The experience of the MEG II drift chamber

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Outline

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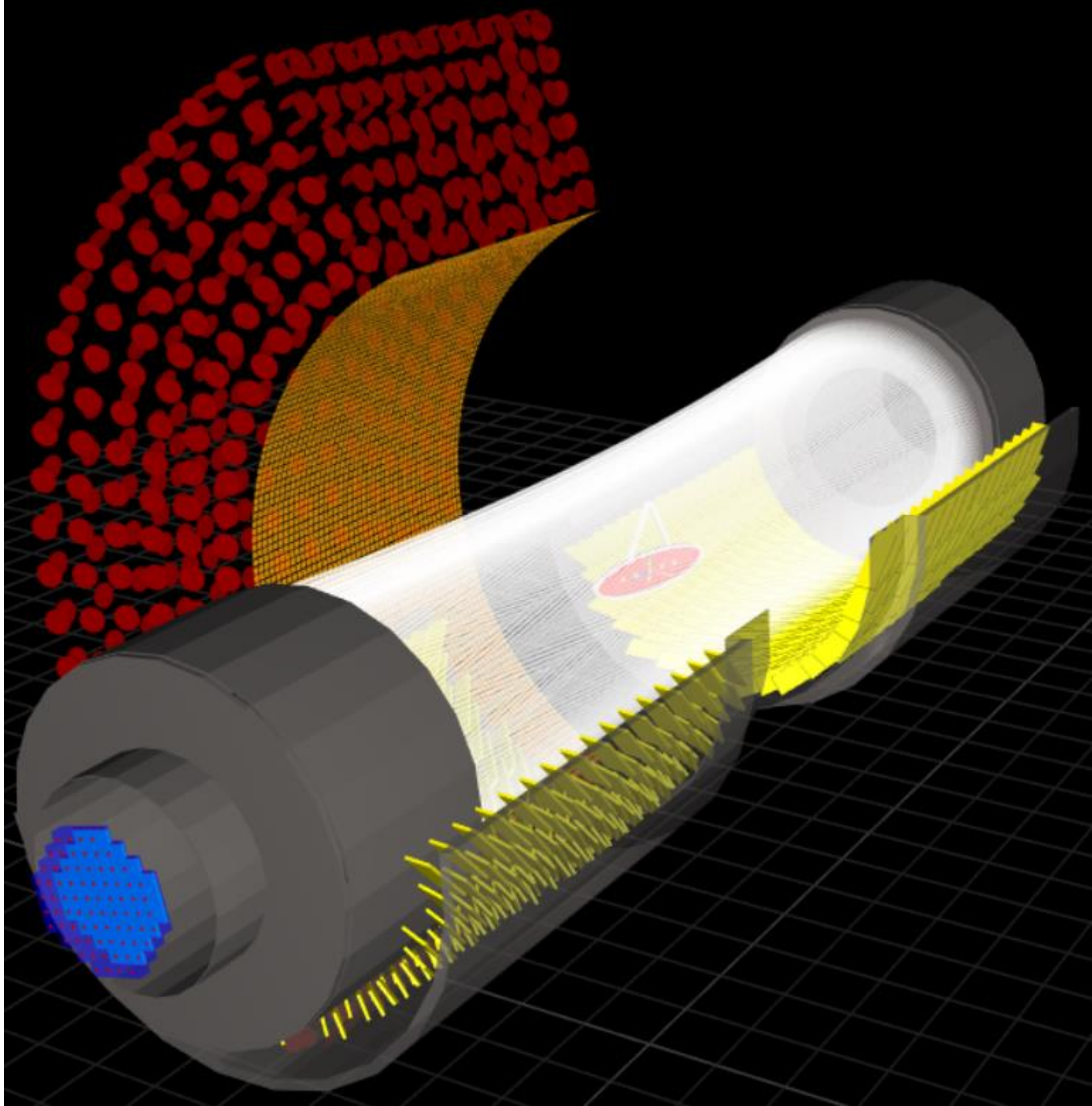
- The MEG II Cylindrical Drift CHamber (CDCH)
  - Detector performances and new design concept
  - Mechanics and electronics
  - Final working point
  - Integration into the MEG II experimental apparatus
- Investigations on wire breakages
- A few examples from data taking
  - Signal waveforms and occupancy
  - First gain studies
- Investigations on high currents
- Accelerated ageing tests on prototypes
- Conclusions



Introduction

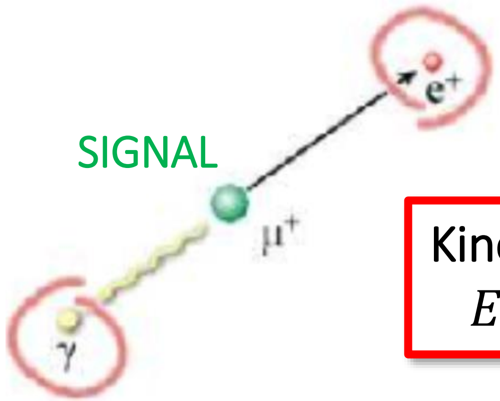
CLFV and $\mu^+ \rightarrow e^+\gamma$ decay

[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

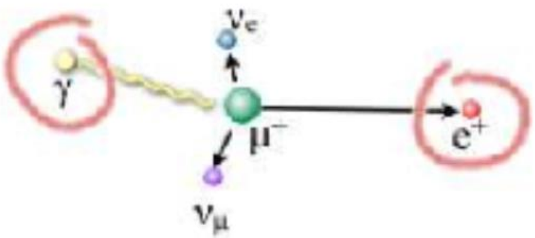
- In this context the MEG experiment represents the state of the art in the search for the CLFV $\mu^+ \rightarrow e^+\gamma$ decay
  - **Final results** exploiting the **full statistics** collected during the 2009-2013 data taking period at **Paul Scherrer Institut** (PSI, Switzerland)
  - $BR(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$ (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 140 μm-thick 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

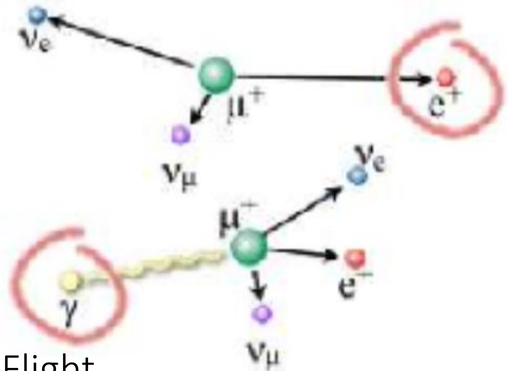


Radiative Muon Decay (RMD)

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

BACKGROUNDS

From RMD, Annihilation-In-Flight or bremsstrahlung

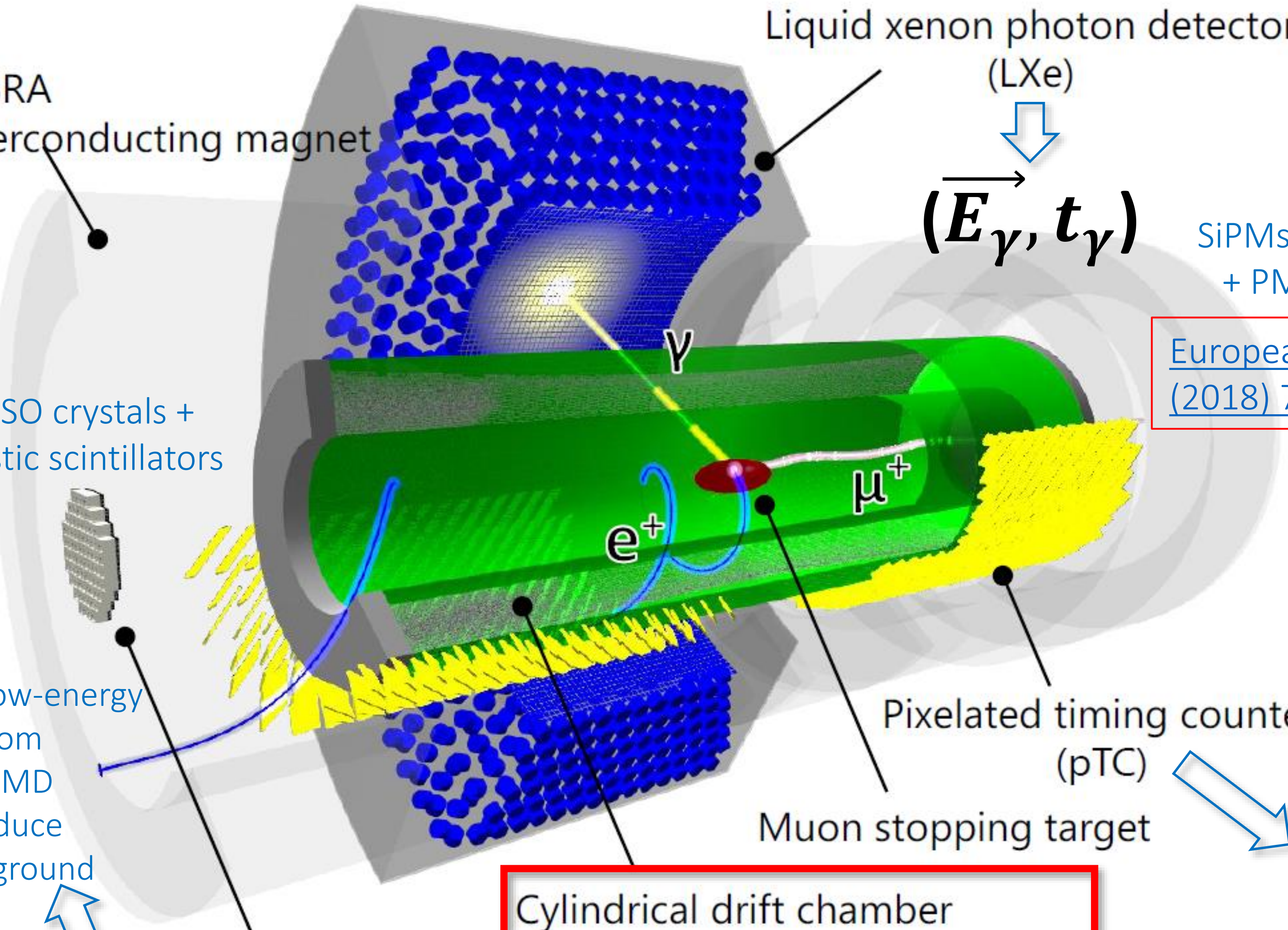


Accidental

- $E_\gamma < 52.8$ 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



COBRA superconducting magnet

Liquid xenon photon detector (LXe)

$(\overrightarrow{E_\gamma}, t_\gamma)$

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

[European Physics Journal C (2018) 78:380]

LYSO crystals + plastic scintillators

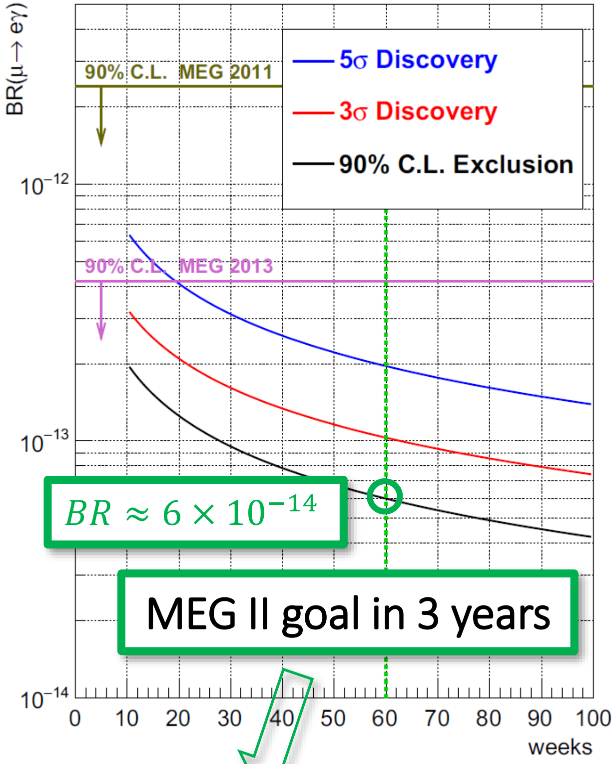
Tag low-energy e^+ from AIF/RMD to reduce background

Radiative decay counter (RDC)

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

Muon stopping target

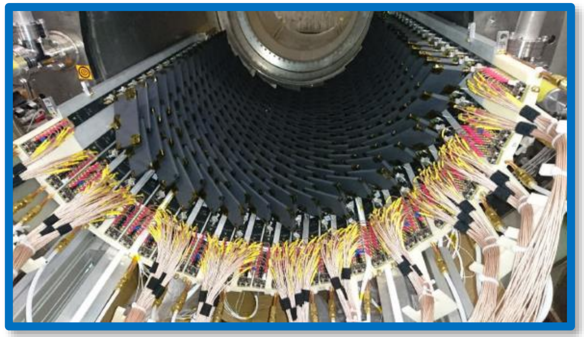
Pixelated timing counter (pTC) t_{e^+}



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

MEG II goal in 3 years

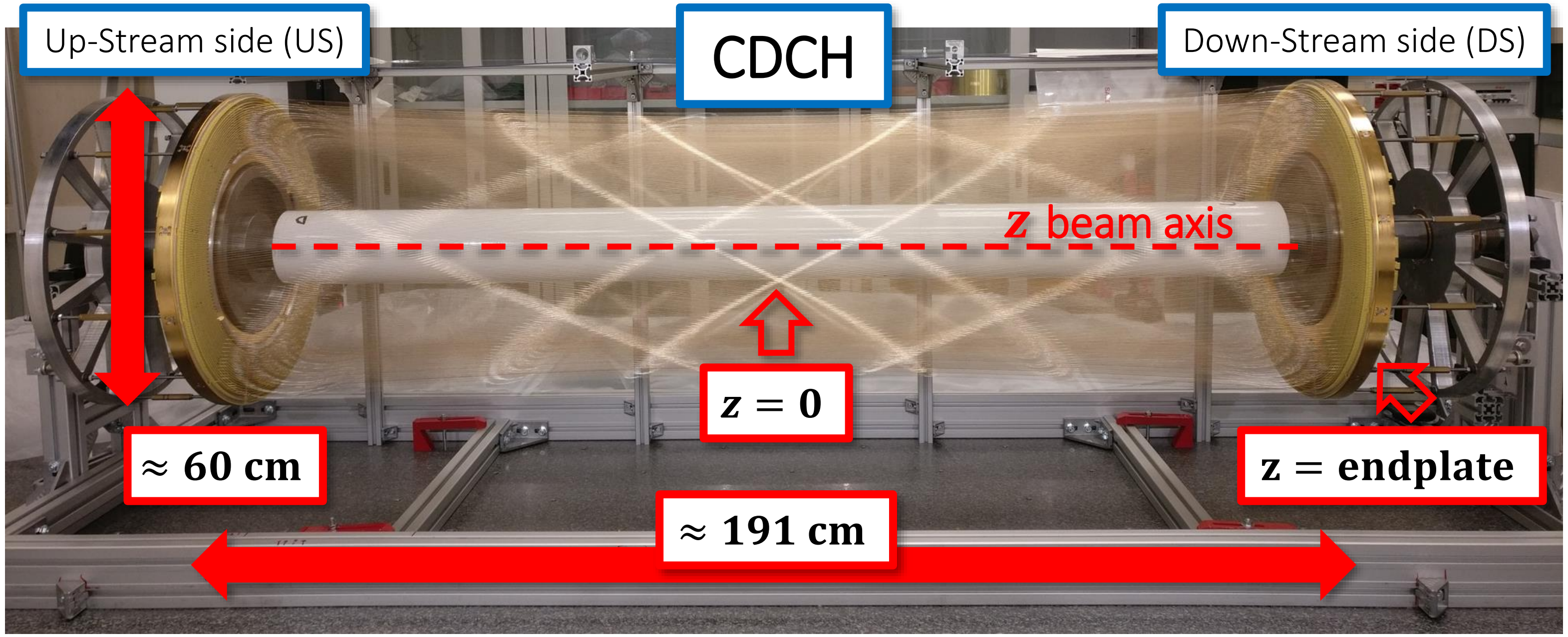
- **Increasing the μ^+ stopping rate** up to $7 \times 10^7\ \mu^+/s$ ($\times$ 2 factor than MEG)
- **Improving the detectors figures of merit** ($\times$ 2 factor than MEG)



Plastic scintillators tiles read out by SiPMs

The MEG II Cylindrical Drift CHamber (CDCH)

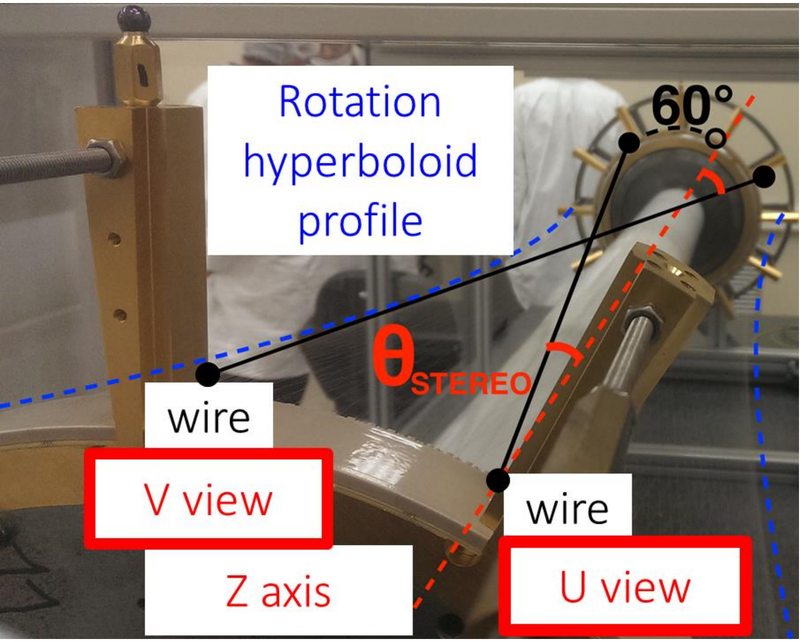
The MEG II Cylindrical Drift Chamber



e^+ variable	MEG	MEG II
ΔE_e (keV)	380	90
$\Delta\theta_e$, $\Delta\varphi_e$ (mrad)	9, 9	6, 5.5
Efficiency_e (%)	40	65

- Low-mass unique volume detector with high granularity filled with **He:Isobutane 90:10 gas mixture**
  - 9 concentric layers of 192 drift cells defined by 11904 wires
  - Small cells few mm wide: occupancy of ≈1.5 MHz/cell at CDCH center near the stopping target
  - High density of sensitive elements: **×4 hits more than MEG drift chamber** (DCH)
- Total radiation length $1.5 \times 10^{-3}\ \mathrm{X_0}$: less than $1.7 \times 10^{-3}\ \mathrm{X_0}$ of MEG DCH
  - **MCS minimization and γ background reduction** (bremsstrahlung and Annihilation-In-Flight)
- Single-hit resolution (measured on prototypes): $\sigma_{hit} < 120\ \mu\mathrm{m}$
- **Extremely high wires density** (12 wires/cm^2) ➜ 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**
- CDCH design is based on the experience gathered with the KLOE drift chamber (http://www.lnf.infn.it/kloe/index2.html)

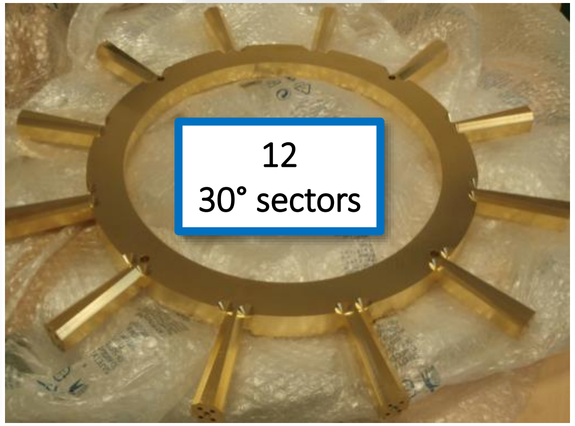
Design and wiring

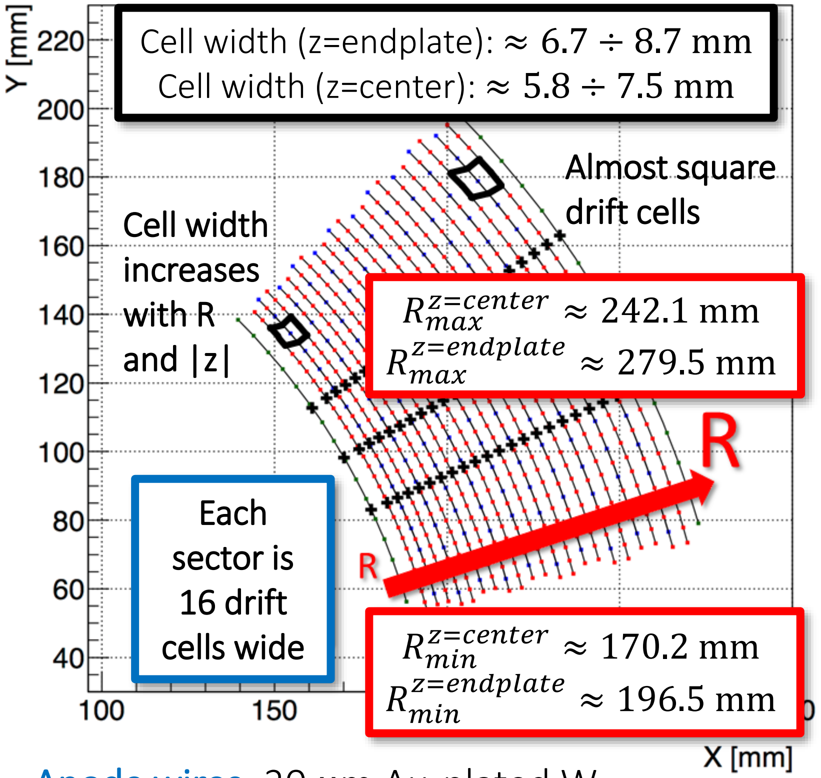


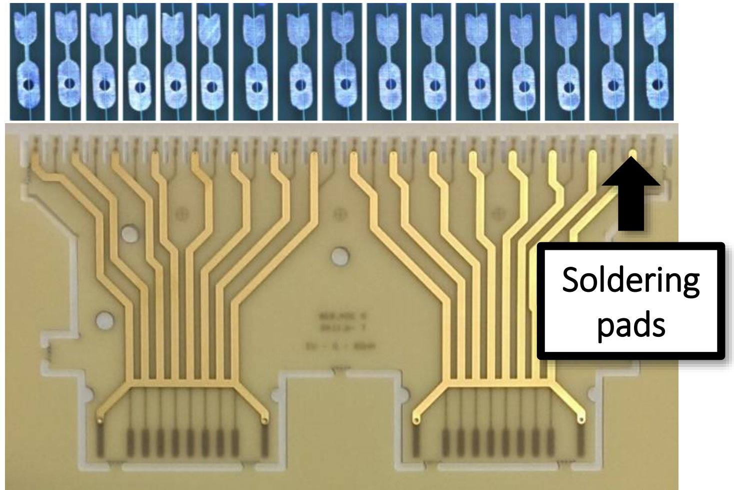
Stereo wires geometry for longitudinal hit localization

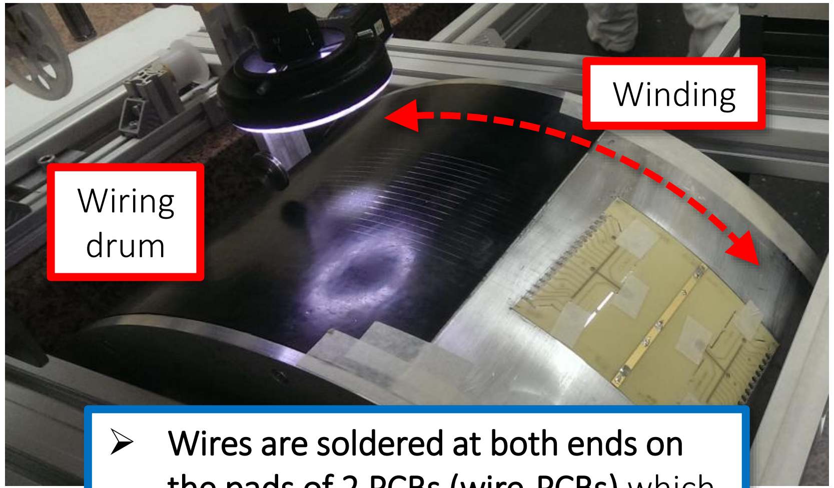
- $\theta_{stereo} \approx 6° \div 8.5°$ as R increases

Endplate



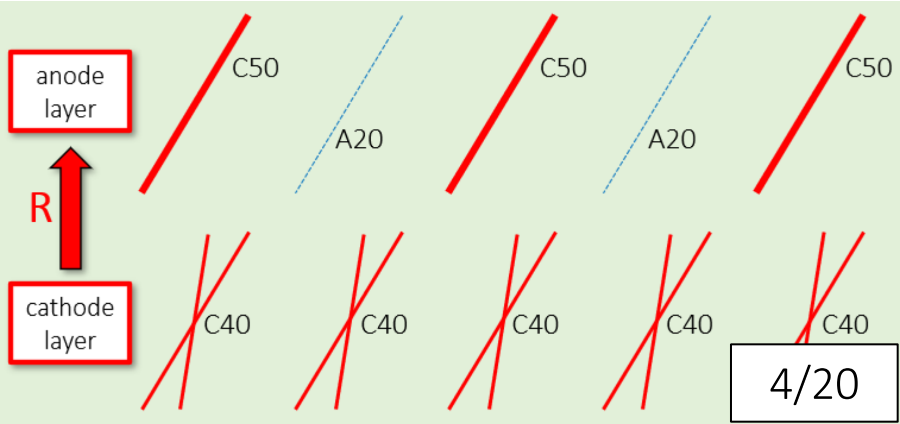






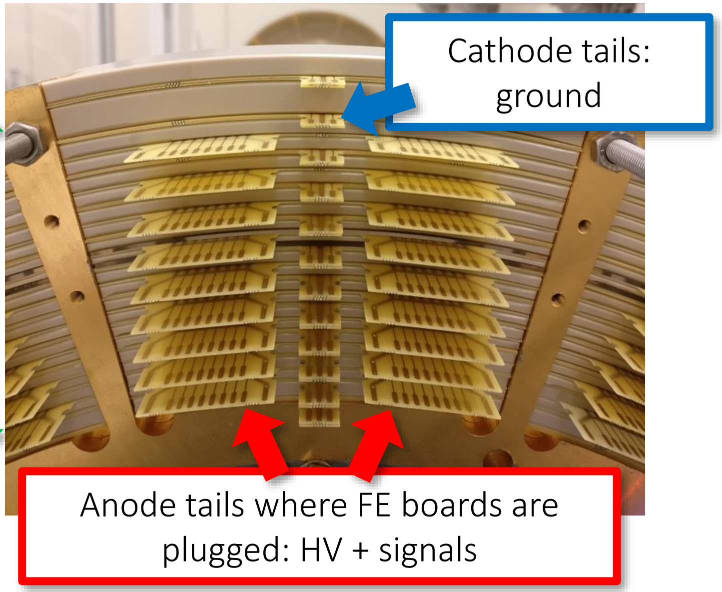
- Wires are soldered at both ends on the pads of 2 PCBs (wire-PCBs) which are then mounted in proper slots of the CDCH endplates
- Wiring inside a cleanroom

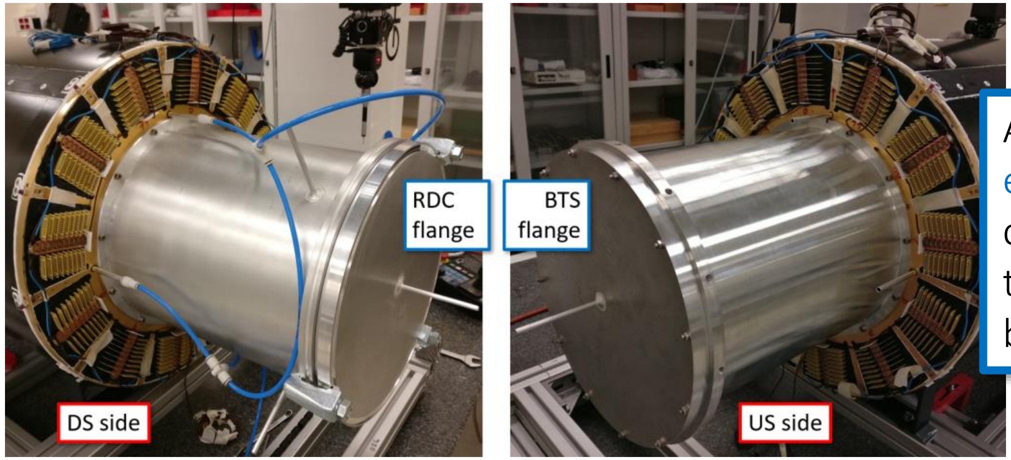
- Anode wires: 20 μm Au-plated W
- Cathode wires: 40/50 μm Ag-plated Al
  - **40 μm ground mesh between layers**
- Guard wires: 50 μm Ag-plated Al
- Field-to-Sense wire ratio 5:1



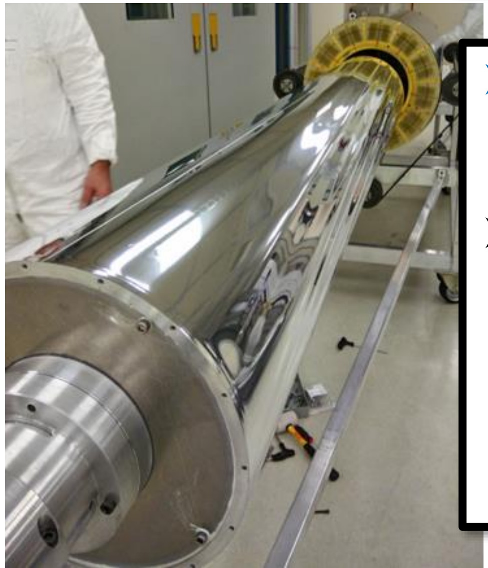
Mechanical structure

- Final stack of wire-PCBs in one sector
- PEEK spacers adjustment after CMM geometry measurements
- **CDCH assembly inside a cleanroom**

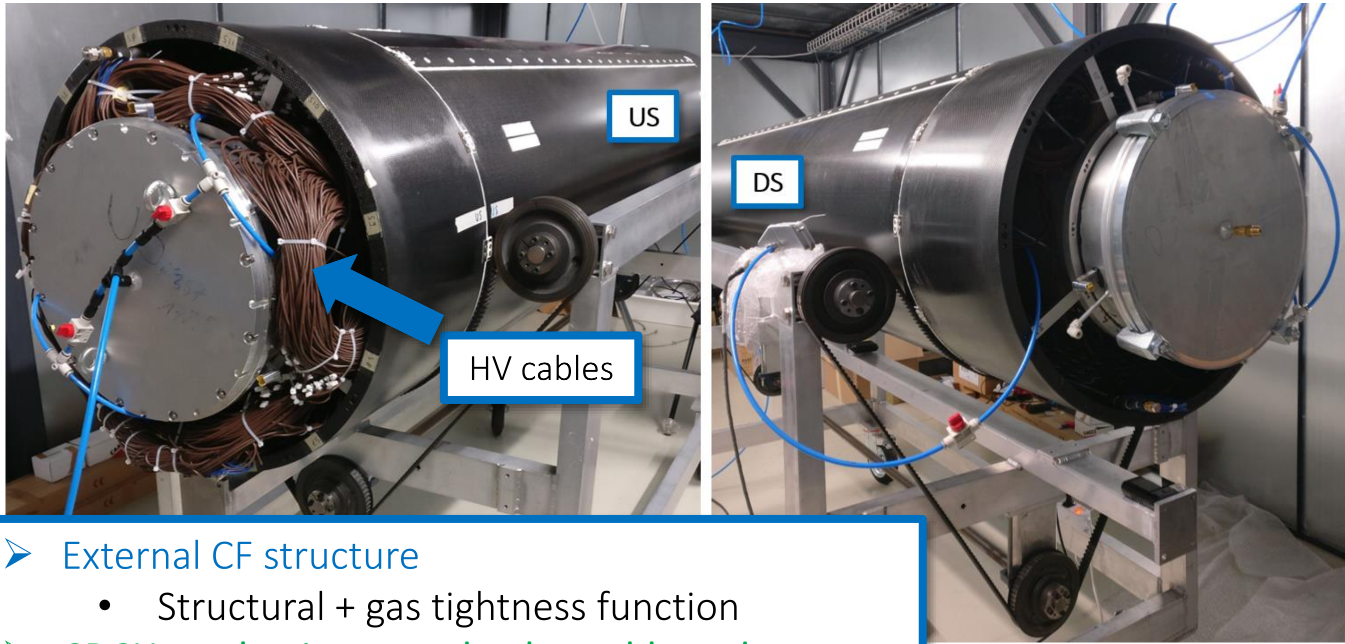




Aluminum inner extensions to connect CDCH to the MEG II beam line

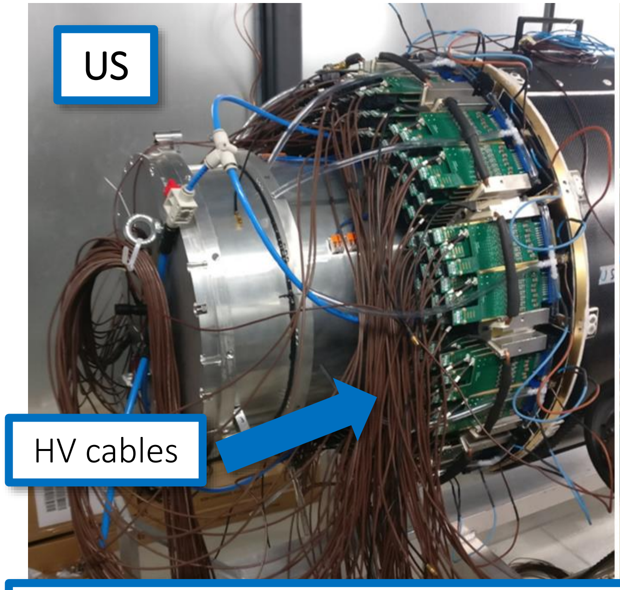


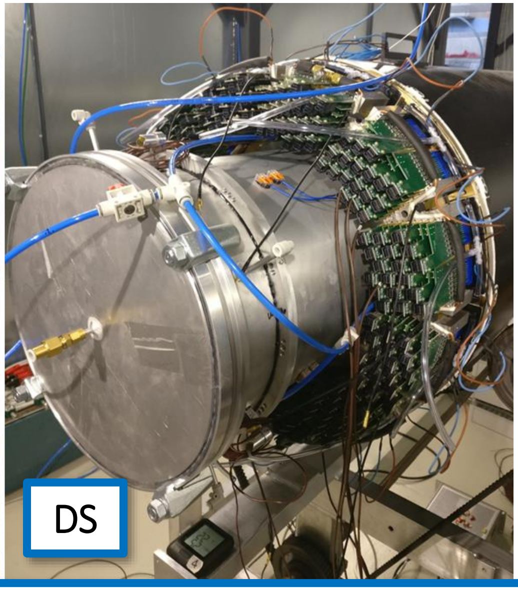
- 20 μm-thick aluminized Mylar foil at inner radius
- To separate the inner beam + target volume filled with pure He from the wires volume filled with He:IsoB 90:10 mixture



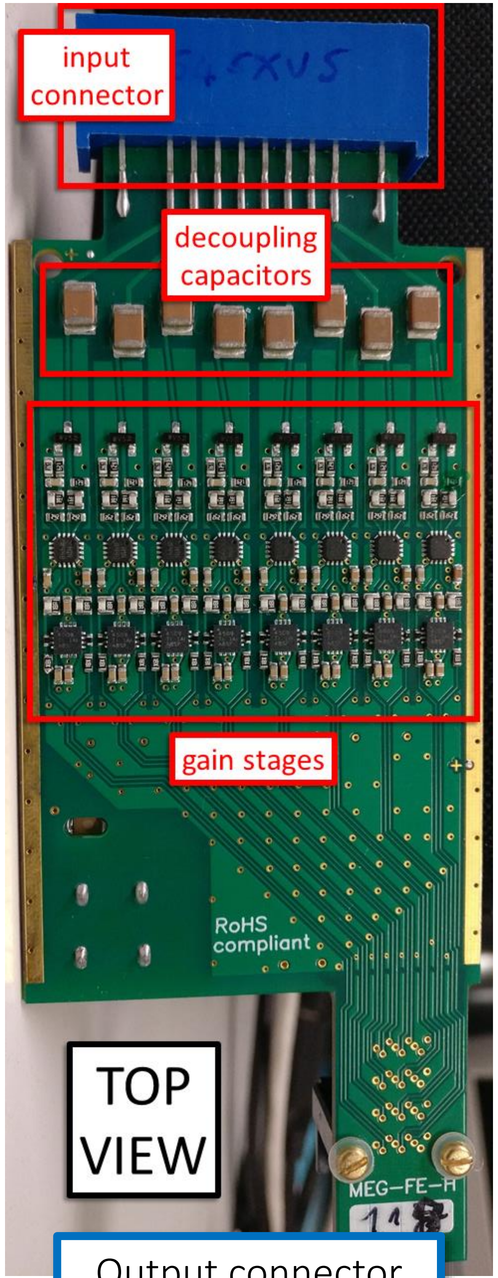
- External CF structure
  - Structural + gas tightness function
- CDCH mechanics proved to be stable and adequate to sustain a full MEG II run

FE electronics

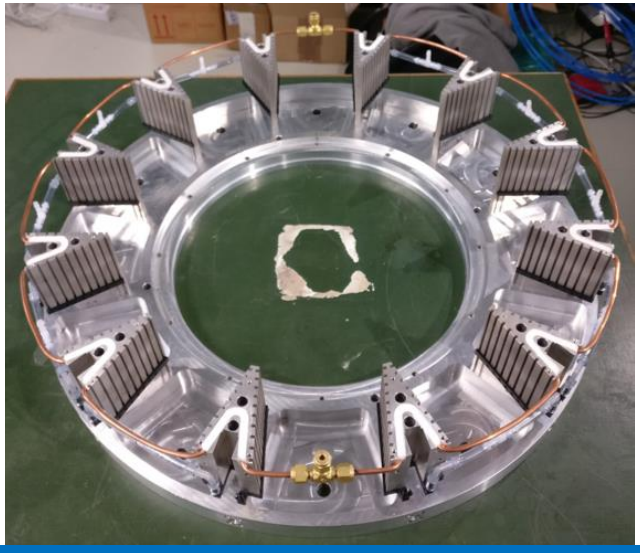




- 216 FE boards per side
  - **8 differential channels** each to read out signal from 8 cells
  - **Double amplification stage** with low noise and distortion
  - **High bandwidth of nearly 900 MHz**
    - To be sensitive to the single ionization cluster and improve the drift distance measurement (cluster timing technique)
- Signal read out from both CDCH sides
- HV supplied from the US side

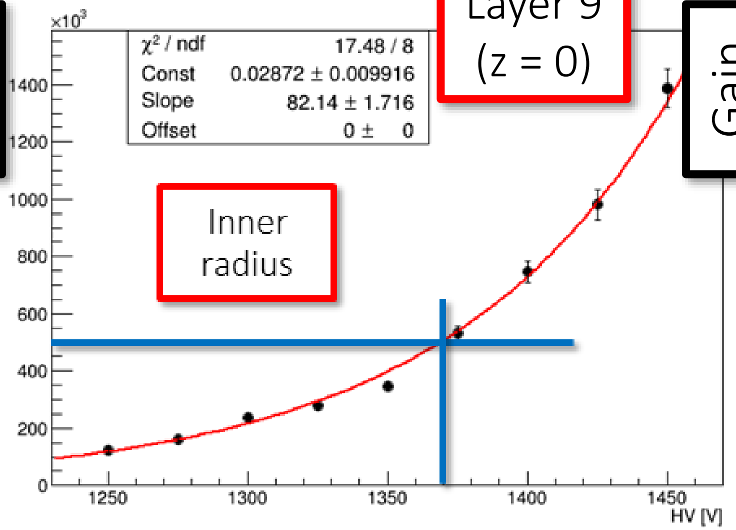


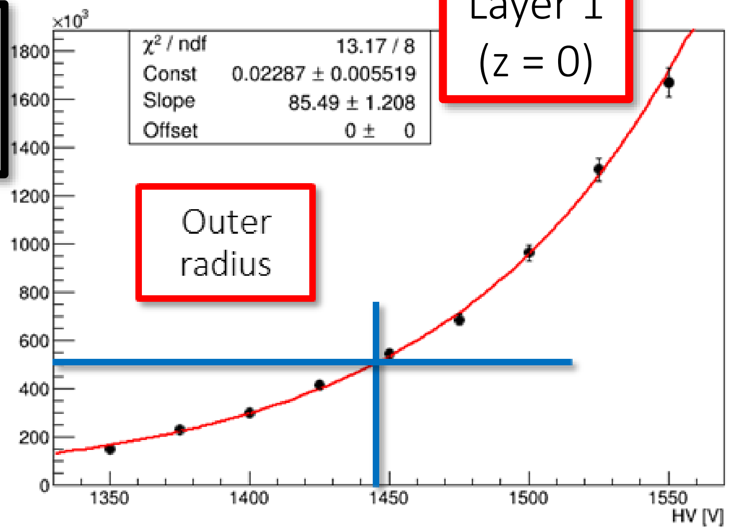
Output connector and HV stage on the bottom side



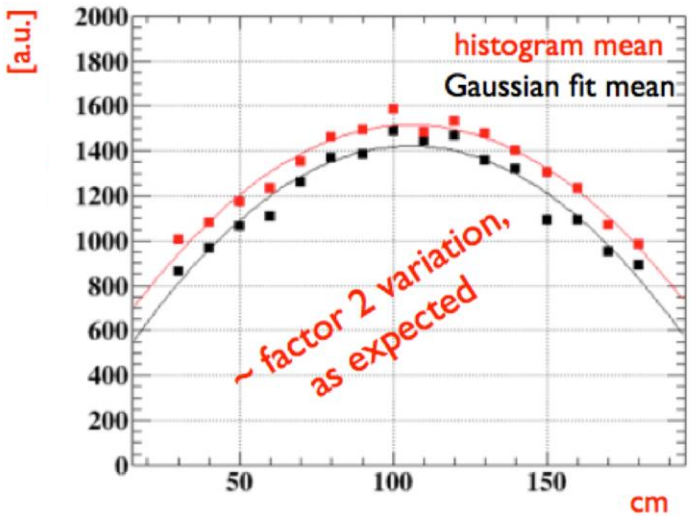
- FE electronics cooling system embedded in the board holders
  - Power consumption for each channel: 60 mA at 2.5 V
  - Heat dissipation capacity granted by a **1 kW chiller system**: 300 W/endplate
- Dry air flushing inside the endcaps to avoid water condensation on electronics and dangerous temperature gradients

HV working point





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



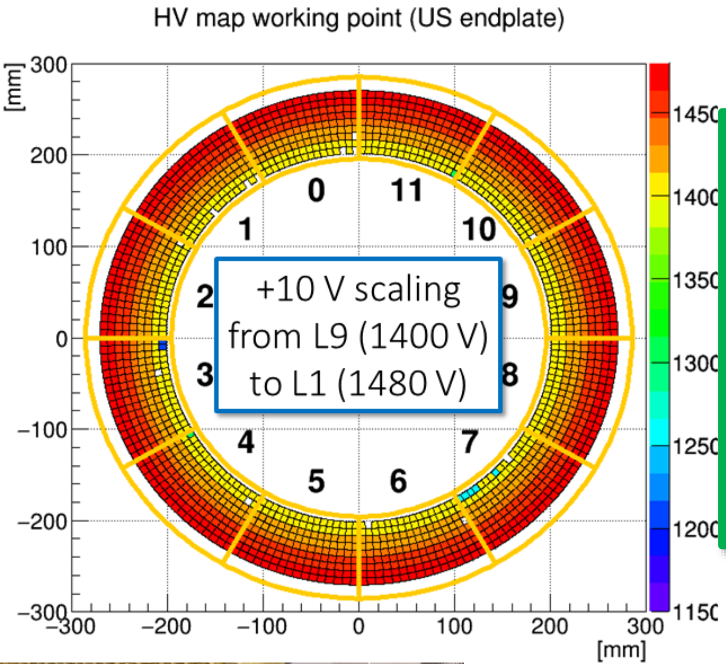
- **Garfield simulations on single electron gain**
  - Gas mixture He:Isobutane 90:10 and P = 970 mbar (typical at PSI)
- Working point ➜ HV for gain $G = 5 \times 10^5$
  - To be sensitive to the single ionization cluster

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

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

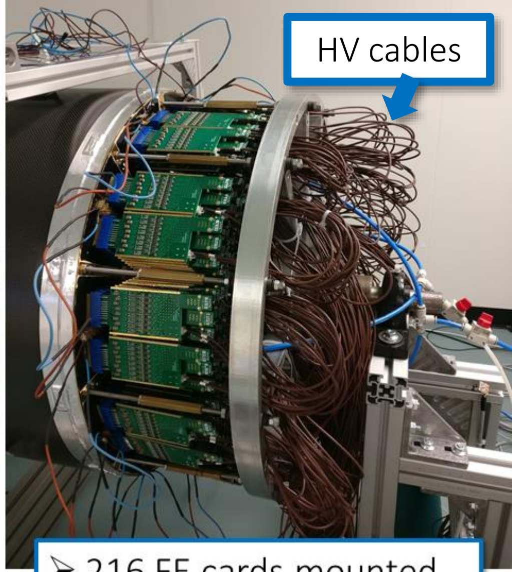
Working length



Cell inefficiency experimentally measured

- Negligible in e^+ reconstruction
  - 0.3% worsening in resolutions
- Tests with high statistics full MC

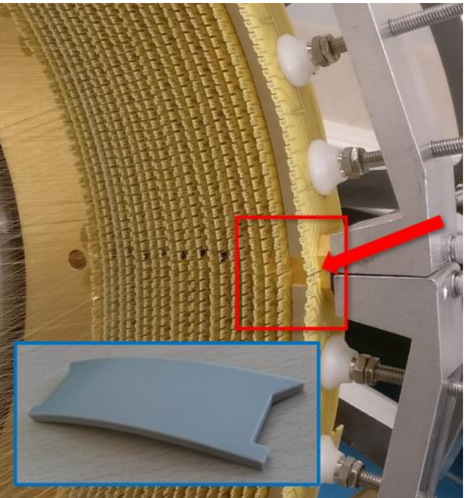
- CDCH temporarily sealed with CF + Al tape
- Nitrogen flux



- 216 FE cards mounted on the US side

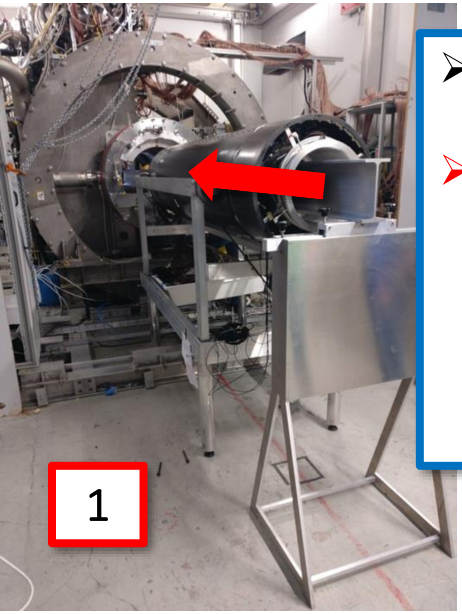
Final CDCH length experimentally found through systematic HV tests at different lengths/wires elongations

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

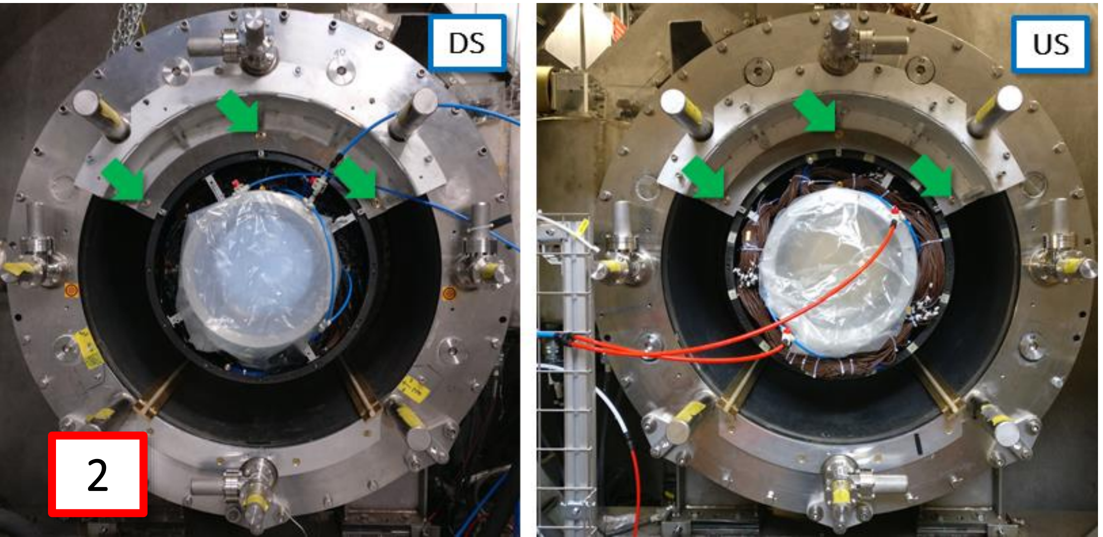


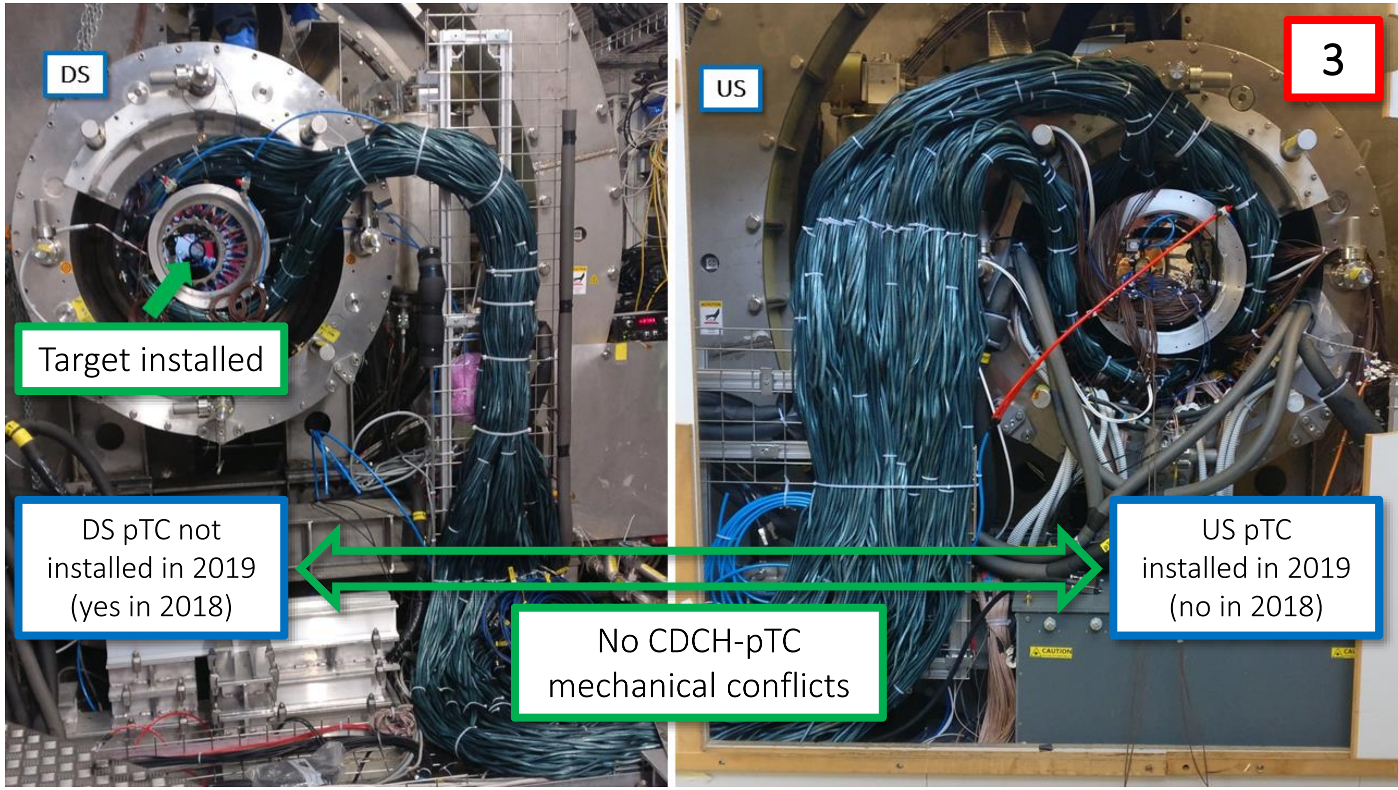
- **Some drift cells at the border between 2 adjacent sectors presented electrostatic instability**
- Due to wire-PCB geometry
- Once the PEEK spacers are mounted the correct circular shape is expected to be recovered
- But sometimes deformations O(a few hundred μm) remain causing electrostatic instabilities
- **HV kept at lower values for the involved cells**

Integration into the MEG II apparatus



- CDCH inside the πE5 area
- Insertion rail through the inner volume to slide CDCH inside the COBRA magnet





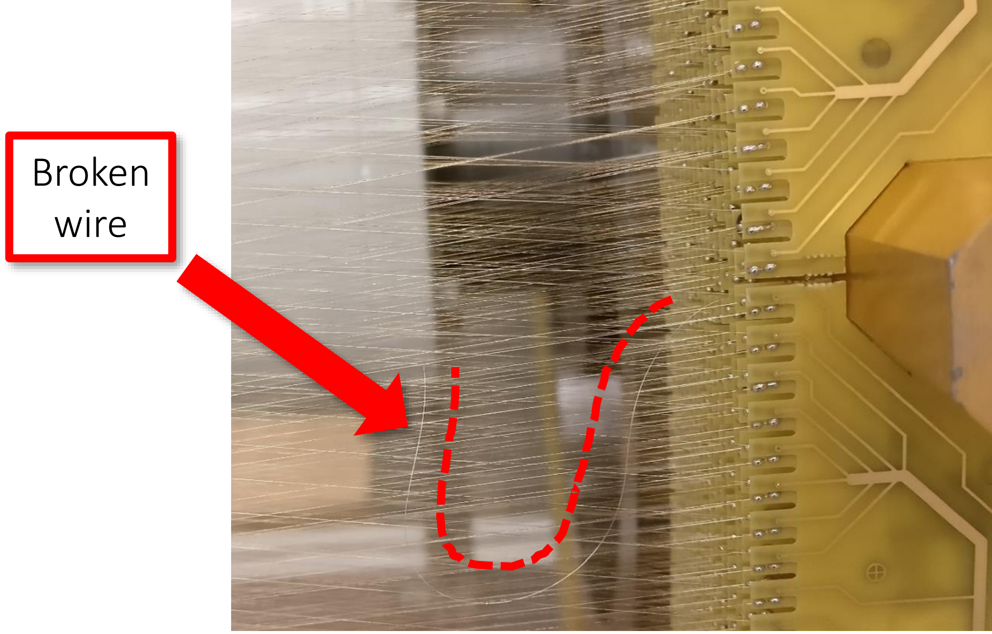
- CDCH locked in the final position hanged to COBRA
- Gas inlet/outlet connection to the MEG II gas system

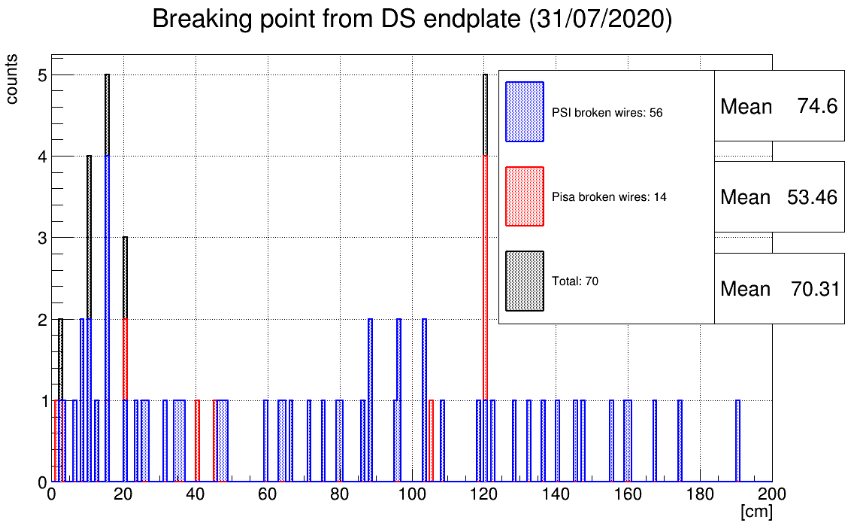
- Signal/HV cabling
- Cooling pipes routing
- Beam line completion is the last operation (not shown here)

Investigations on wire breakages

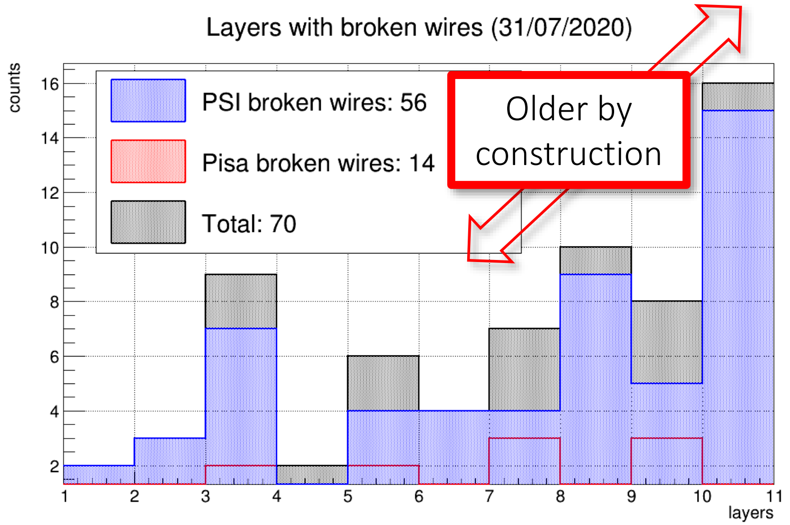
Wire breakages

- During assembly at Pisa and the final lengthening operations at PSI we experienced the breakages of Al wires in the chamber
  - Mainly the 40 μm cathodes were affected
  - A few 50 μm cathodes and guards
- **70 broken wires in total during CDCH life** (14 at Pisa)
  - 63 cathodes (40 μm)
- **Consequent delay in construction and commissioning**



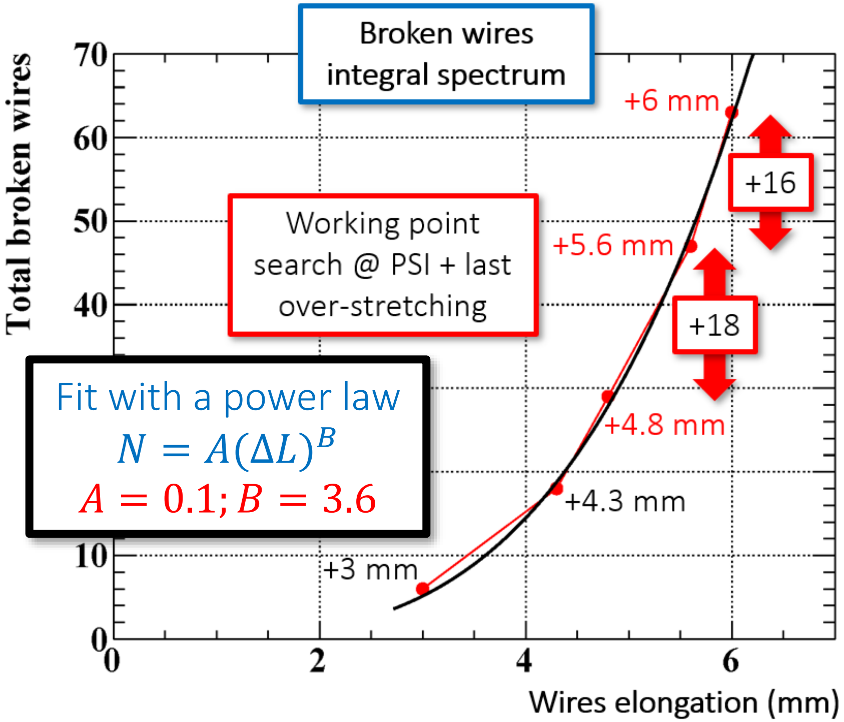


Wires length ≈ 193 cm



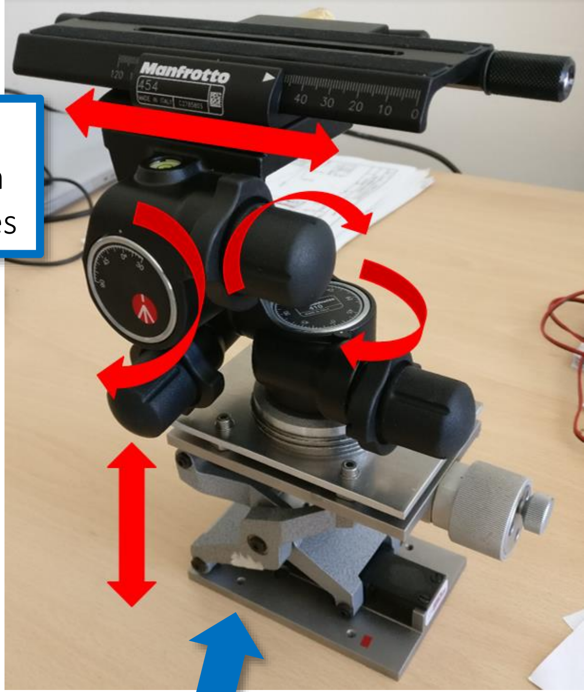
Outer layers

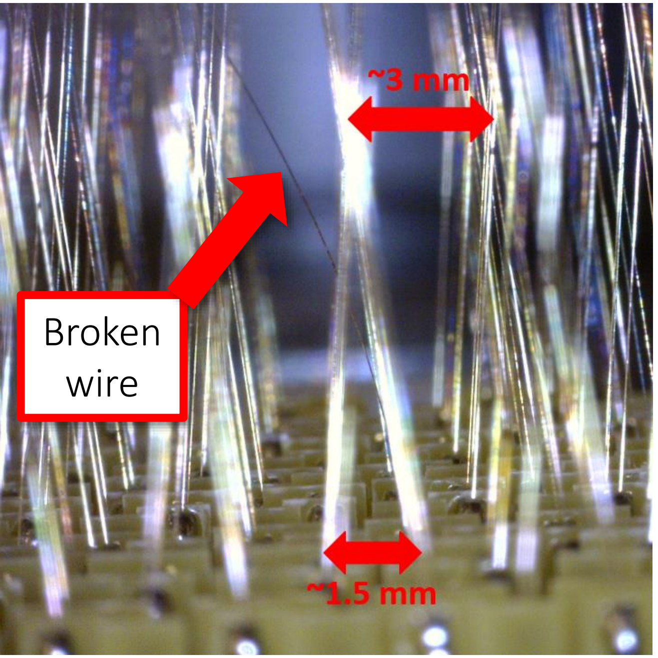
Inner layers



Broken wires extraction

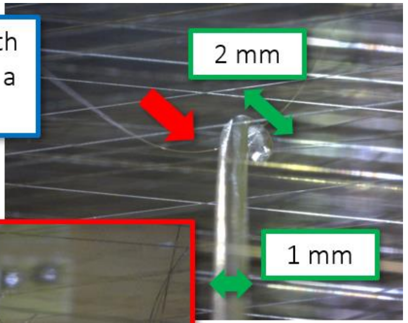
Commercial camera mount with precision movements for all axes



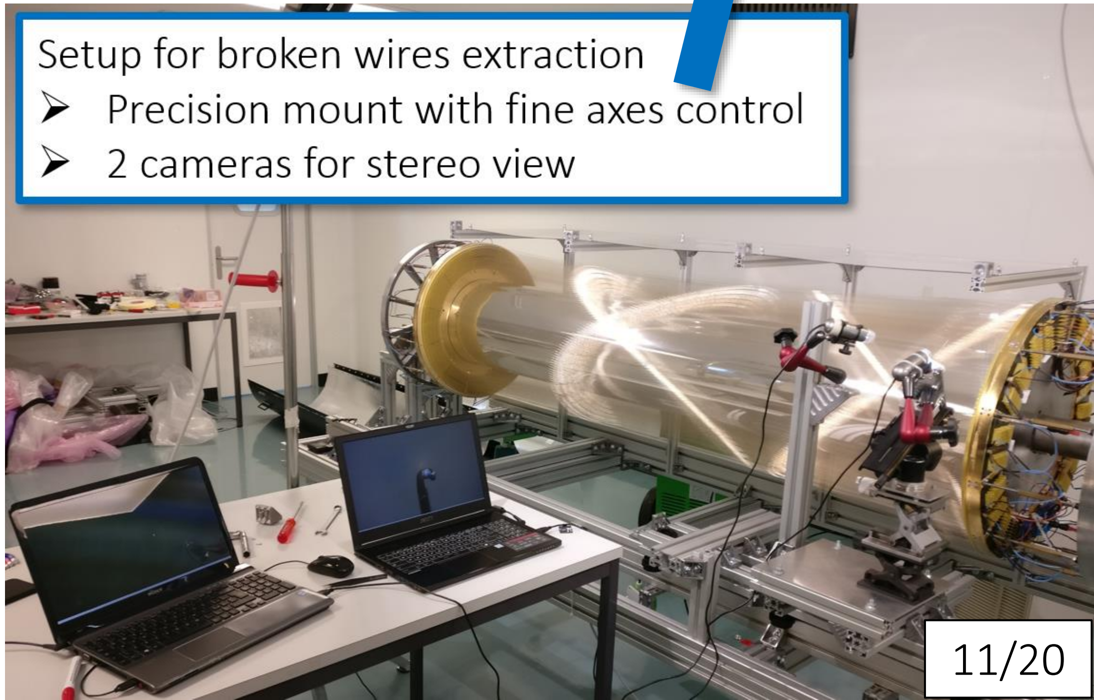


- Each broken wire piece can randomly put to ground big portion of the chamber
- They must be removed from the chamber
  - Very delicate and time-consuming operation
- We developed a safe procedure to extract the broken wires from inside CDCH
  - Exploiting the radial projective geometry given by the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

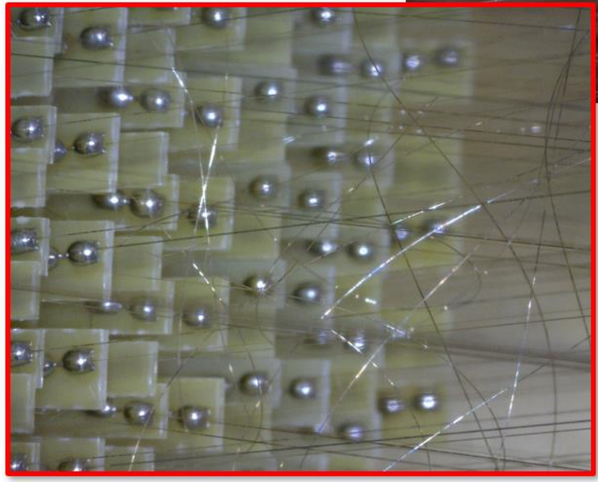
Example of extraction with a broken wire hooked by a stainless steel rod



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

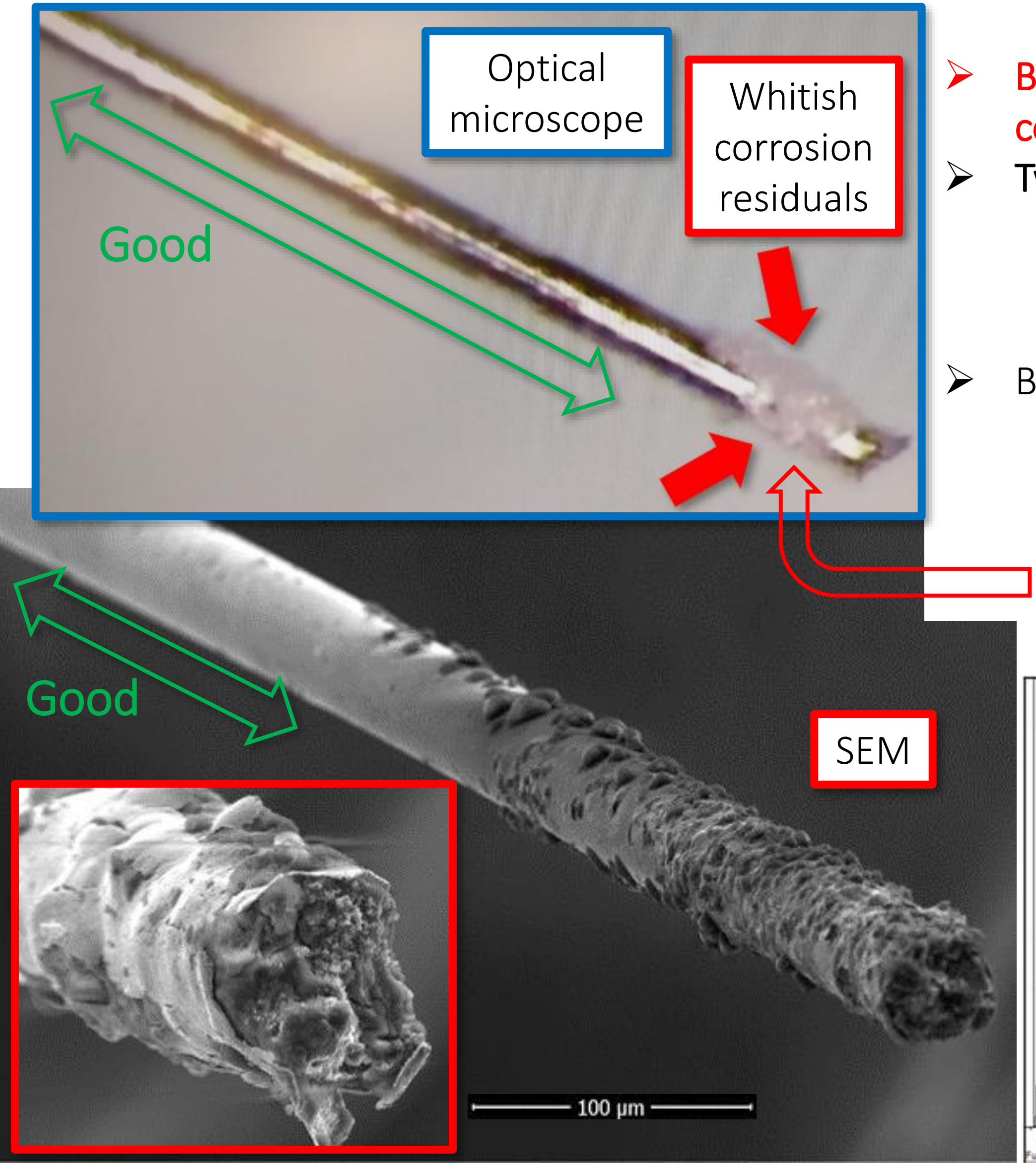


1. Enter with a small tool inside the chamber (few mm space)
2. Hook the wire piece as close as possible to the wire-PCB
3. Extract the wire segment
4. Pull it perpendicularly in the radial direction to break it at the soldering pad

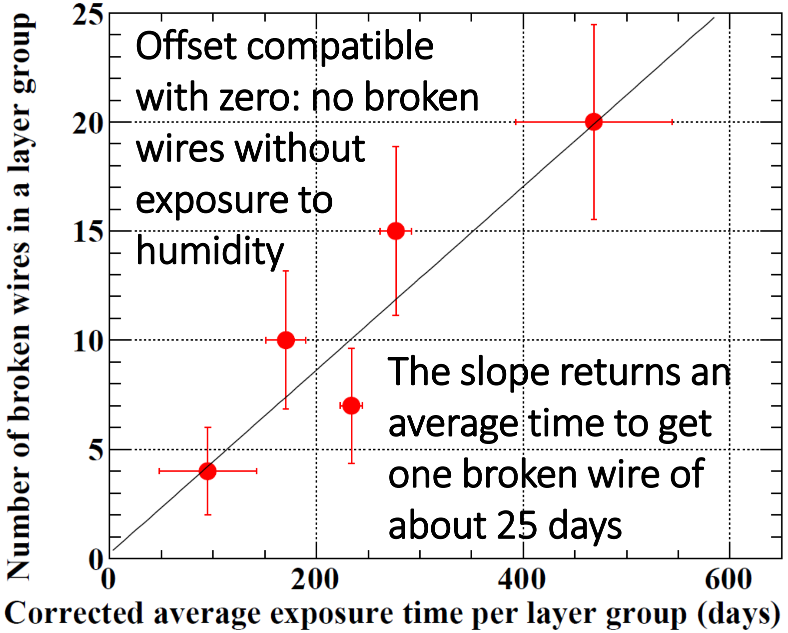


One of the worst case…

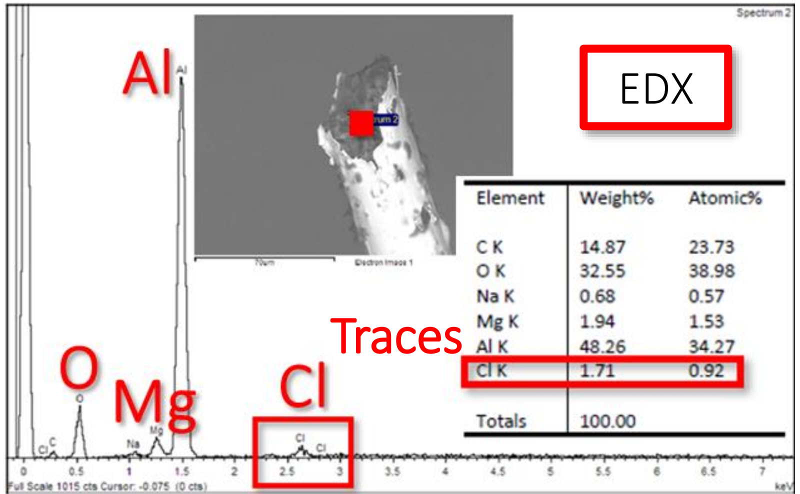
Investigations on wire breakages



- Breakages due to corrosion of the Al 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



- 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 for 2 years since CDCH was flushed with Nitrogen or Helium once sealed

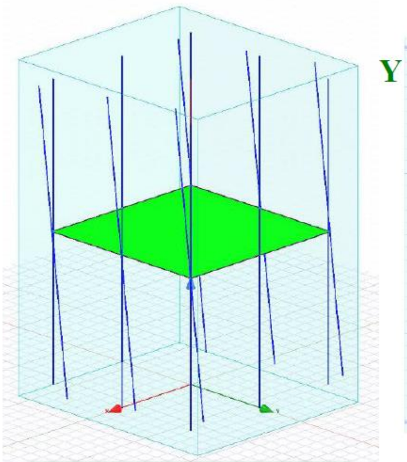


Element	Weight%	Atomic%
C K	14.87	23.73
O K	32.55	38.98
Na K	0.68	0.57
Mg K	1.94	1.53
Al K	48.26	34.27
Cl K	1.71	0.92
Totals	100.00	

Missing wire effect

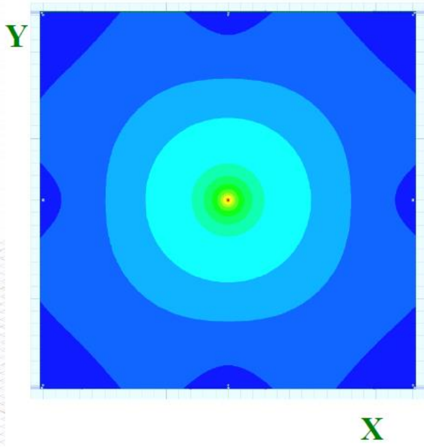
Drift distance vs. drift time relations computed with **Garfield**

ANSYS 3D model



Ideal case

E field



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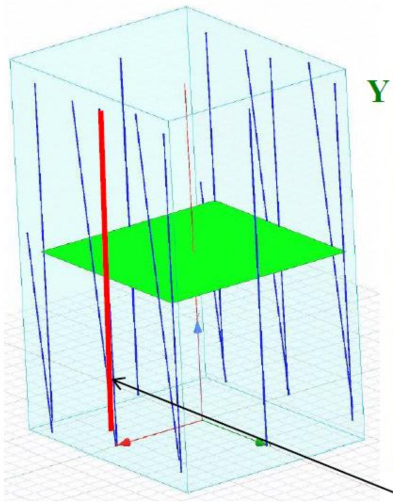
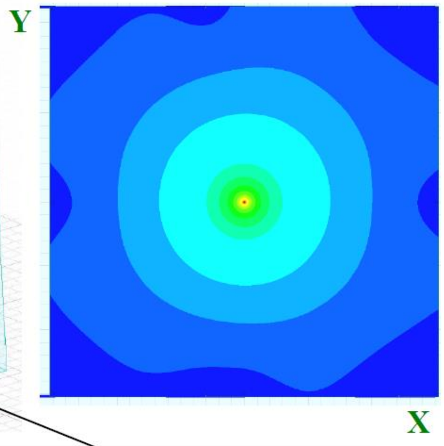
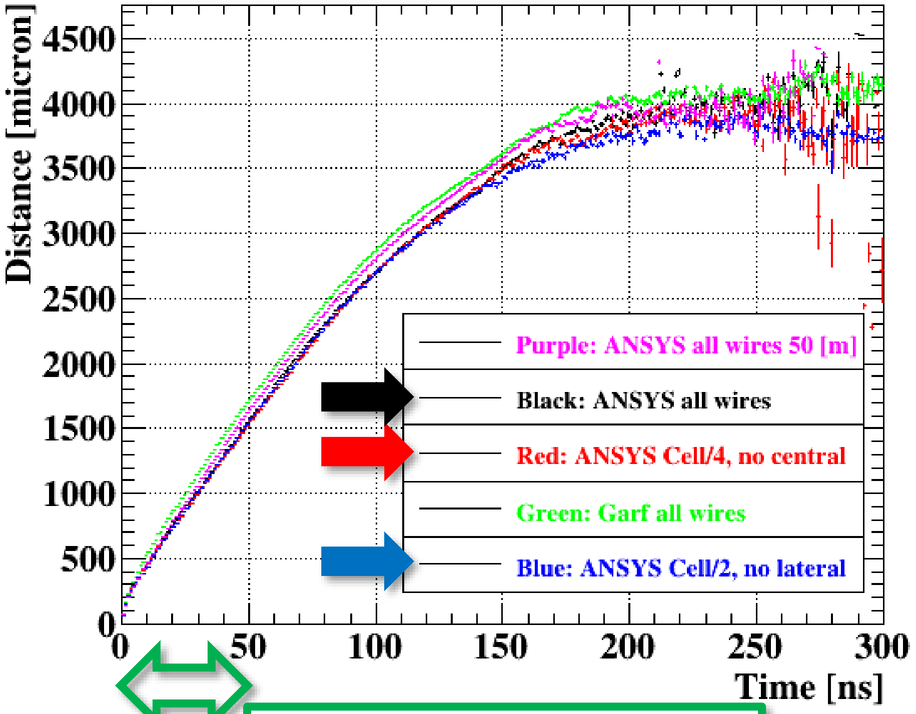
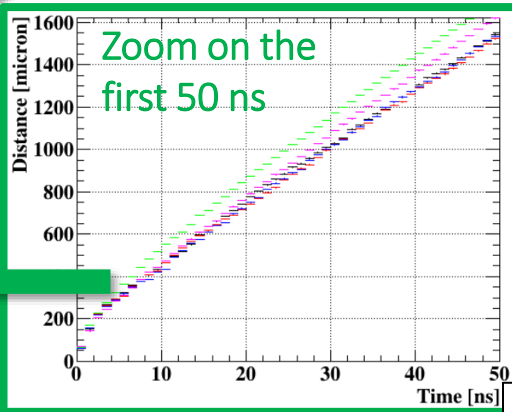


Missing wire removed

E field





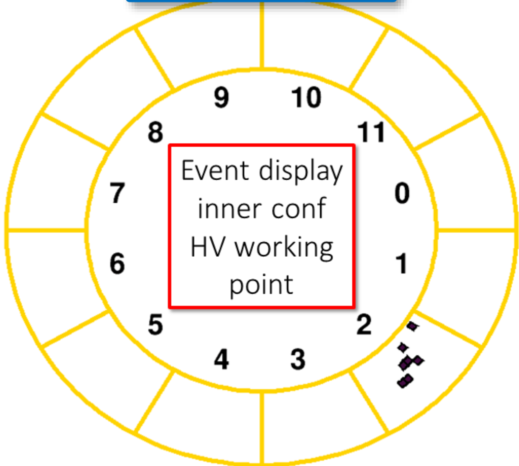


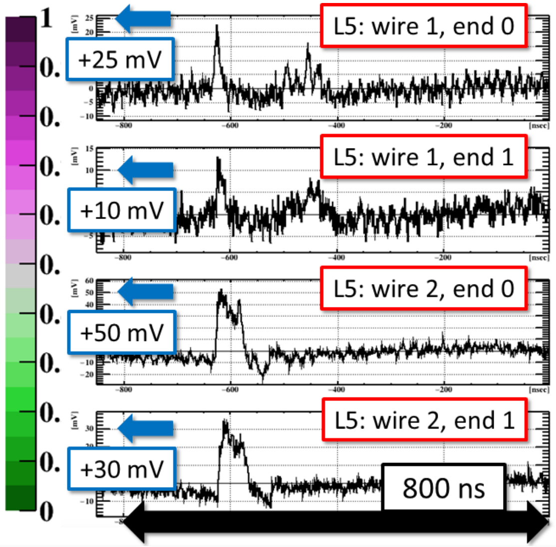
- ➢ Study the effect of a missing cathode on isochrones → e^+ reconstruction
- ➢ Used **Garfield** and **ANSYS** to **simulate the electric field in a $6 \times 6\ \mathrm{mm}^2$** representative drift cell
  - Single-hit resolution $\sigma_{hit} < 120\ \mu\mathrm{m}$
  - Difference between different curves → $\approx 10\ \mu\mathrm{m}$
- ➢ Missing wire effect negligible

A few examples from data taking

First collected data

Cosmic ray

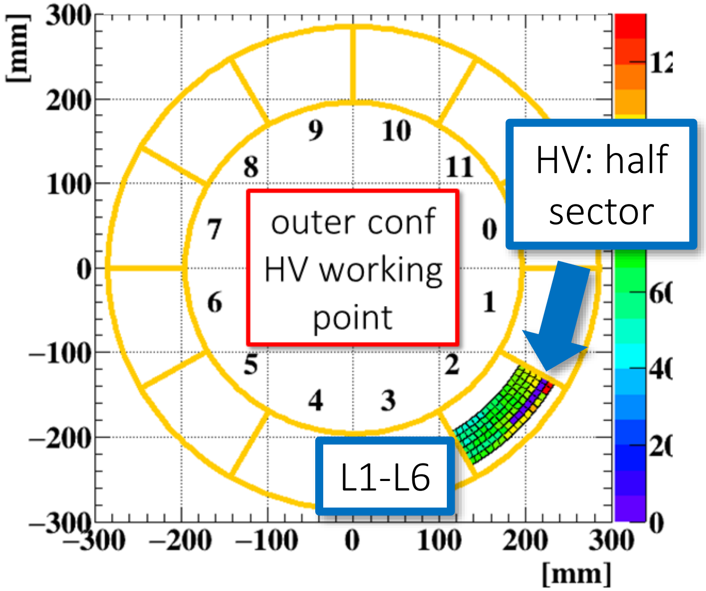




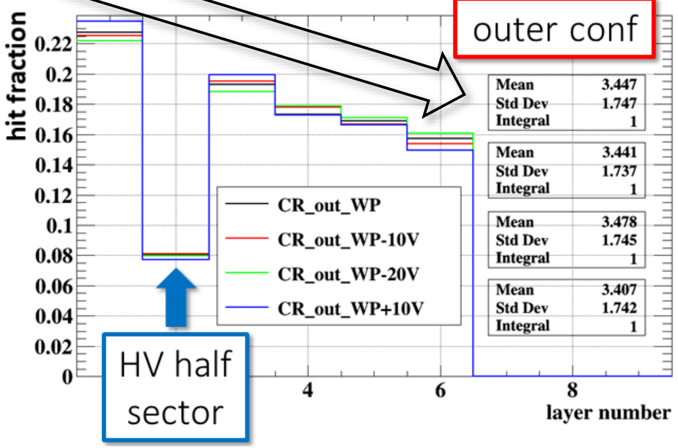
Only a limited number of DAQ channels is available

- 192 in 2018 and 2019
  - 6 layers in one sector
  - Inner configuration (L4-L9)
  - Outer configuration (L1-L6)
- 256 in 2020
  - Data taking ongoing
- Expected full read out in 2021

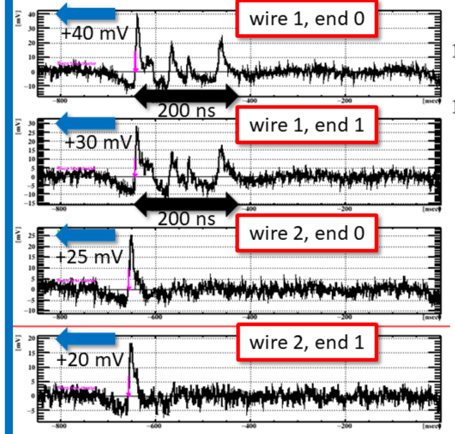
25000 events from cosmics



Occupancy L1-L6 from data



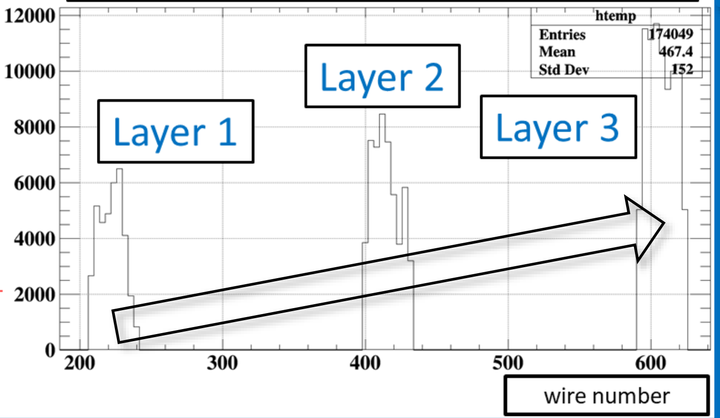
Signal WF on L3: 1460 V at low intensity



Hit scaling of Michel e^+ as expected

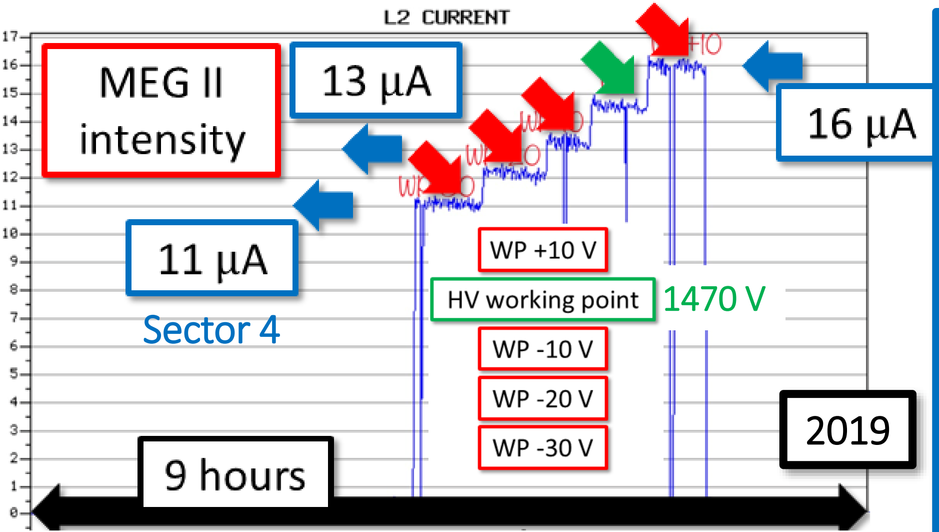
Occupancy: 1460 V at MEG II intensity

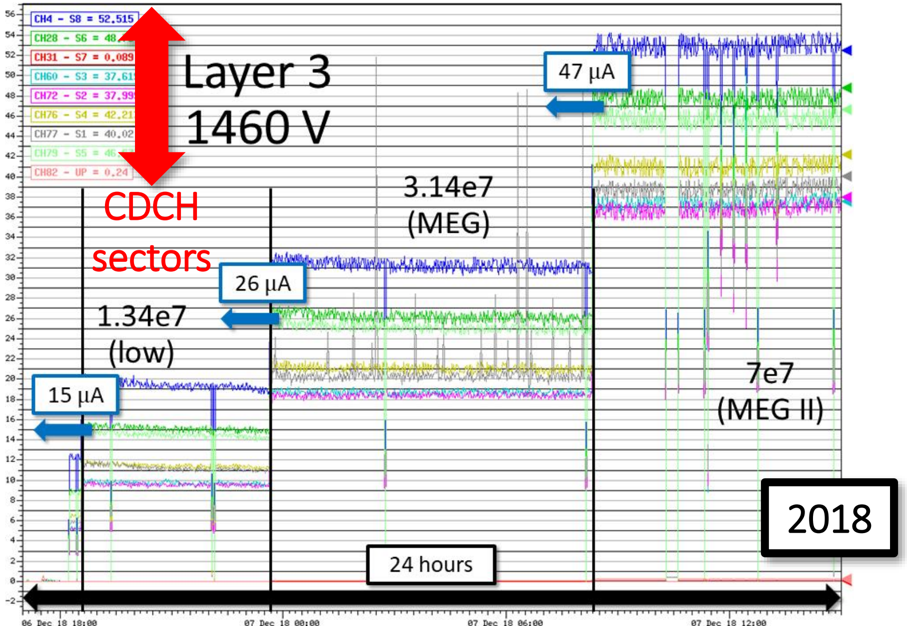
μ⁺ beam



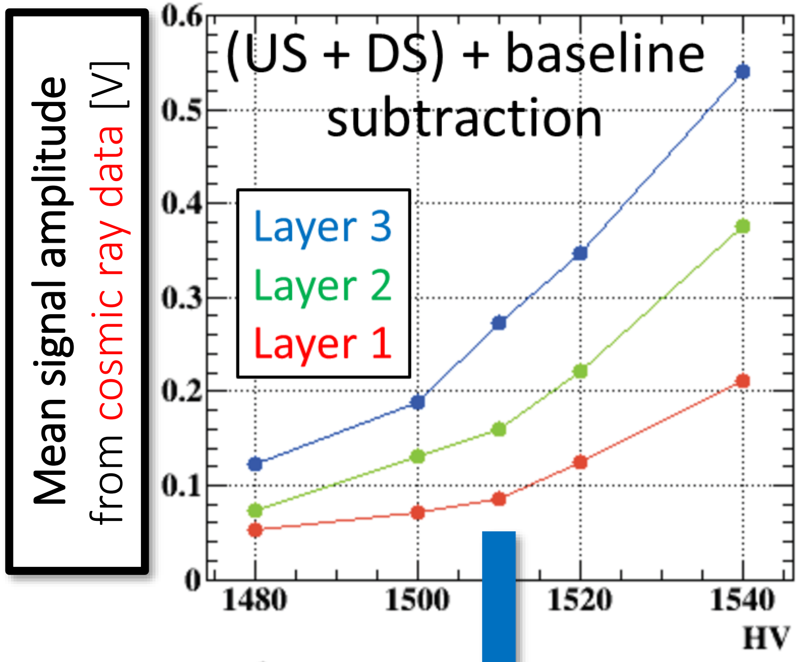
- Hit scaling as expected from the outer layer (L1) to the inner layer (L9)
- Different HV configurations tested around the working point

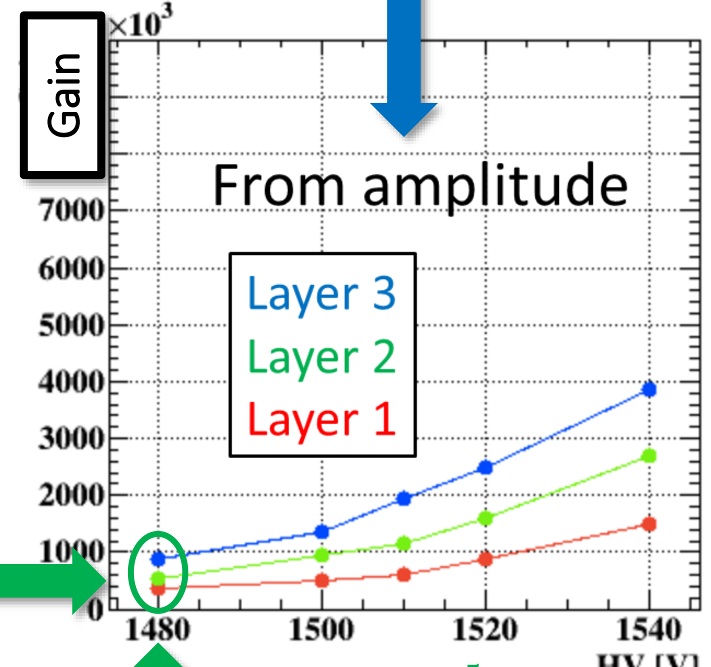
First gain studies





- Example of gain curves for L2 and L3
  - Currents drawn by the HV channels with **μ^+ beam at different intensities**
- ~ exponential behaviour in the current value with the HV increase as expected from simulations





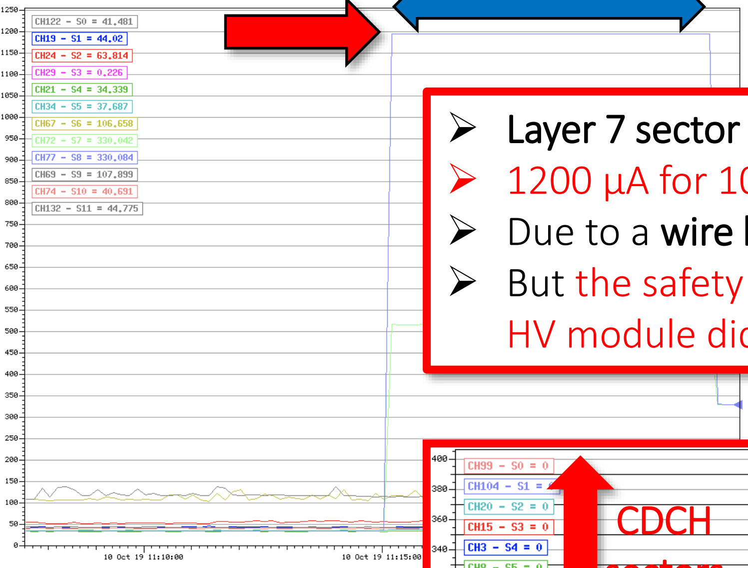
The mean amplitude from cosmic ray data are converted into the effective gas gain G

- By means of simulations of the ionization clusters and the response of the FE amplification stage
- **Calibrated gain curves in agreement with simulations**

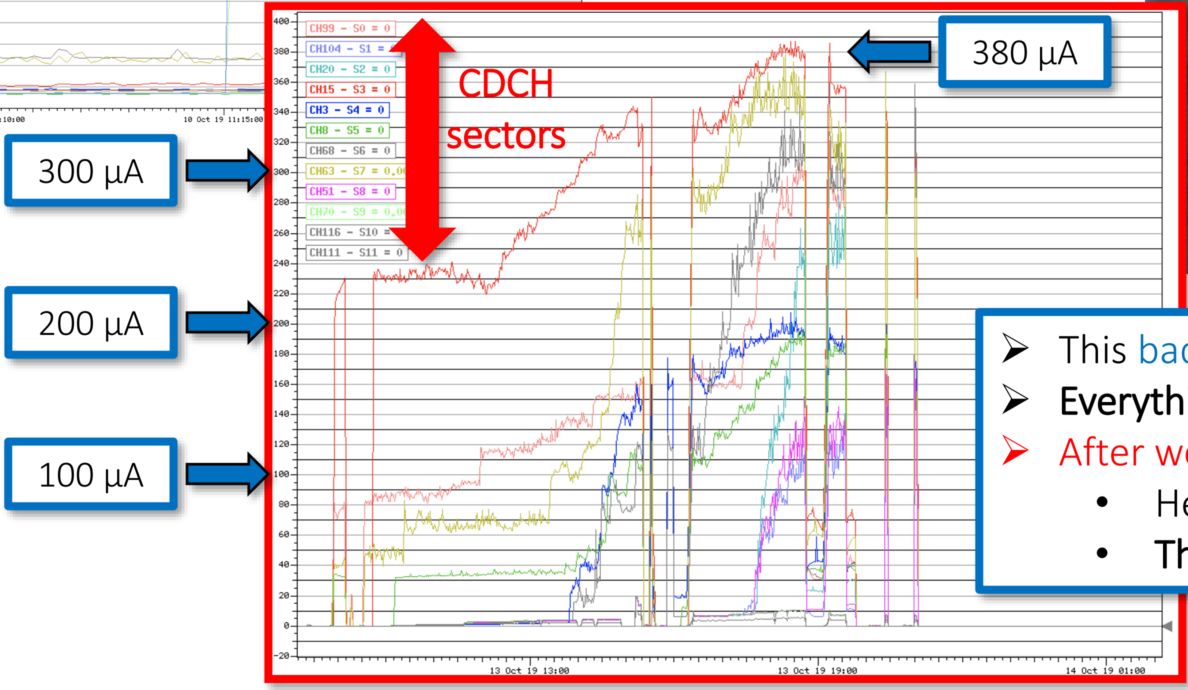
$G \approx 5 \times 10^5$ at Working Point

Investigations on high currents

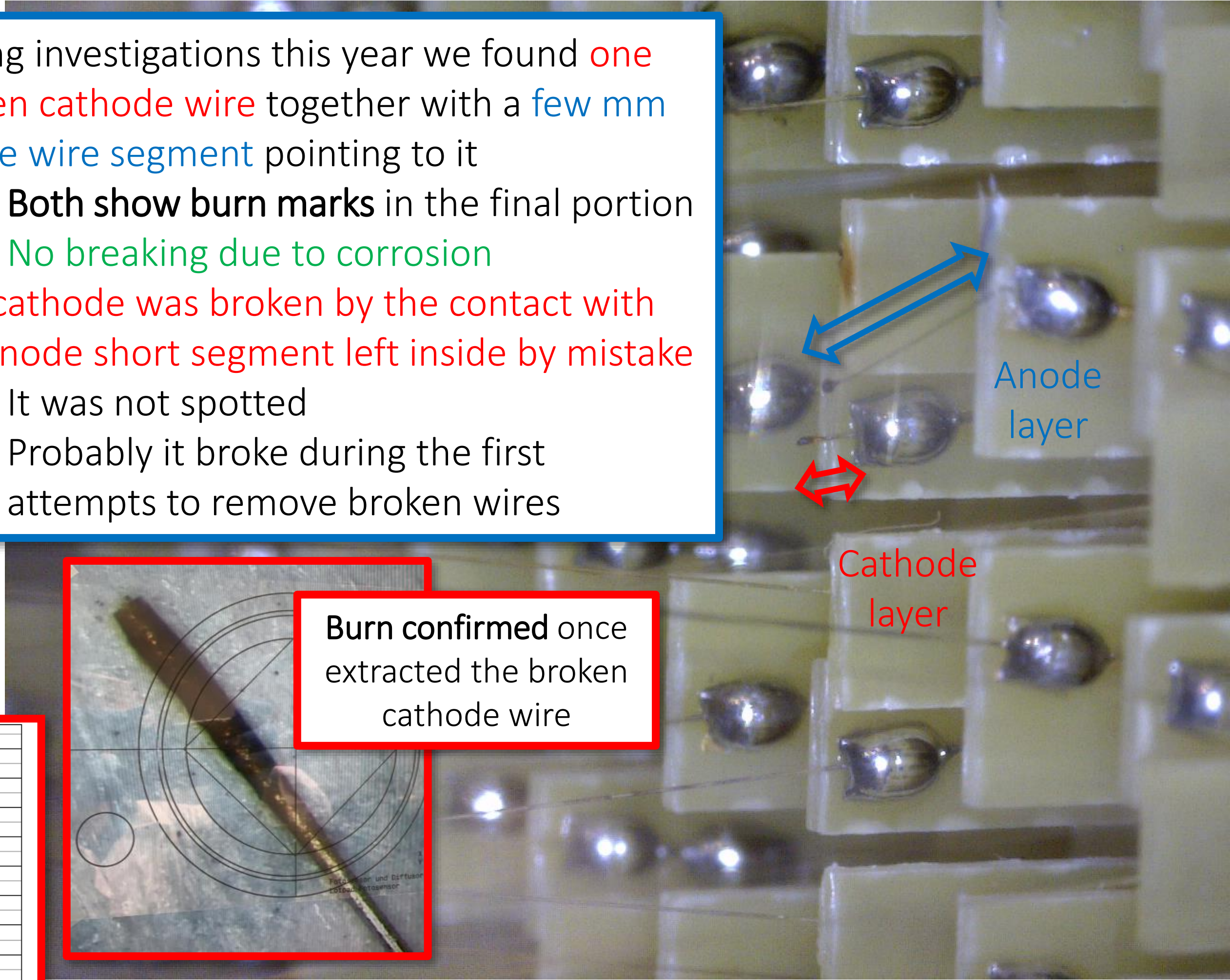
Bad event last year



- Layer 7 sector 8
- 1200 µA for 10 minutes
- Due to a **wire breaking**
- But the safety control of the HV module did not work



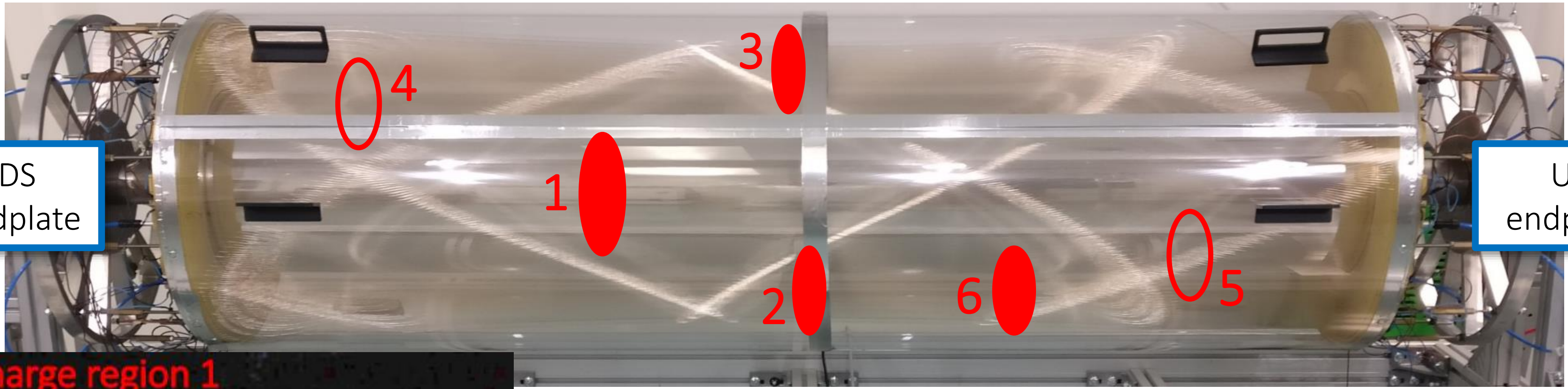
- During investigations this year we found one broken cathode wire together with a few mm anode wire segment pointing to it
  - **Both show burn marks** in the final portion
  - No breaking due to corrosion
- This cathode was broken by the contact with the anode short segment left inside by mistake
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

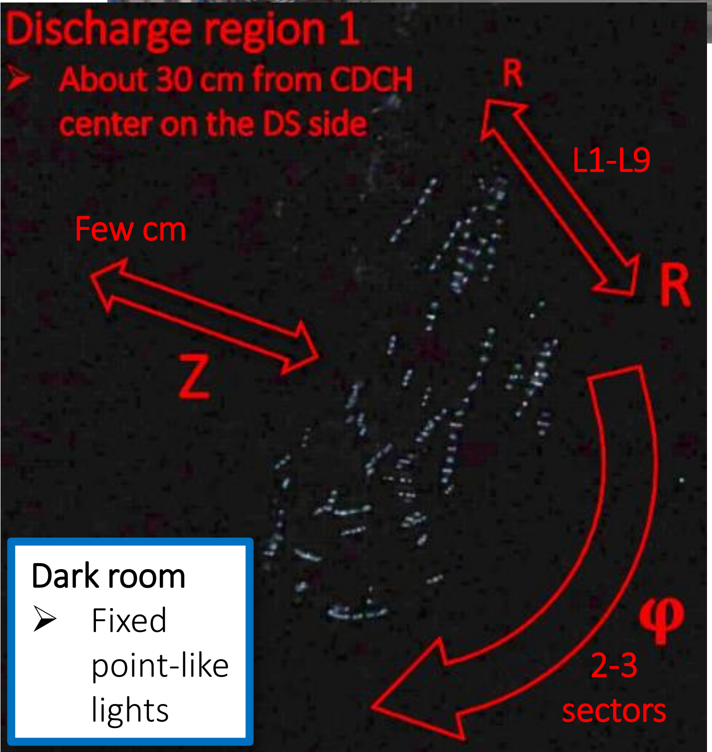


Burn confirmed once extracted the broken cathode wire

- This bad event occurred during the Michel e^+ data taking with μ^+ beam
- **Everything was good up to this moment**
- After we experienced anomalous high currents is several sectors/layers
  - Here an example for layer 2 at the HV working point + beam ON
  - **The problem has been investigated and it is not fully understood yet**

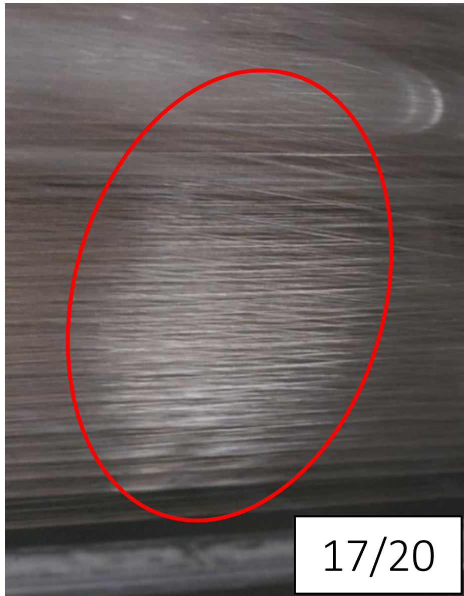
Investigations on high currents



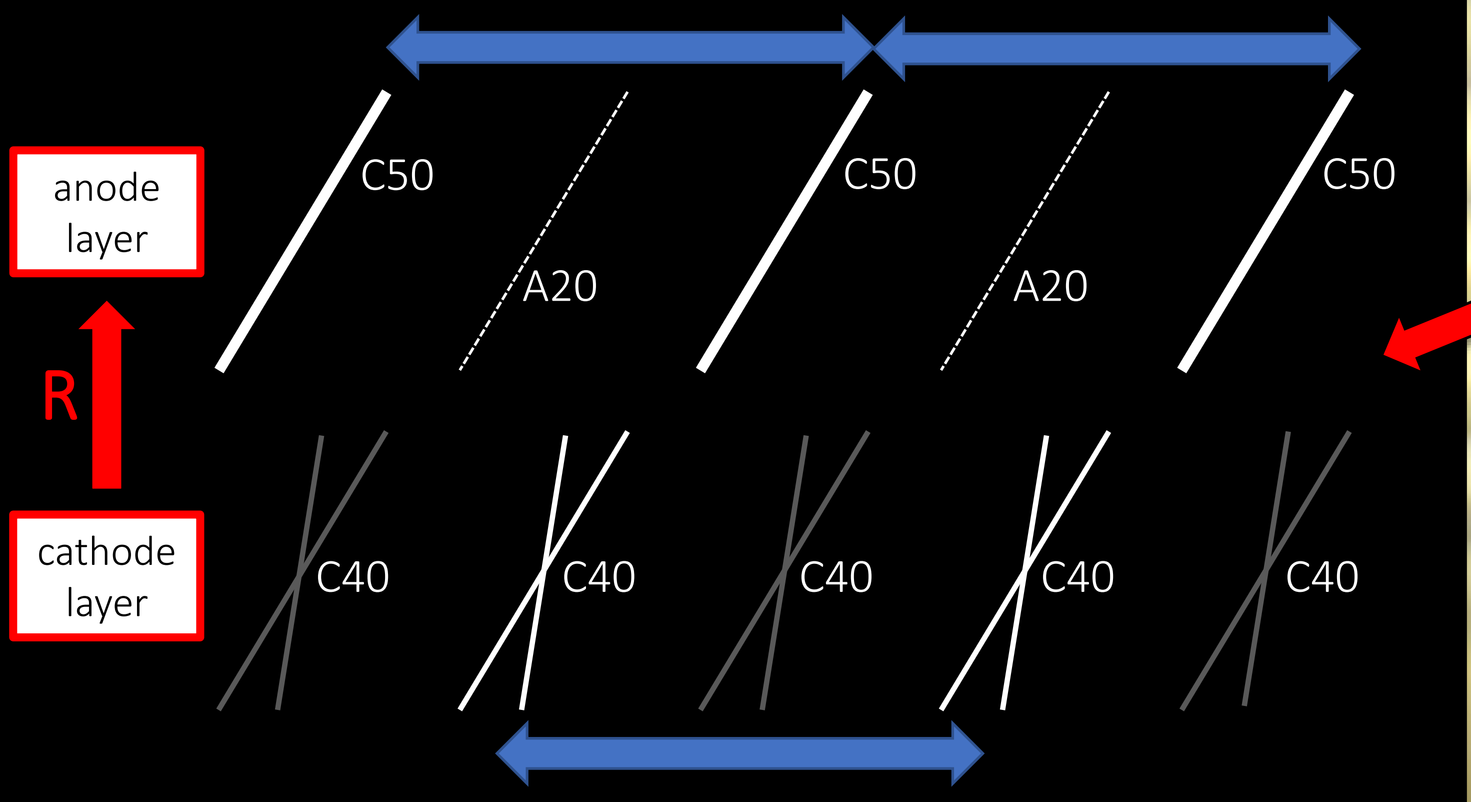


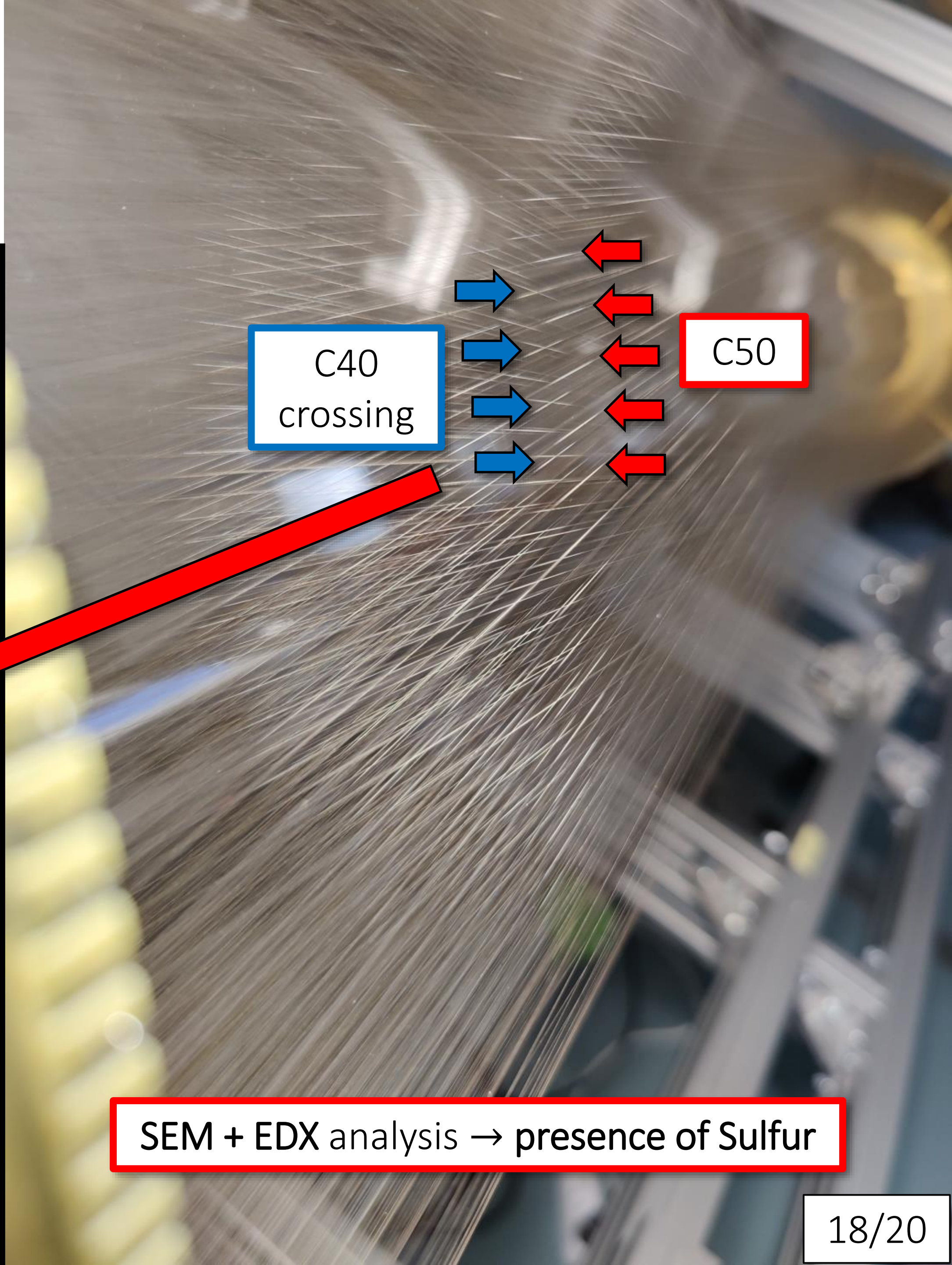
- We performed HV tests with CDCH closed with a transparent shell and filled with the standard He:IsoB 90:10 gas mixture
- We saw corona-like discharges in correspondence of 6 whitish regions
- **Further investigations are ongoing during the 2020 data taking run**
- We are trying different additives to the standard gas mixture to **test the CDCH stability** and **try to recover the normal operation**
  - 5% CO_2
  - 2000-4000 ppm of H_2O
  - From 500-600 ppm to 1% of O_2 (also in combination with H_2O)
- Oxygen seems to be effective in reducing high currents (plasma cleaning?)

Two of the discharge regions



Pattern in the white spots





- White spot in correspondence of the 40 µm cathode wire crossing points
- The period is that of the 50 µm cathode wire: higher E field?

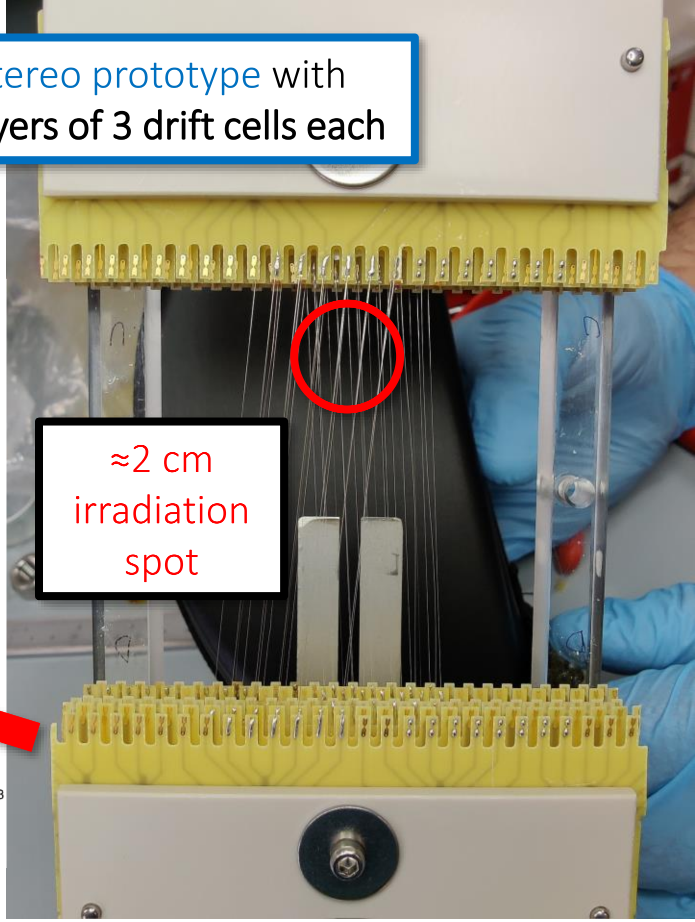
SEM + EDX analysis → **presence of Sulfur**

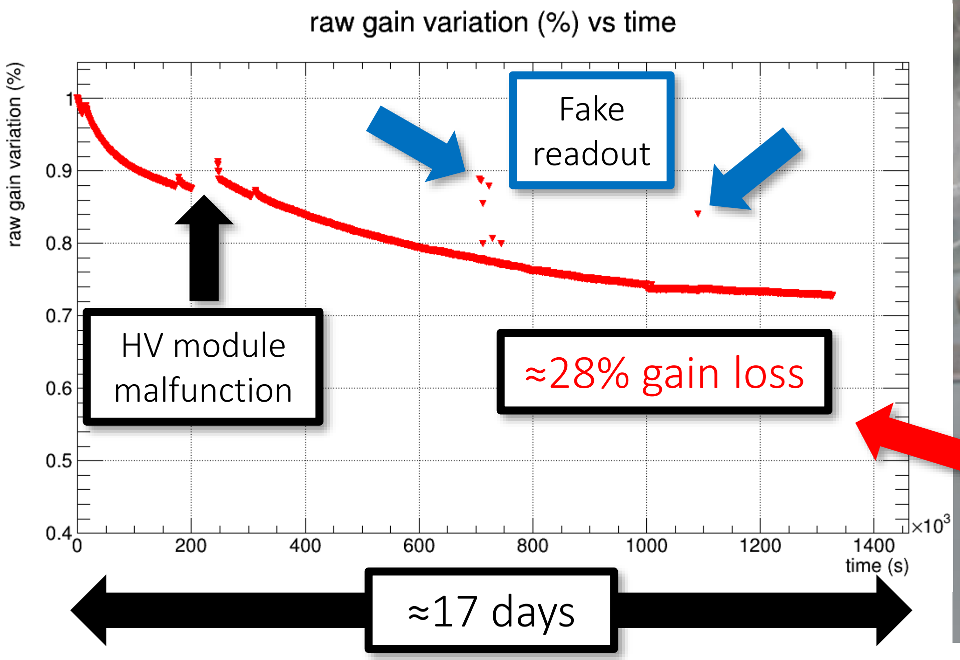
Accelerated ageing tests on prototypes

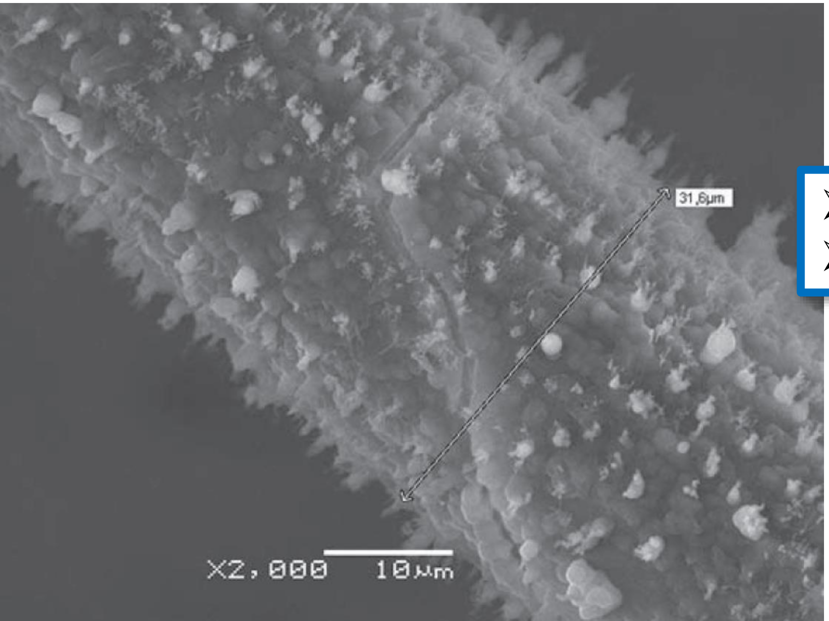
Ageing tests on prototypes

- Accelerated ageing tests on different prototypes were performed
- Prototypes with increasing complexity were used
  - From a 1-cell prototype to a **small 2-layer stereo prototypes** (6 cells)
  - This latter is presented here and it featured the **same geometry and materials of the CDCH endplates**

Stereo prototype with 2 layers of 3 drift cells each

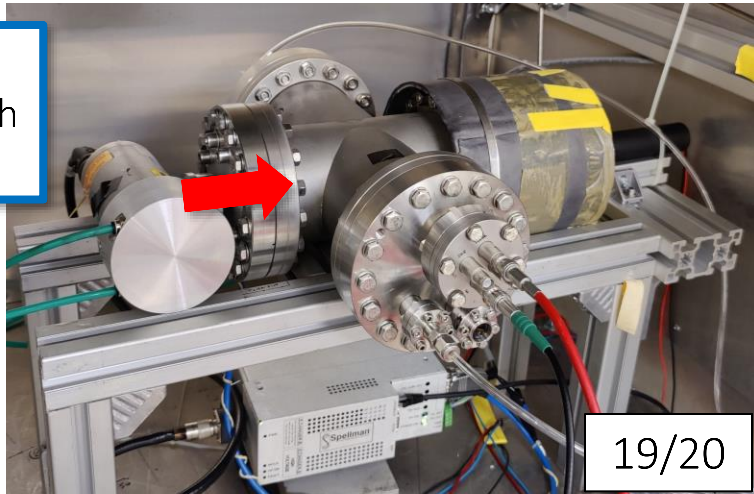






- SEM image of an aged anode wire
- No problems on cathode wires

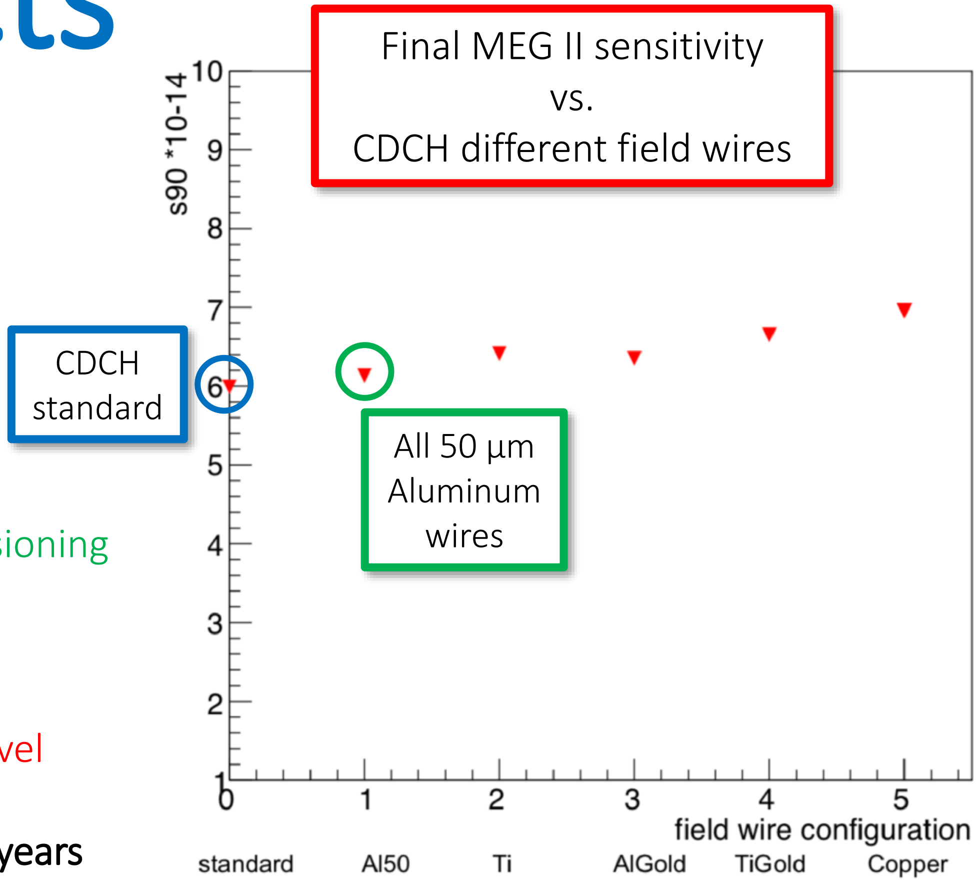
Ageing facility with X-ray gun



- Total **ageing acceleration factor 10 < *A* < 100**
  - Accumulated charge comparable to the total MEG II life
- No issues/discharges observed

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**: low MCS and background
  - **High granularity**: 1728 drift cells few mm wide in $\Delta R \approx 8$ cm active region
    - Improve angular and momentum resolutions of the e^+ kinematic variables
  - Stereo design concept, modular construction, light and reliable mechanics, fast and low noise electronics
  - Accelerated ageing tests on prototypes pointed out NO design criticalities
- Despite the **COVID-19 situation in the World** we were able to perform the 2020 commissioning of all the MEG II subdetectors and the experiment is currently in data taking
  - Engineering run: **full DAQ electronics available next year**
- Problems along the path
  - Corrosion and breakage of 70 Al(Ag) field 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: **no breakages for 2 years**
  - Anomalous high currents still under investigations
    - Probably triggered by a **bad event last year**
    - Attempts to recover the CDCH operation are ongoing by using **different additives to the standard He:IsoB 90:10 gas mixture**
- The construction of a new chamber (CDCH2) is under study
  - Simulations show that the **final MEG II sensitivity** is **marginally affected** for example **by using all 50 µm field wires**



THANKS
FOR YOUR ATTENTION