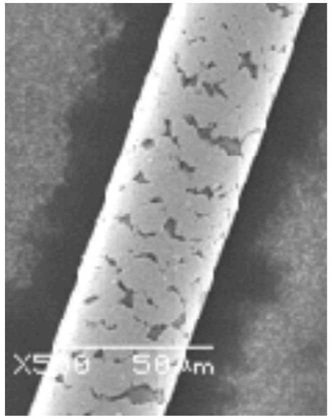


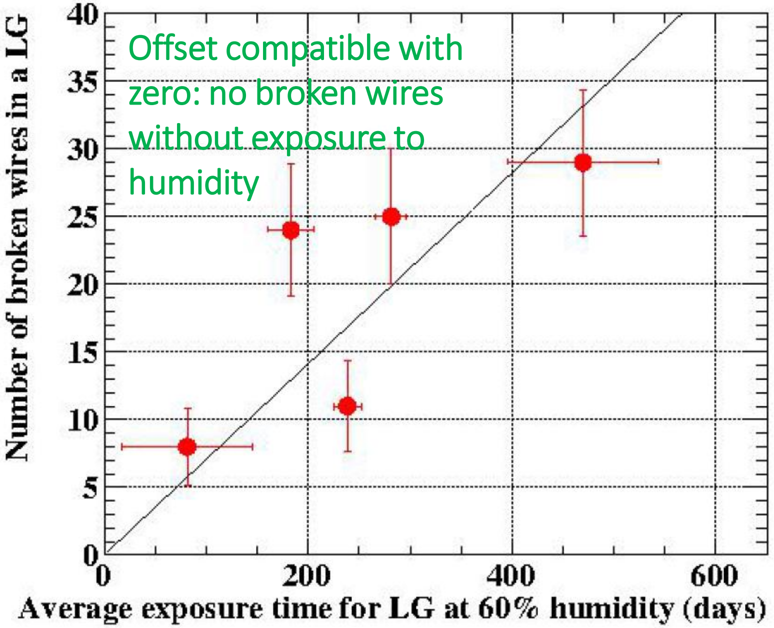
Investigations on wire breakages

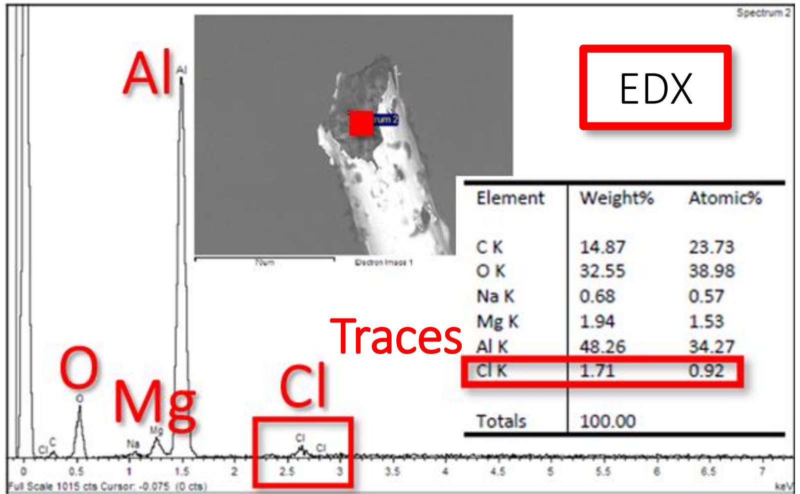




- Breakings due to corrosion of the aluminum wire core
- Two hypotheses
  1. Galvanic process between Al and Ag coating
  2. Al corrosion by Cl
- Both imply water as catalyst
  - Air moisture condensation inside cracks in the Ag coating even at low Relative Humidity (RH) levels $< 40\%$
  - Al oxide or hydroxide deposits





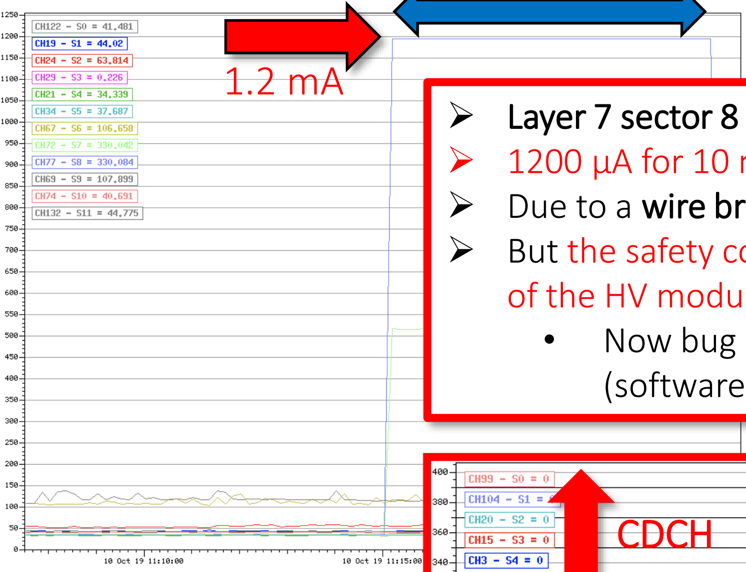


Element	Weight%	Atomic%
C K	14.87	23.73
O K	32.55	38.98
Na K	0.68	0.57
Mg K	1.94	1.53
Al K	48.26	34.27
Cl K	1.71	0.92
Totals	100.00	

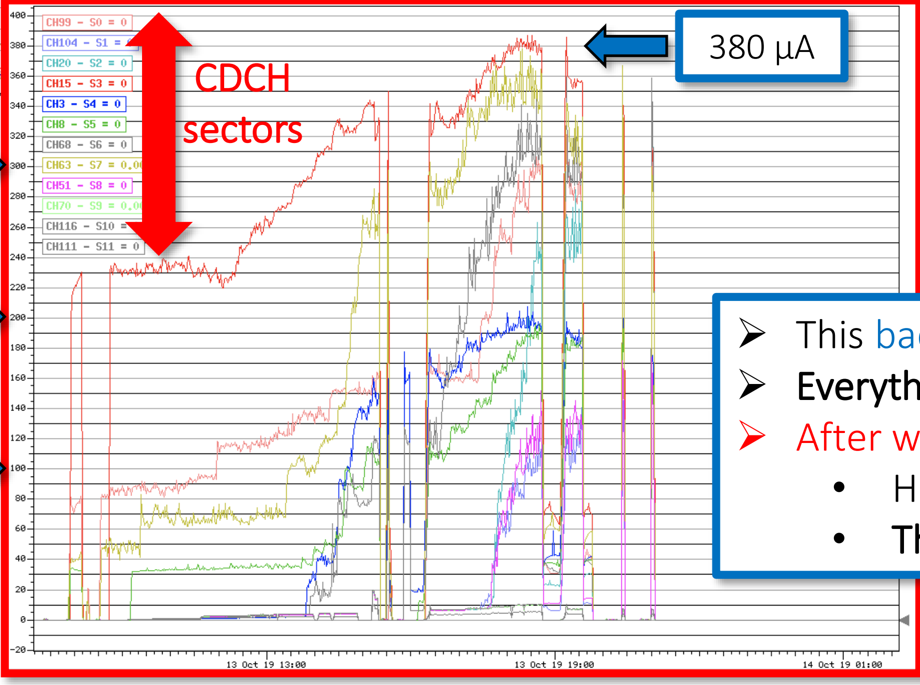
- Found a good linear correlation between number of broken wires and exposure time to humidity
- The only way to **stop the corrosion** is to keep the **wires in an inert atmosphere**
- No more broken wires due to corrosion since CDCH flushed with Nitrogen or Helium once sealed

Investigations on anomalous currents

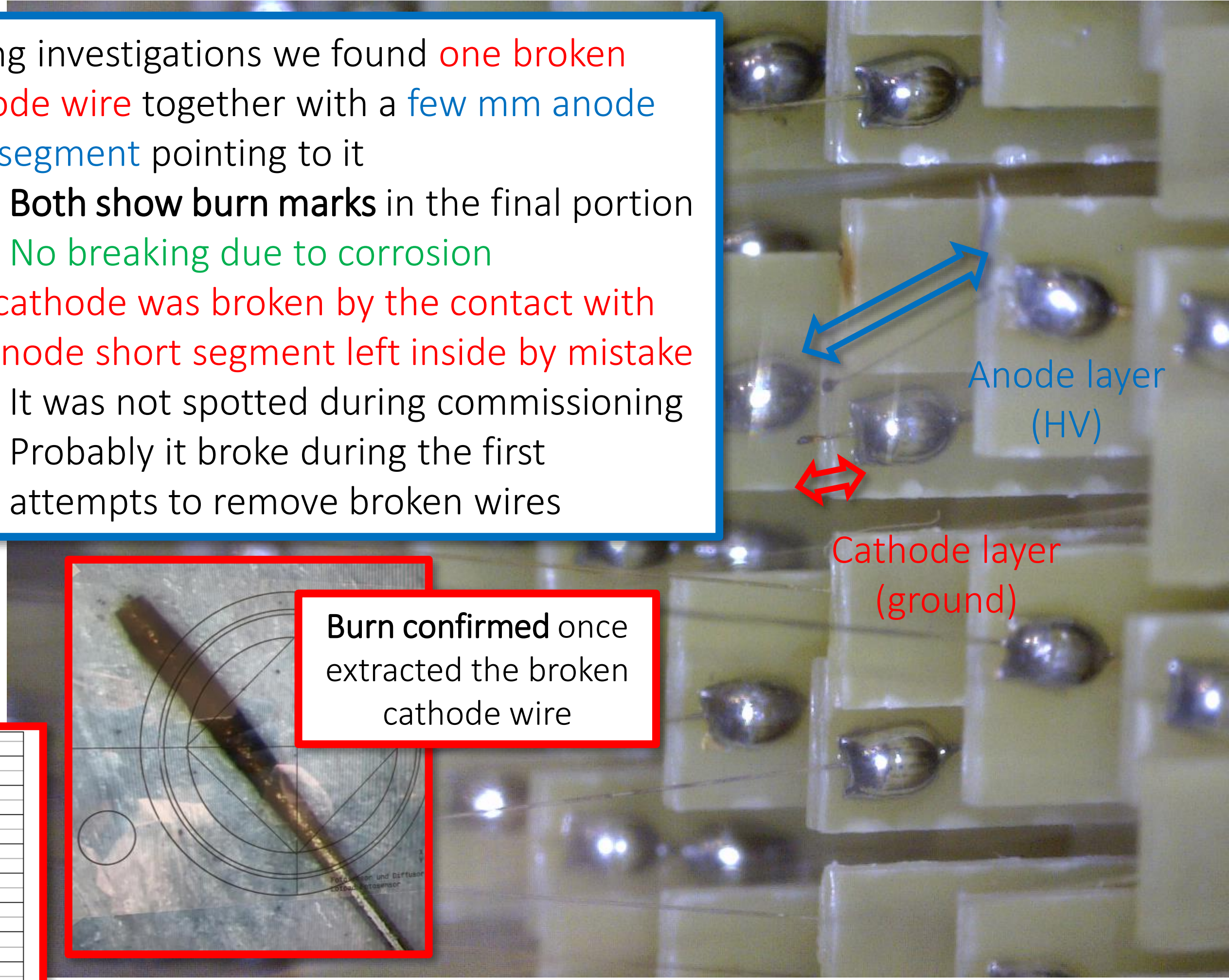
Bad event in 2019



- Layer 7 sector 8
- 1200 µA for 10 minutes
- Due to a **wire breaking**
- But the safety control (firmware) of the HV module did not work
  - Now bug solved + extra (software) safety systems



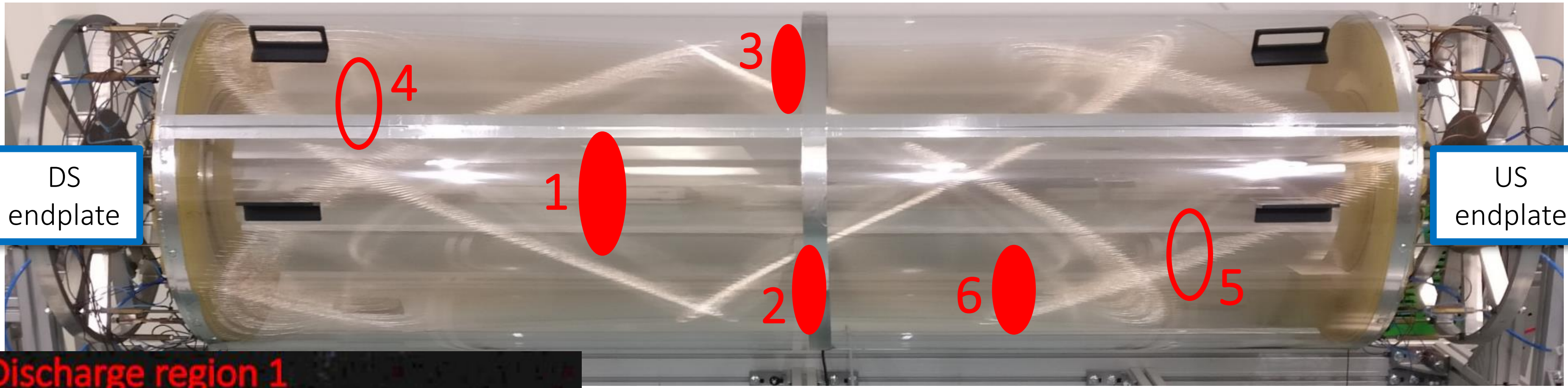
- During investigations we found one broken cathode wire together with a few mm anode wire segment pointing to it
  - **Both show burn marks** in the final portion
  - No breaking due to corrosion
- This cathode was broken by the contact with the anode short segment left inside by mistake
  - It was not spotted during commissioning
  - Probably it broke during the first attempts to remove broken wires

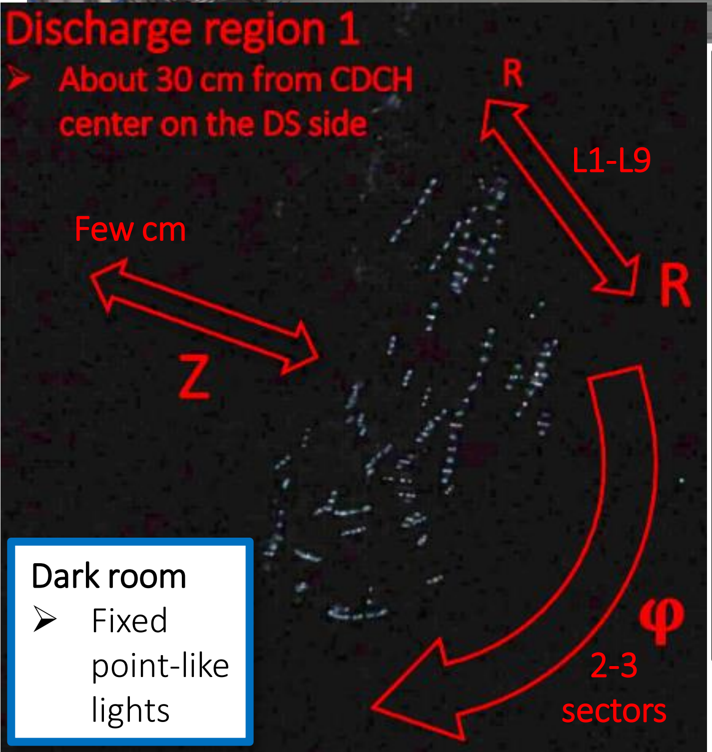


Burn confirmed once extracted the broken cathode wire

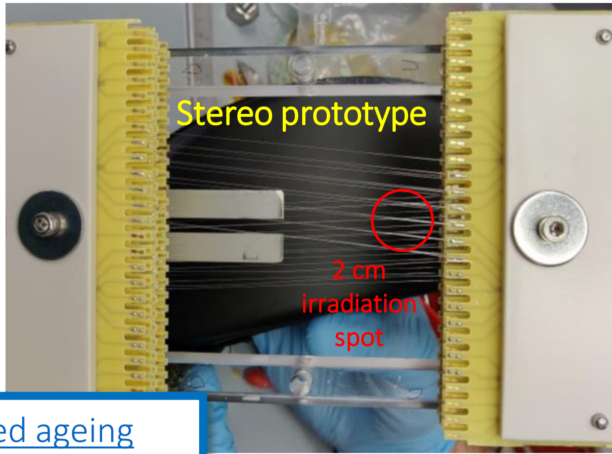
- This bad event occurred during the Michel e^+ data taking with μ^+ beam
- **Everything was good up to this moment**
- After we experienced anomalously high currents is several sectors/layers
  - Here an example for layer 2 at the HV working point + beam ON
  - **The problem has been investigated**

Investigations on high currents

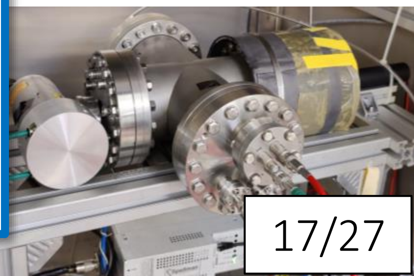




- ➢ HV tests with CDCH closed with a transparent shell and filled with the standard He:IsoB 90:10 gas mixture to spot the discharges
- ➢ We saw corona-like discharges in correspondence of 6 whitish regions
- ➢ Gas mixture optimization: different additives to the standard mixture to **test the CDCH stability** and **try to recover the normal operation**
  - Up to 5% CO_2 and 10% synthetic air (80% N + 20% O_2)
  - 2000-4000 ppm of H_2O (≈10% RH inside CDCH)
  - 1-1.5% Isopropyl alcohol
  - From 500 ppm to 2% of O_2
    - Also in combination with H_2O and IsoP alcohol
- ➢ Oxygen proved to be effective in reducing high currents (plasma cleaning?)
- ➢ Isopropyl alcohol crucial to keep stable the current level



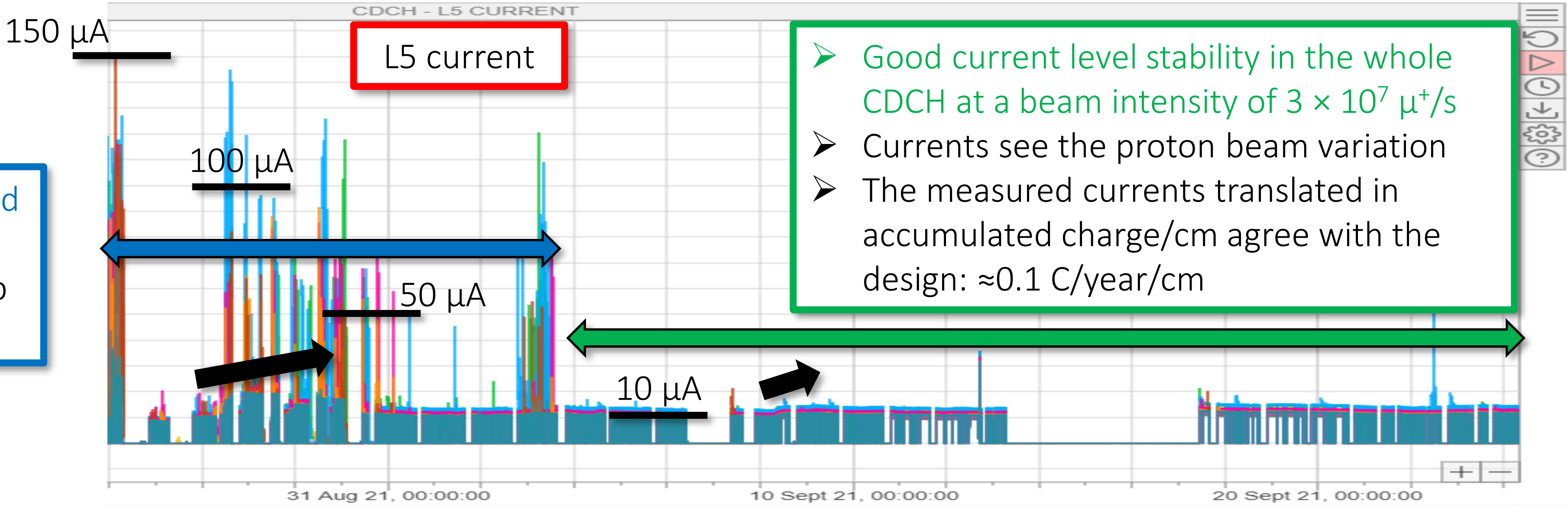
- ➢ Accelerated ageing tests on prototypes returned no issues or discharges
- ➢ Ageing facility at INFN Pisa with **X-ray gun**



CDCH conditioning with μ^+ beam

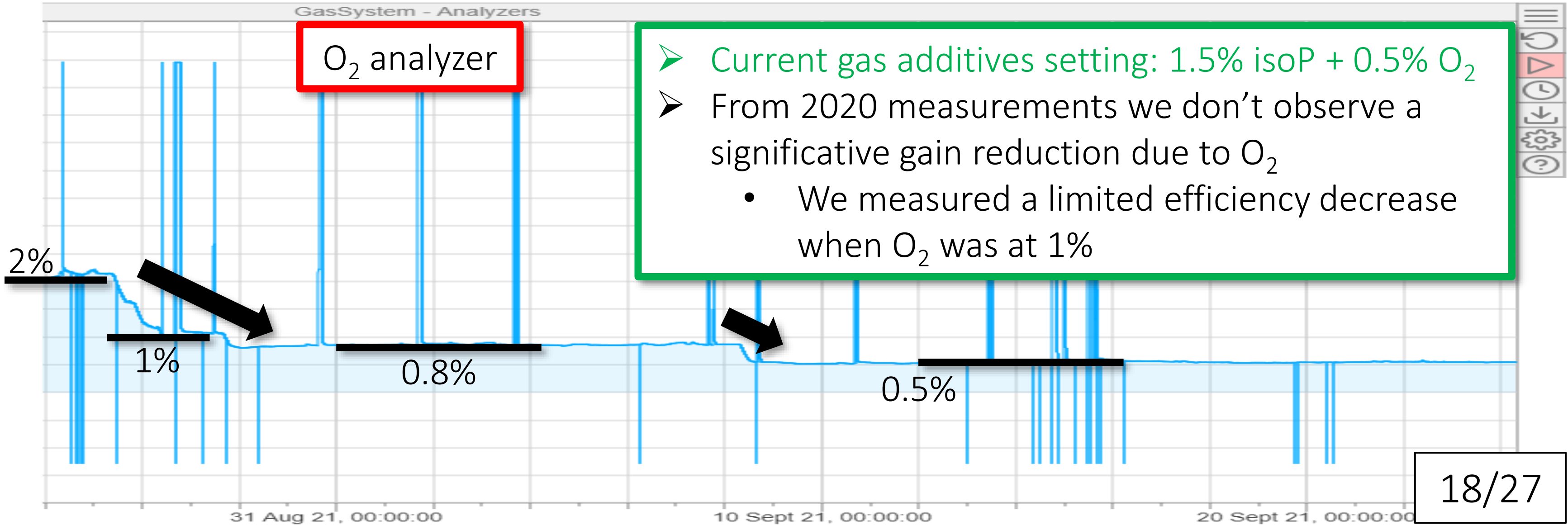
Conditioning with μ^+ beam

- Example of conditioning period with current discharges
- HV up to WP+40V to speed up the O_2 cleaning



- Good current level stability in the whole CDCH at a beam intensity of $3 \times 10^7\ \mu^+/s$
- Currents see the proton beam variation
- The measured currents translated in accumulated charge/cm agree with the design: ≈0.1 C/year/cm

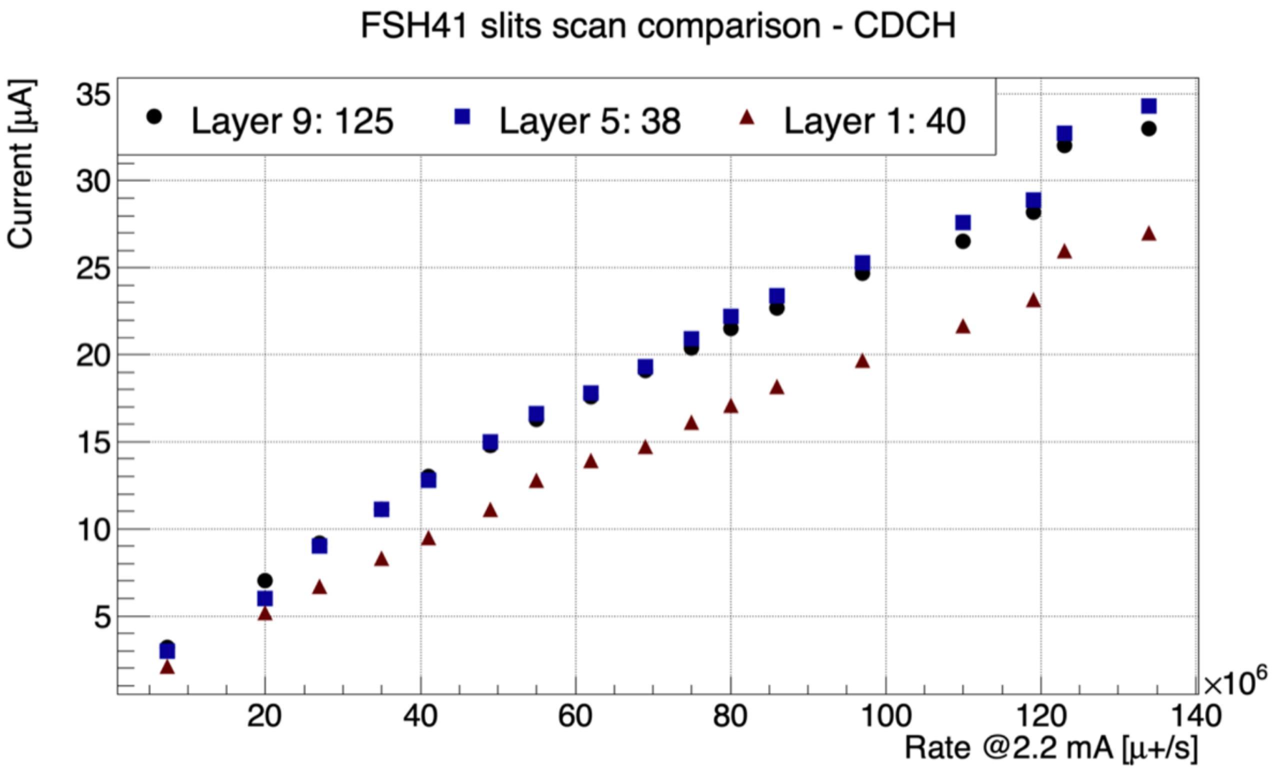
- We are very sensitive to the isopropyl alcohol concentration
- We experienced that 1-1.5% isoP concentration is crucial to keep the stability

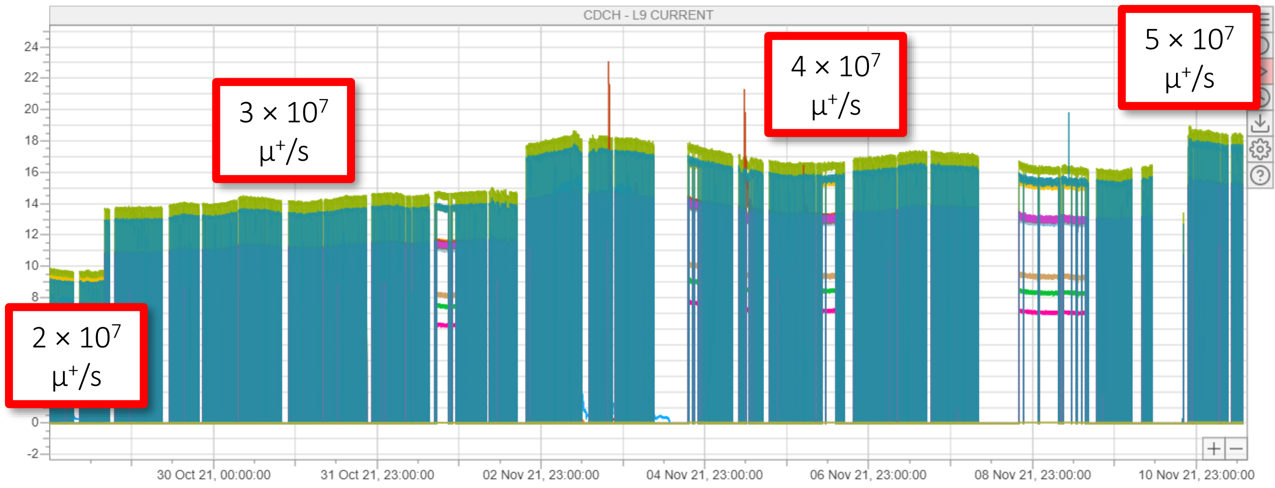


- Current gas additives setting: 1.5% isoP + 0.5% O_2
- From 2020 measurements we don't observe a significative gain reduction due to O_2
  - We measured a limited efficiency decrease when O_2 was at 1%

CDCH currents vs. μ⁺ beam intensity

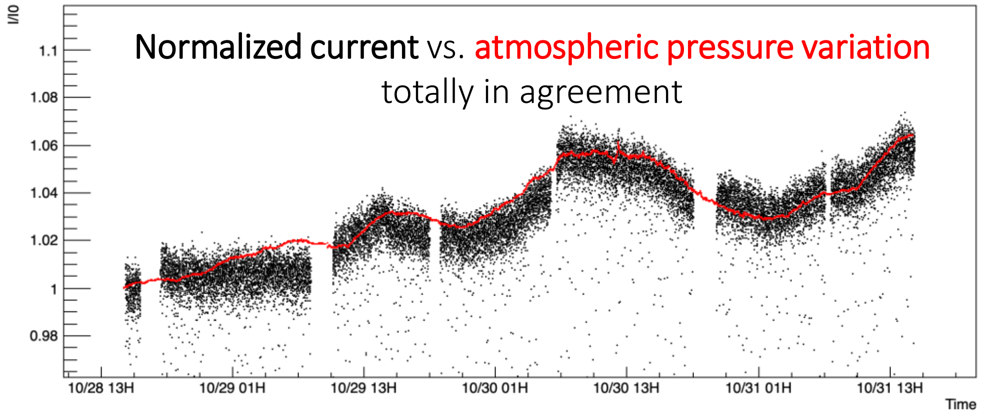
- CDCH currents followed reasonably well the beam intensity up to intensities never reached before
- Good proportionality with the μ^+ rate





- Currents correctly follow the beam intensity
- Gas gain is also sensitive to the variations of the atmospheric pressure

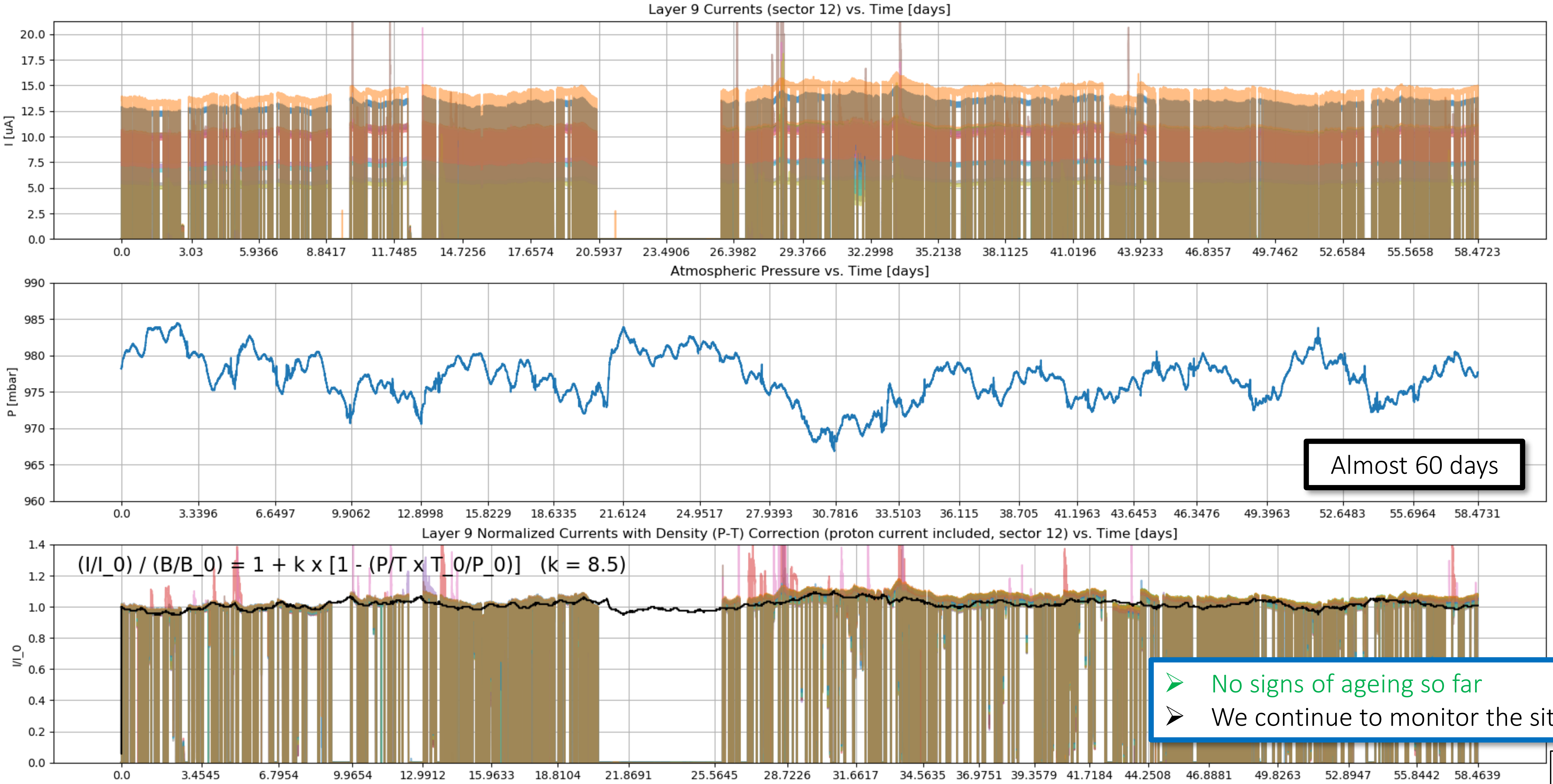
$$\frac{\Delta G}{G} = -k\frac{\Delta P}{P}$$



$$\frac{I}{I_0} = 1 - k\frac{\Delta P}{P}$$

$$k = 5$$

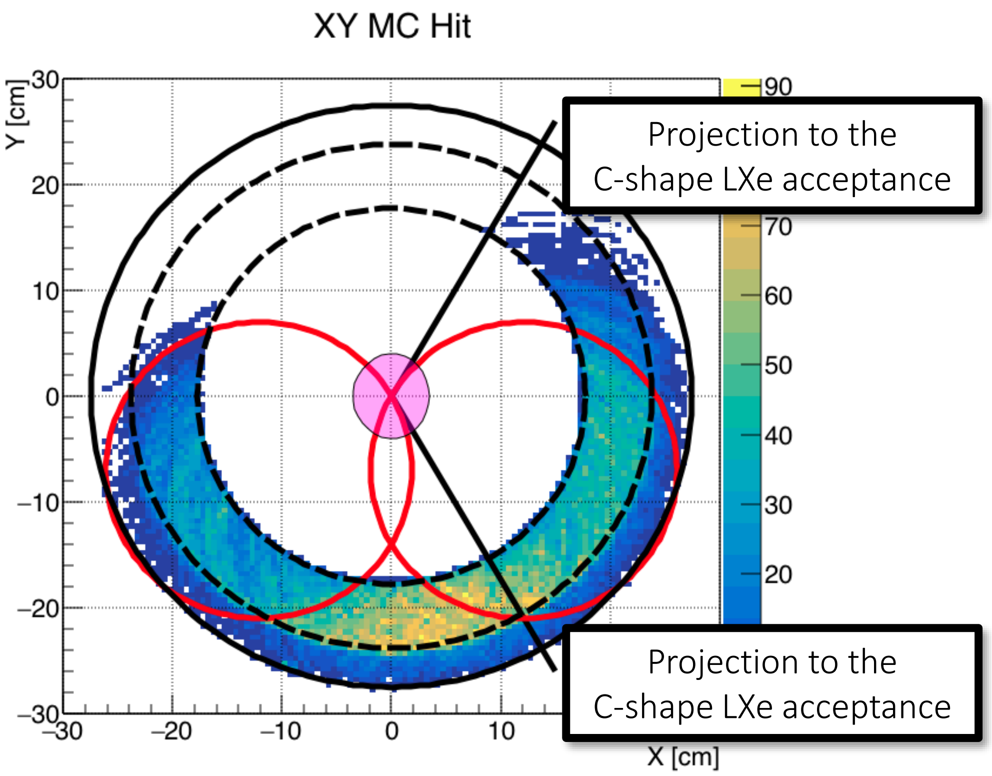
L9 normalized current vs. gas density (P, T)



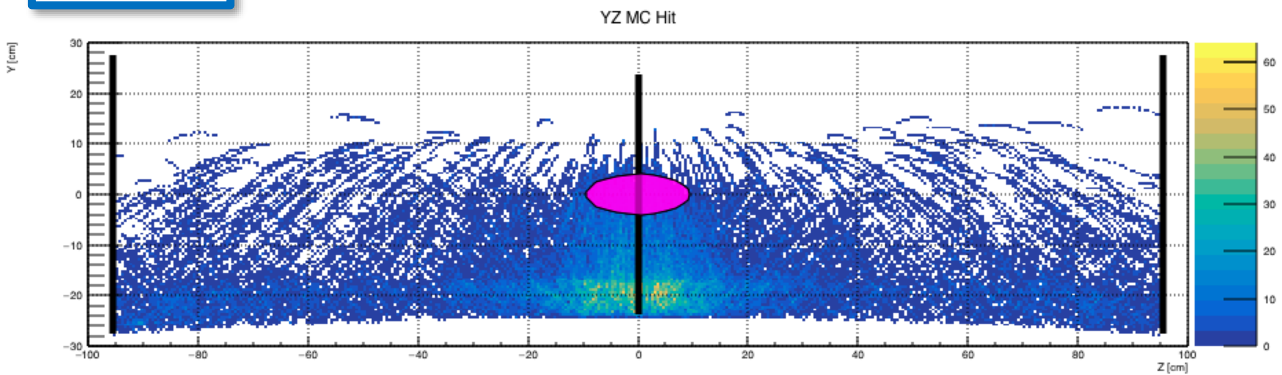
- No signs of ageing so far
- We continue to monitor the situation

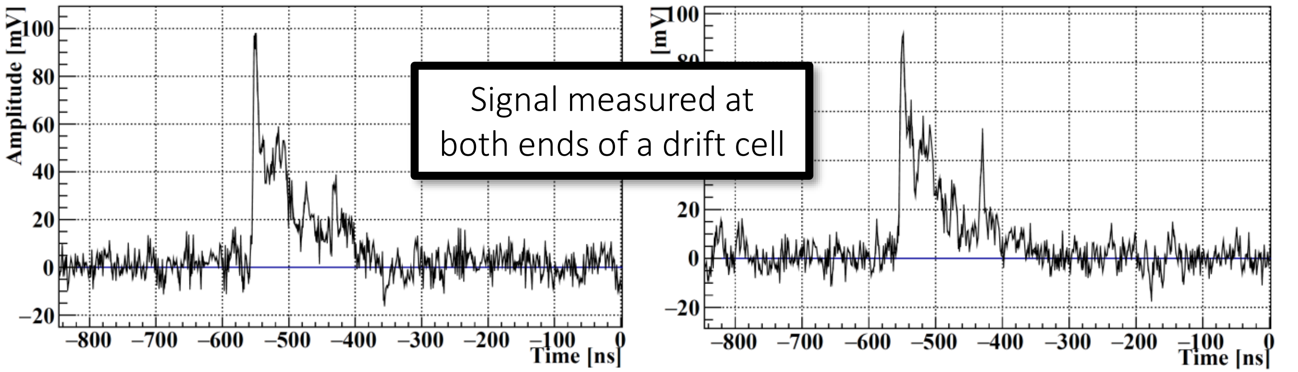
Physics data taking (planned 2021-2026)

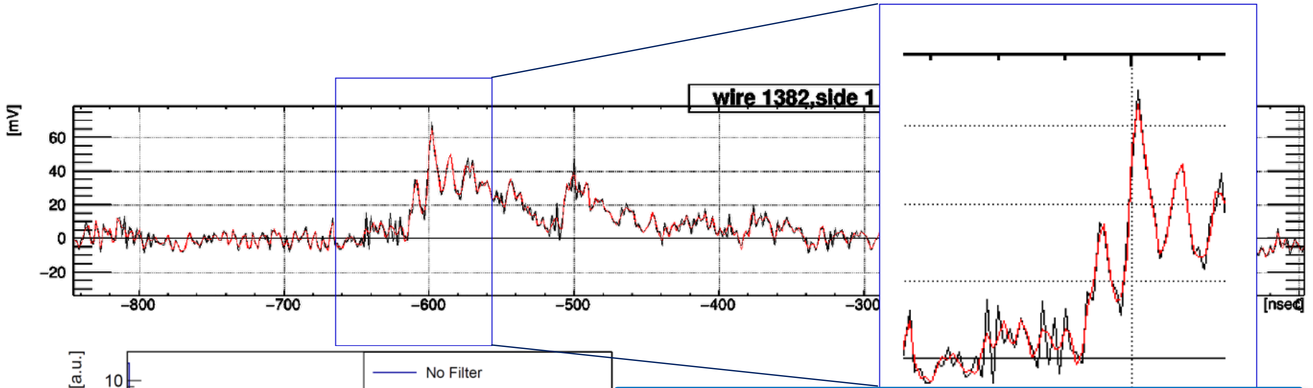
Signal occupancy and Waveforms

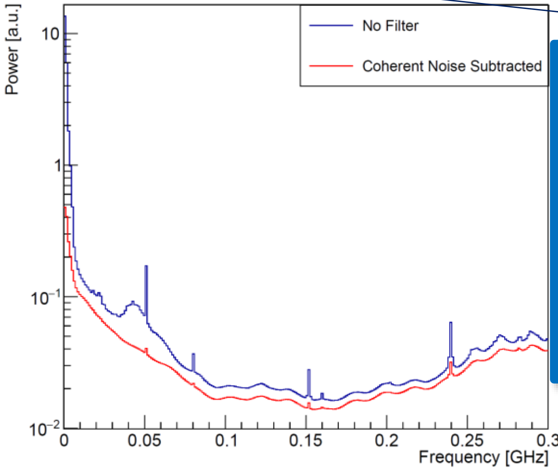


Signal e^+



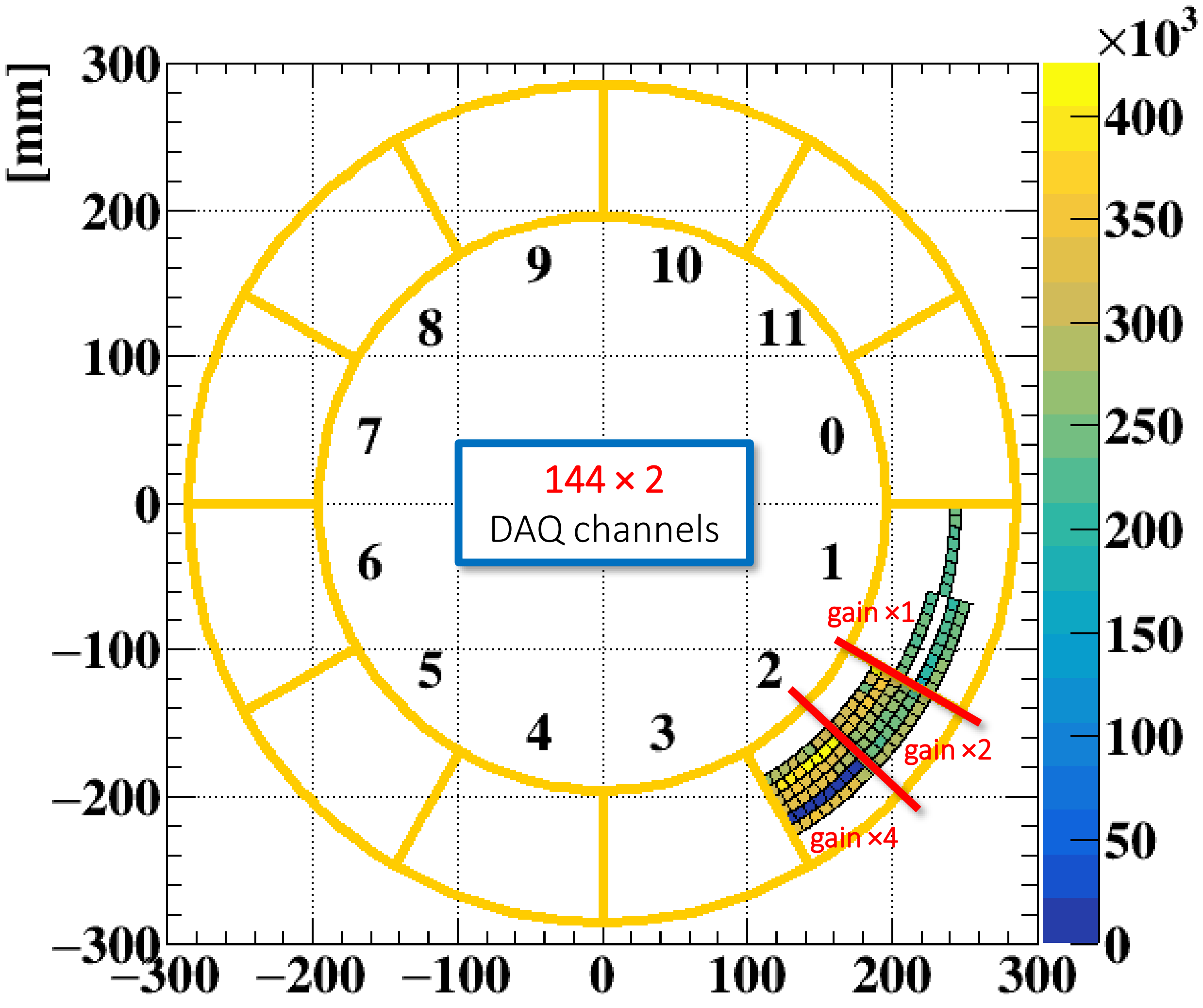




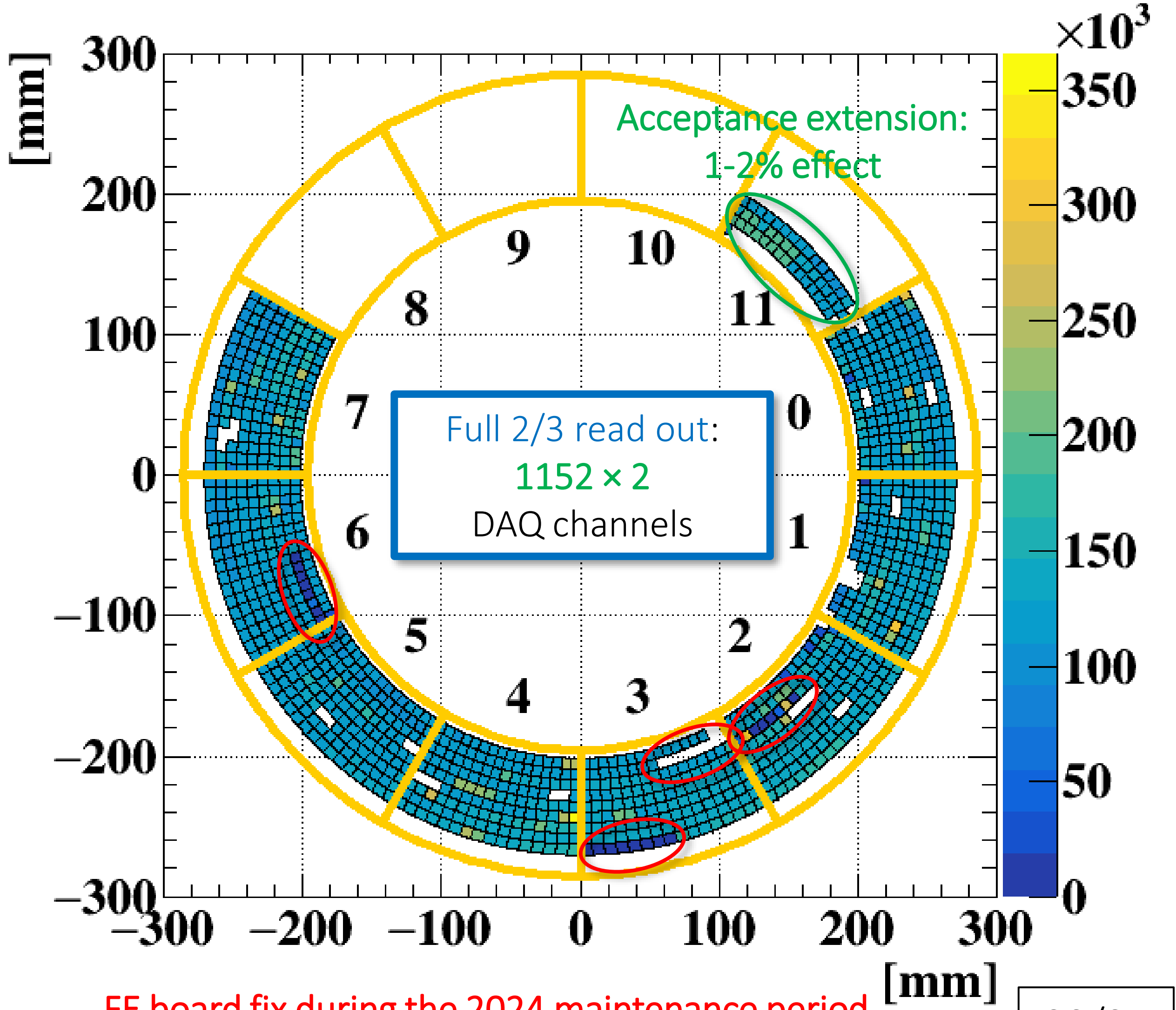


- In MEG all the signal WF is recorded
- Then a fine analysis is made offline to get the hit information
  - Timing, signal amplitude, signal integral, position
- Coherent noise subtraction + 225 MHz digital low-pass filter are applied

2020 vs. 2023 readout (run 2024 ongoing)



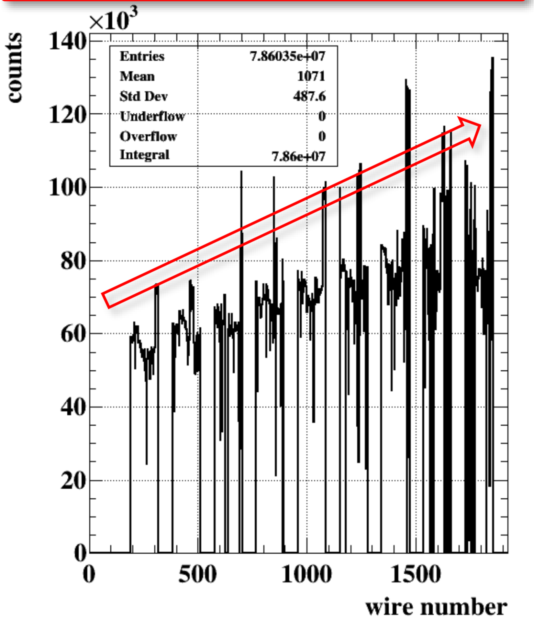
3 FE gain configurations tested:
gain x4 chosen → best SNR



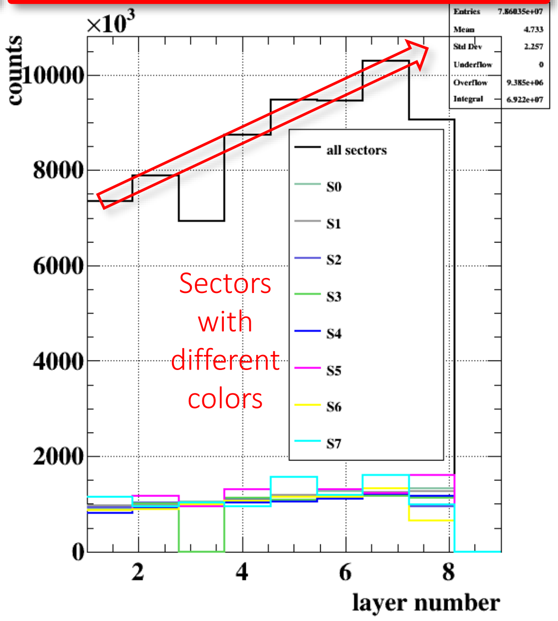
FE board fix during the 2024 maintenance period

Detector occupancy and WF features

Occupancy vs. wire number



Occupancy vs. layer number



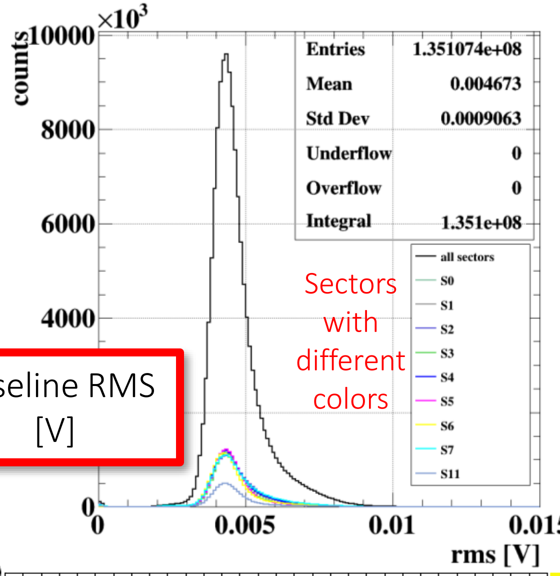
Outer layer

Inner layer

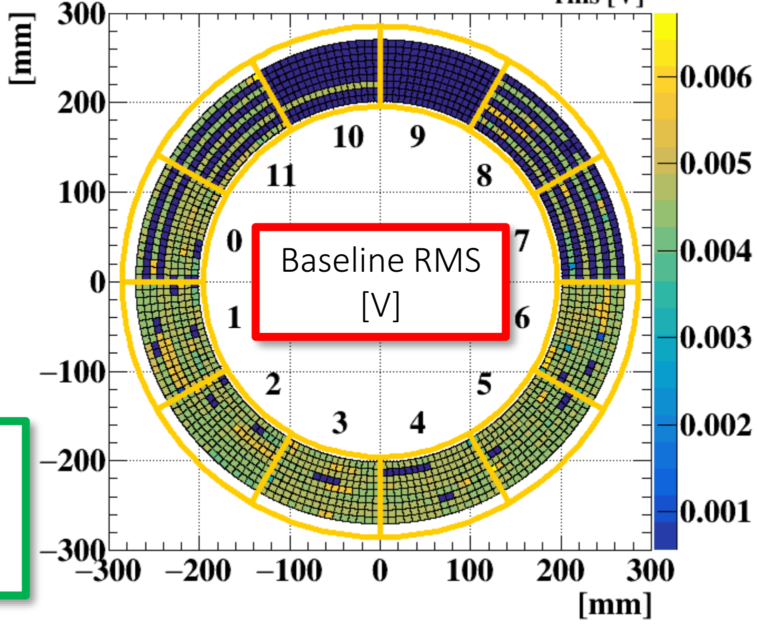
Outer layer

Inner layer

Scaling by radius as expected with Michel e^+ events

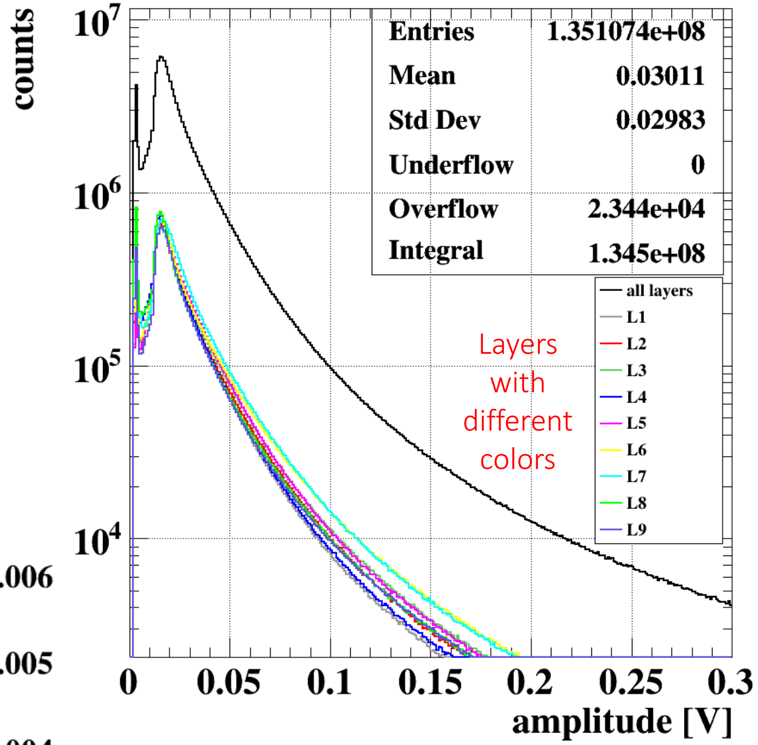


Baseline RMS [V]



Baseline RMS [V]

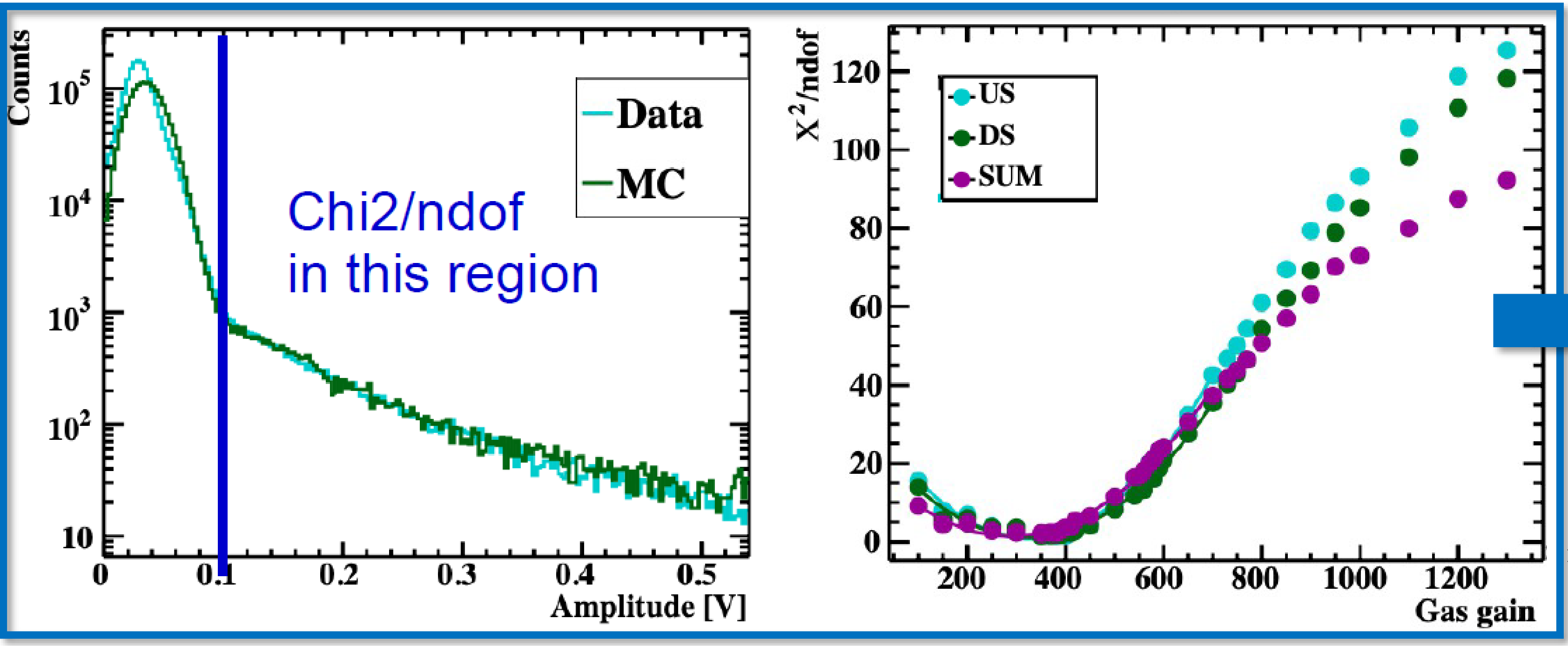
Good noise level at <4.5 mV>

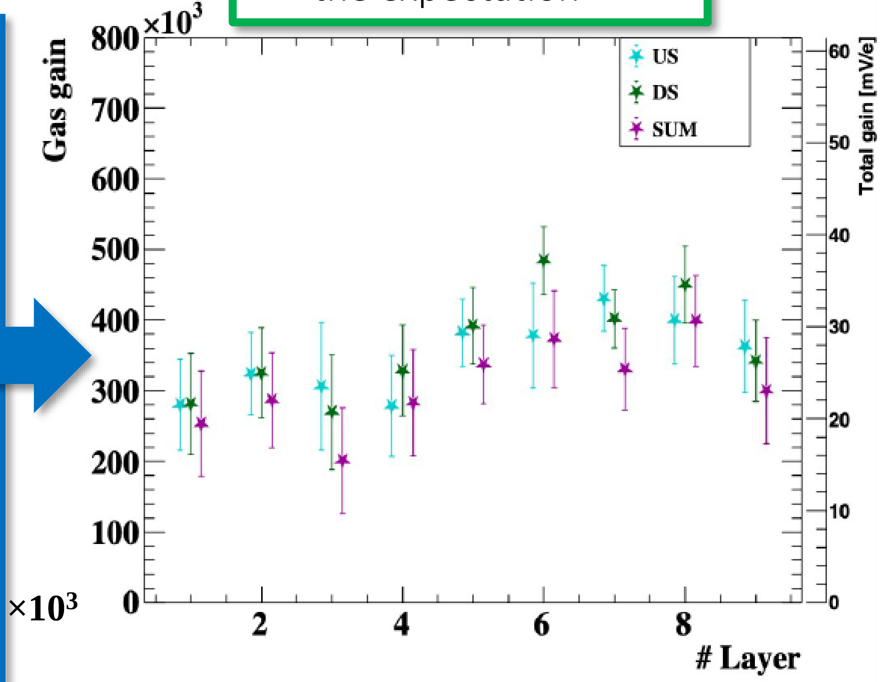


- Good uniformity of the **signal amplitude** between layers
- 10 V scaling of the HV works well

Gas gain measurement

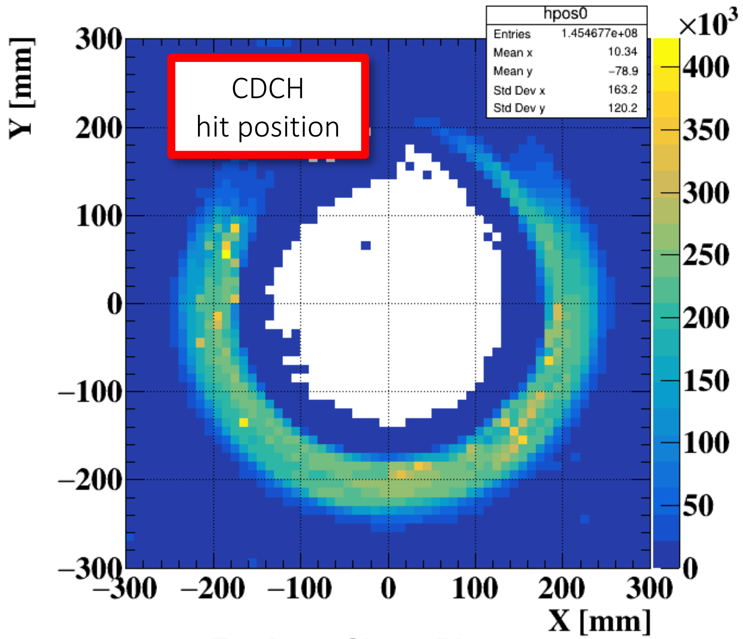
- 2021 measurement
- Gas gain = $(2 \div 4) \times 10^5$ in agreement with the expectation



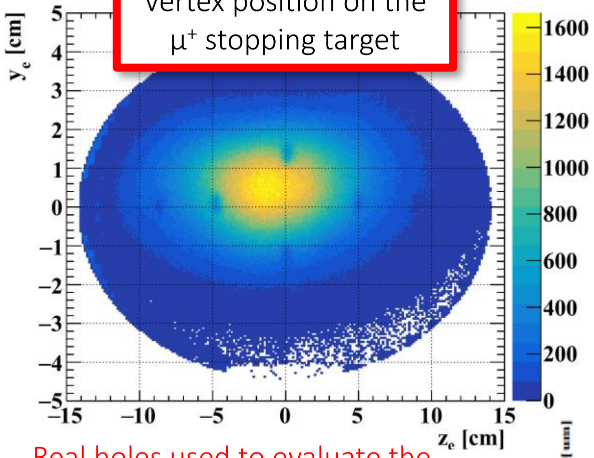


- **Signal amplitude distribution** from Cosmic Ray events: clean environment
- The only parameter to be tuned in MC to reproduce data is the Total gain = Gas gain × FE gain
- FE gain measured to be 0.120 mV/fC
    - FE response to real single-electron drift chamber signals produced by laser ionization on a prototype
- Gas gain = Total gain / FE gain

Hit reconstruction and resolution

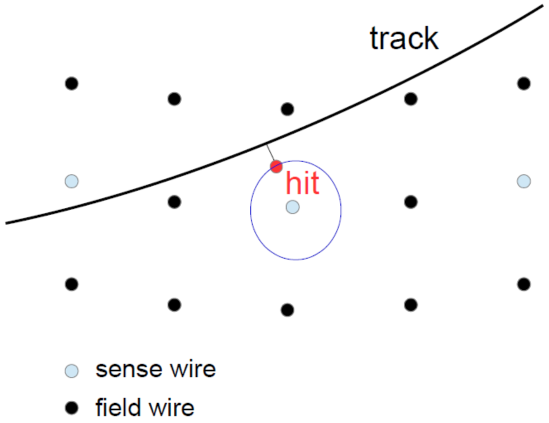


CDCH hit position

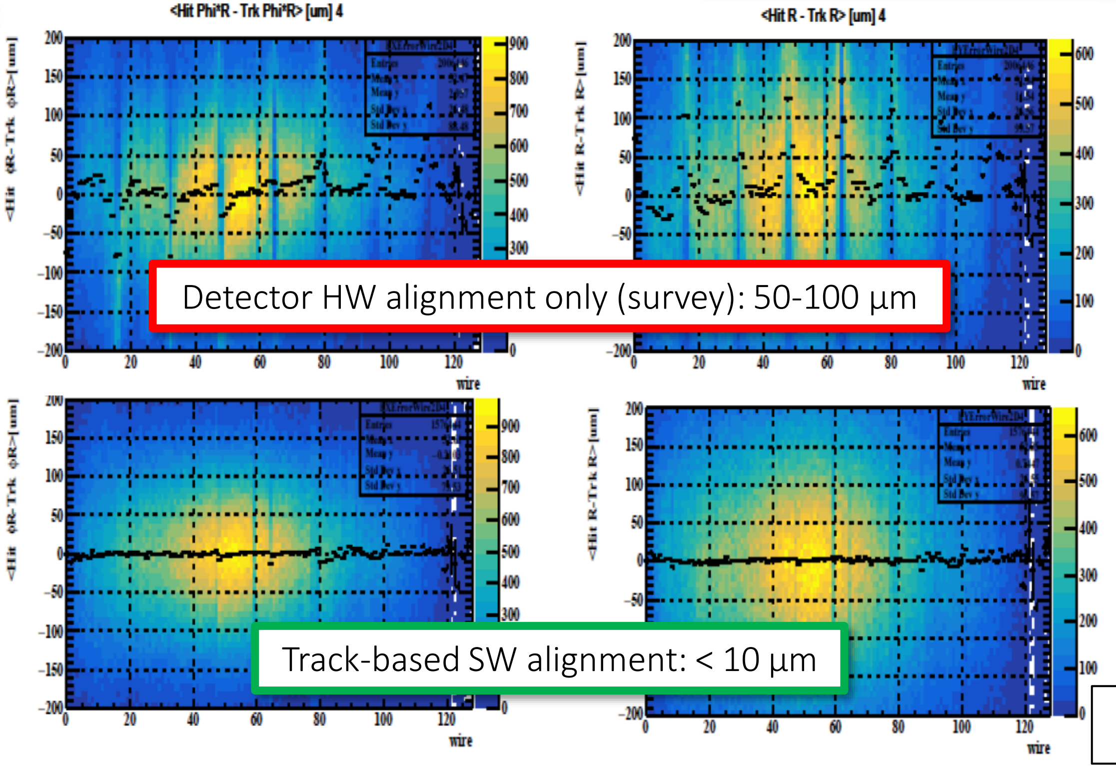


Vertex position on the μ^+ stopping target

Real holes used to evaluate the vertex reconstruction accuracy

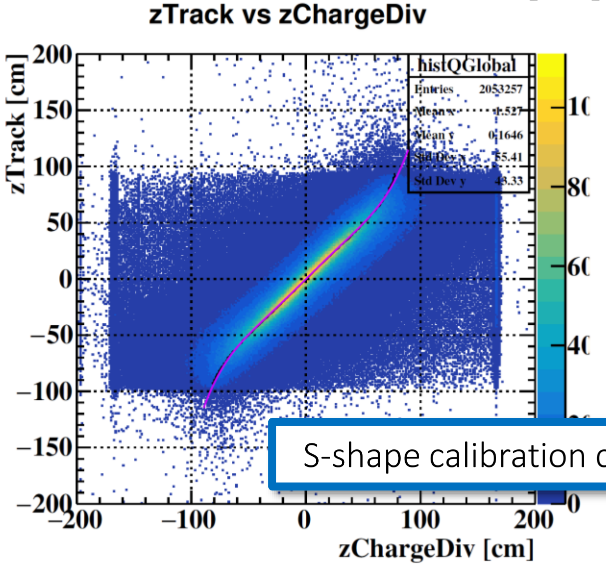


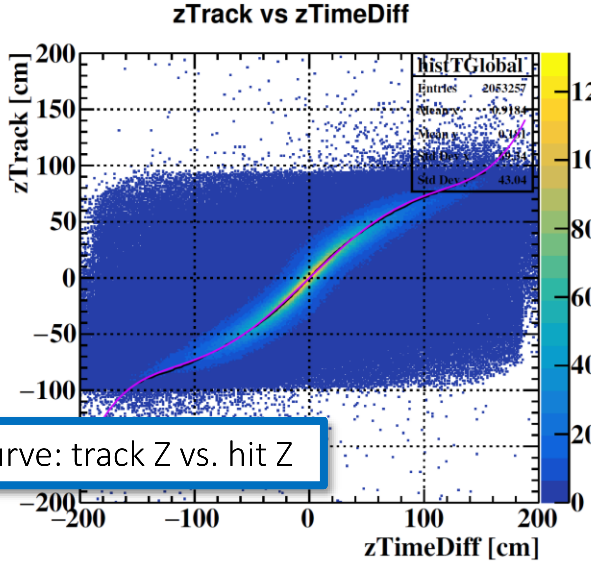
Hit-track residual give a measurement of how misalignments, single-hit resolution and other systematics (B field) combine to determine the reconstruction performance



Detector HW alignment only (survey): 50-100 μm

Track-based SW alignment: < 10 μm



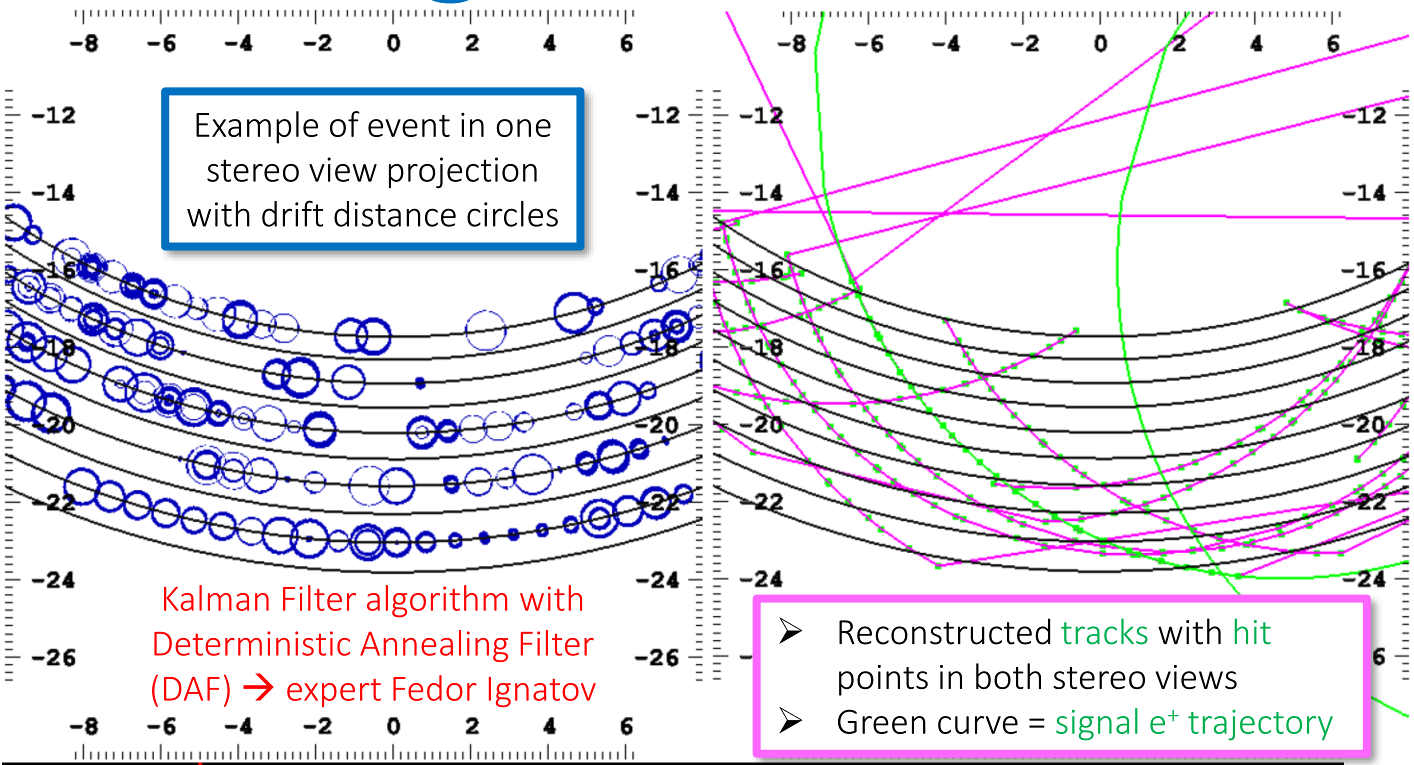


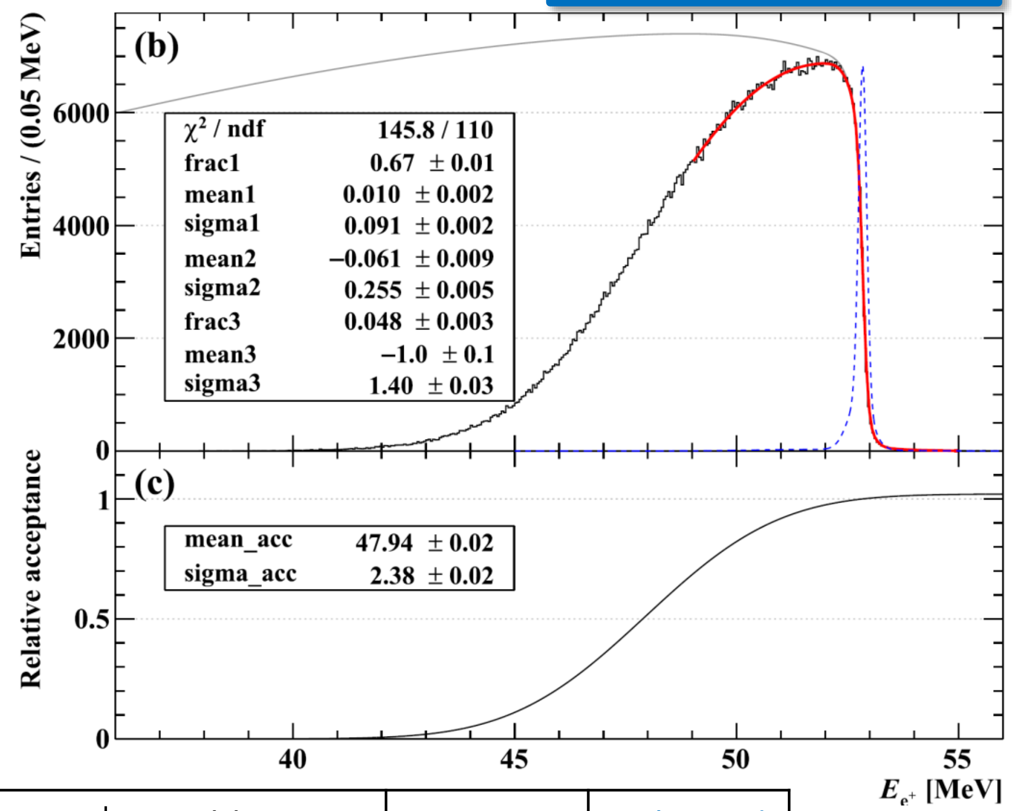
S-shape calibration curve: track Z vs. hit Z

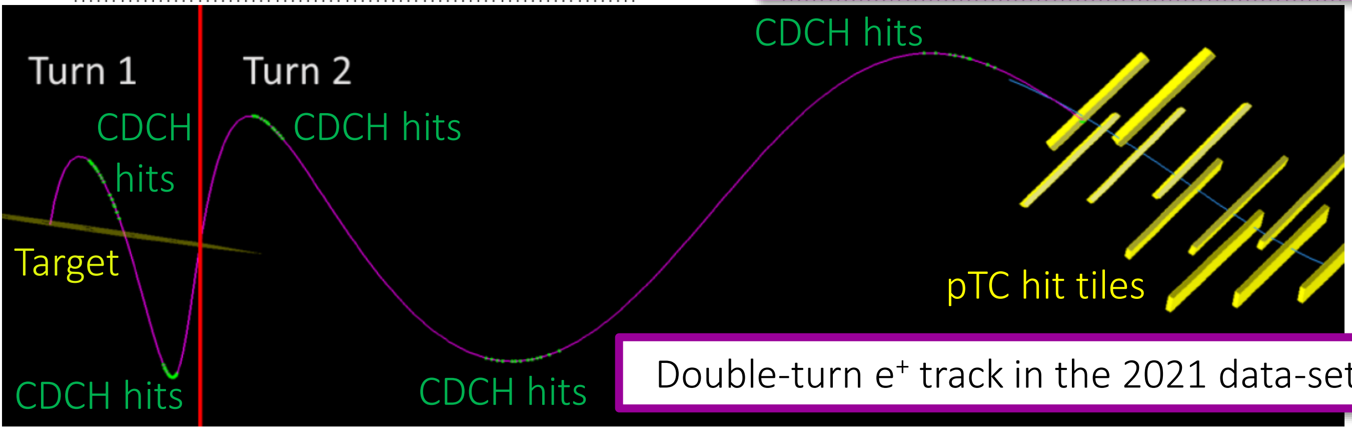
$3 \times 10^7\ \mu^+/s$

Tracking and Momentum resolution

$PDF(p) = [PDF_{THEORY}(p) \times Acceptance(p)] \otimes Resolution_{TRIPLE\text{-}GAUSSIAN}(\Delta p)$



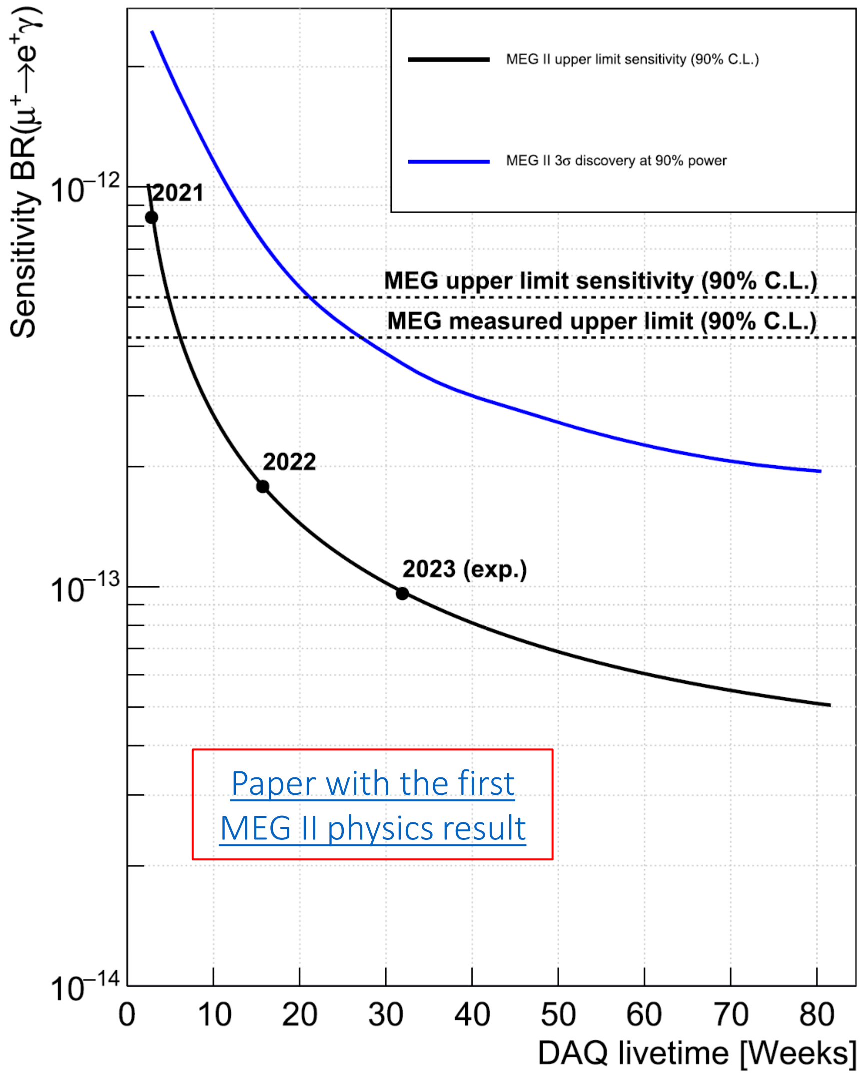




Double-turn e⁺ track in the 2021 data-set

e^+ variable	Foreseen	Achieved
ΔE_e (keV)	100	91
$\Delta\theta_e$, $\Delta\varphi_e$ (mrad)	6.7, 3.7	7.2, 4.1
ΔZ, ΔY (at target, mm)	1.6, 0.7	2.0, 0.7
ε_e (%)	65	67

Conclusions and prospects



- The new drift chamber CDCH of the MEG II experiment has been presented
  - **Full azimuthal coverage** around the stopping target
  - **Extremely low material budget**: minimization of MCS and γ background
  - **High granularity**: 1728 drift cells few mm wide in ΔR ≈ 8 cm active region
    - Improve angular and momentum resolutions of the e^+ kinematic variables
  - Stereo design concept, modular construction, light and reliable mechanics
- Despite the **COVID-19 situation** we were able to perform the 2020 and 2021 commissioning of all the MEG II subdetectors and the experiment started the physics data taking in 2021
  - Some **results from 2021-2023 data** have been presented (full data taking 2021-2026)
  - Data analysis and continuous developments ongoing
- Problems along the path
  - Corrosion and breakage of 107 aluminum wires in presence of 40-65% humidity level
    - Especially 40 μm wires (90%) proved to be prone to corrosion
    - Problem fully cured by keeping CDCH in dry atmosphere
  - Anomalously high currents experienced
    - Probably triggered by a bad event during the 2019 engineering run
    - CDCH operation recovered by using additives (**0.5% O_2 + 1.5% Isopropyl alcohol**) to the standard He:iC_4H_{10} 90:10 gas mixture

- **Beyond $\mu^+ \to e^+\gamma$: the X(17) boson search**
  - Atomki collaboration (2016): excess in the angular distribution of the Internal Pair Creation (IPC) in the $^7Li(p, e^+e^-)^8Be$ nuclear reaction
  - Possible interpretation with a new physics boson mediator with mass expected around 17 MeV: p N → N'* → N' (X →) e^+e^-
  - MEG II has all the ingredients (CW accelerator + Spectrometer) to repeat the measurement → data unblinding (13/11/2024)

THANKS
FOR YOUR ATTENTION