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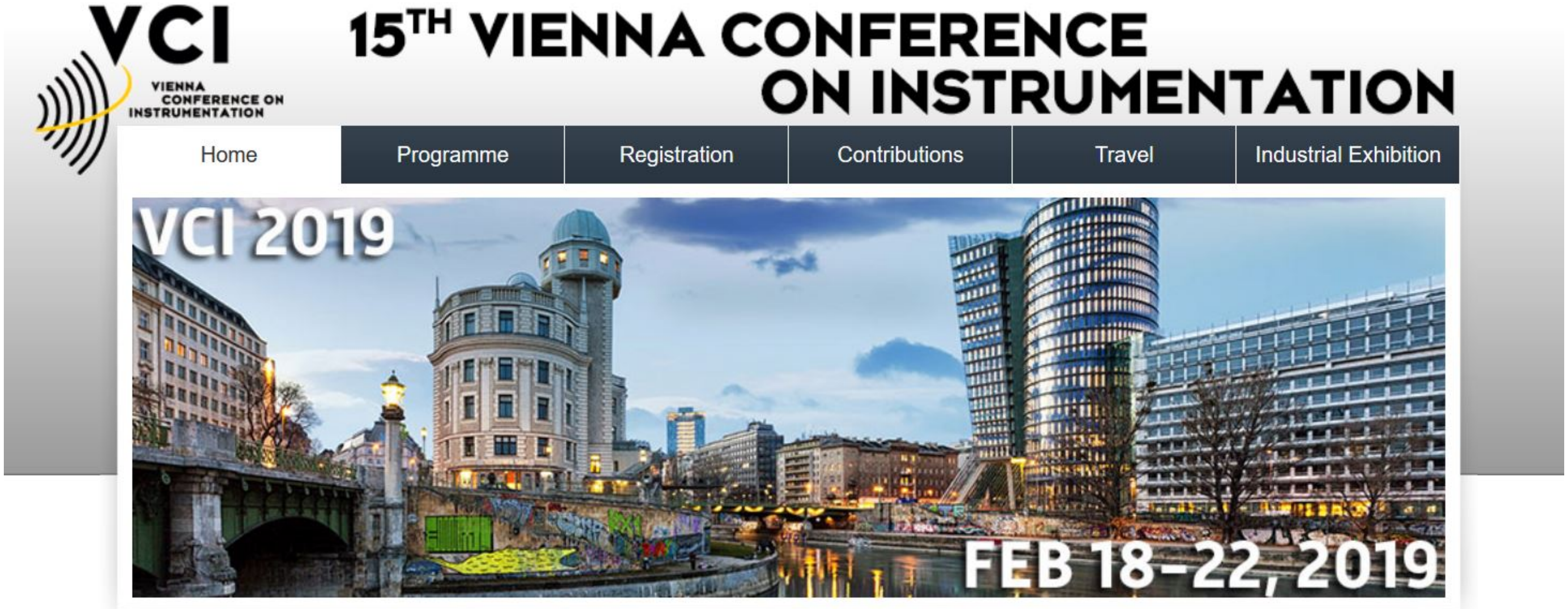
M. Hildebrandt :: Paul Scherrer Institut
on behalf of the CDCH team of the MEG II Collaboration

The ultra-light Drift Chamber of the MEG II Experiment

LTP Seminar, PSI, March 25, 2019

VCI - Vienna Conference on Instrumentation



- «traditional» conference on instrumentation
- every 3 years, alternating with
  «Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba (I)» and
  «Instrumentation for Colliding Beam Physics INSTR, Novosibirsk (RUS)»
- 1978 - 1998: Wire Chamber Conference WCC in Vienna
- since 2001: Vienna Conference on Instrumentation VCI

SiPM – still increasing Interest

NIM-A Special Issue on SiPMs

AUTHOR	TITLE	DOI
R. Klanner, F. Sauli	Editorial	https://doi.org/10.1016/j.nima.2018.11.040
A. Gola, C. Piemonte	Overview on the main parameters and technology of modern SiPMs	https://doi.org/10.1016/j.nima.2018.11.119
F. Acerbi, S. Gundaker	Understanding and simulating SiPMs	https://doi.org/10.1016/j.nima.2018.11.118
R. Klanner	Characterisation of SiPMs	https://doi.org/10.1016/j.nima.2018.11.083
P. P. Calo, F. Ciciriello, C. Marzocca, S. Petrignani	SiPM Readout Electronics	https://doi.org/10.1016/j.nima.2018.09.030
E. Garutti, Yu. Musienko	Radiation damage of SiPMs	https://doi.org/10.1016/j.nima.2018.10.191
F. Simon	SiPMs in Particle and Nuclear Physics	https://doi.org/10.1016/j.nima.2018.11.042
G. Llosa	SiPM-based Compton cameras	https://doi.org/10.1016/j.nima.2018.09.053
M. Grodzicka-Kobylka, M. Moszynski, T. Szczęśniak	SiPMs in gamma spectroscopy with scintillators	https://doi.org/10.1016/j.nima.2018.10.065
M. G. Bisogni, A. Del Guerra, N. Belcari,	Medical applications of SiPMs	https://doi.org/10.1016/j.nima.2018.10.175
M. Caccia, L. Nardo, R Santoro, D. Schaffhauser	SiPMs and SPAD imagers in bio-photonics: Advances and perspectives	https://doi.org/10.1016/j.nima.2018.10.204

Analysis methods for highly radiation-damaged SiPMs

S. Cerioli, E. Garutti, R. Klanner, D. Lomidze,
S. Martens, J. Schwandt, M. Zvolsky
Hamburg University

VCI-2019 --- Robert Klanner --- 18 - 22.2.2019

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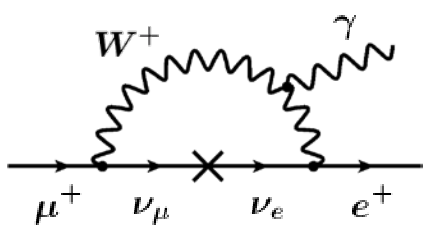
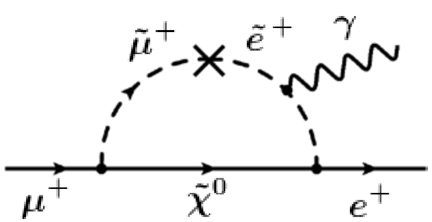
charged Lepton Flavour Violation

- MEG experiment at the Paul Scherrer Institut (Villigen, CH) is searching for the charged lepton flavour violating (cLFV) decay $\mu^+ \rightarrow e^+ \gamma$
- Standard Model (SM): forbidden decay
- Standard Model with ν masses and oscillations: strongly supressed due to small ν masses



BR ($\mu^+ \rightarrow e^+ \gamma$) ≈ 10^{-54}

- Beyond Standard Model (BSM) theories: enhanced probability due to mixing of new particles



BR ($\mu^+ \rightarrow e^+ \gamma$) >> 10^{-54} (10^{-11} - 10^{-14})

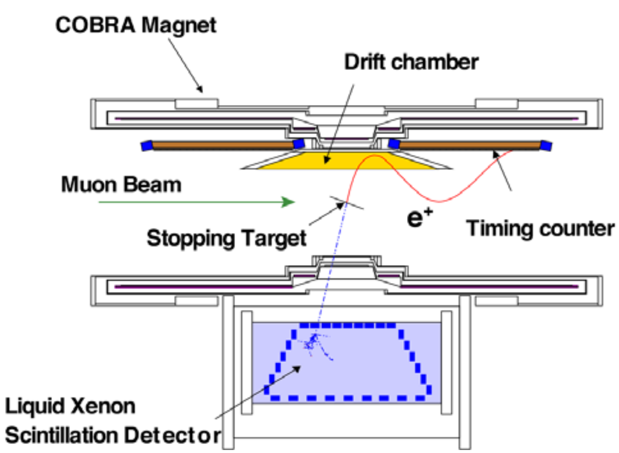
→ experimental observation of $\mu^+ \rightarrow e^+ \gamma$ is clear signature of “New Physics” beyond the SM

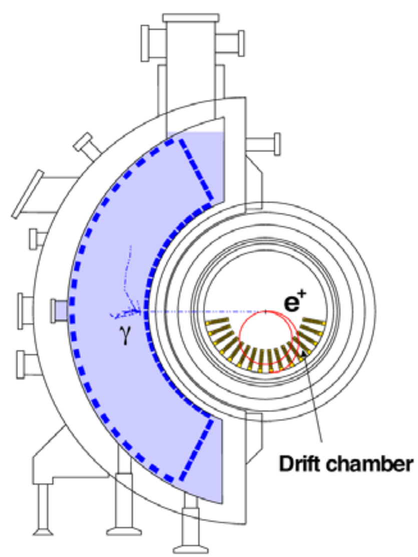
MEG Experiment

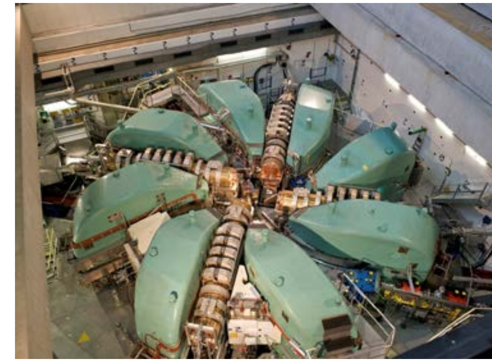
- located at the Paul Scherrer Institut (PSI)
  - p-cyclotron: 590 MeV, 2.4 mA (→1.4 MW)
  - πE5: most intense DC low momentum (28 MeV/c) muon beam in the world, intensity $O(10^8\ \mu/s)$
- dedicated detector to measure the observables characterising the $\mu^+ \rightarrow e^+ \gamma$ event (E_γ, E_e, $t_{e\gamma}$, $\vartheta_{e\gamma}$, $\varphi_{e\gamma}$)
- 2016: analysis of full data sample 2009-2013

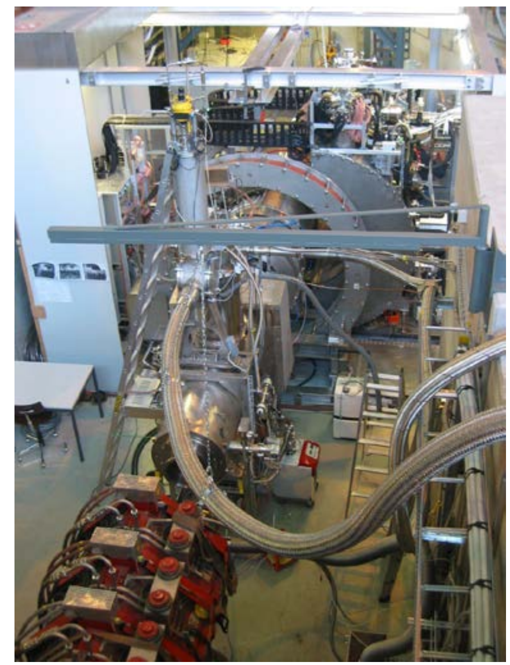
$$\mathbf{BR}\ (\mu^+ \rightarrow e^+ \gamma) < 4.2 \cdot 10^{-13}\ \text{(90\% CL)}$$

→ factor ~30 improvement compared to MEGA experiment (1999)









Baldini *et al.*, Eur. Phys. J. C (2013) 73:2365
Baldini *et al.*, Eur. Phys. J. C (2016) 76:434

How to increase the Experiment's Sensitivity

- increase the sensitivity for the signal (SES – single event sensitivity)

$$\mathbf{SES} = \frac{1}{R \cdot T \cdot A_g \cdot \varepsilon(e^+) \cdot \varepsilon(\gamma) \cdot \varepsilon(TRG) \cdot \varepsilon(sel)}$$

beam rate
acquisition time
geometrical acceptance
detector efficiency
selection efficiency

- reduce the background

$$B_{acc} \sim R \cdot \Delta E_e \cdot (\Delta E_\gamma)^2 \cdot \Delta T_{e\gamma} \cdot (\Delta\Theta_{e\gamma})^2$$

e^+ energy resolution
γ energy resolution
relative timing resolution
relative angular resolution

- MEG → MEG II:
  - increased beam rate (2x)
  - improved resolutions of sub-detectors (2x)
  - aiming for a sensitivity of ~$6 \cdot 10^{-14}$

How to increase the Experiment's Sensitivity

- increase the sensitivity for the signal (SES – single event sensitivity)

$$\mathrm{SES} = \frac{1}{R \cdot T \cdot A_g \cdot \varepsilon(e^+) \cdot \varepsilon(\gamma) \cdot \varepsilon(TRG) \cdot \varepsilon(sel)}$$

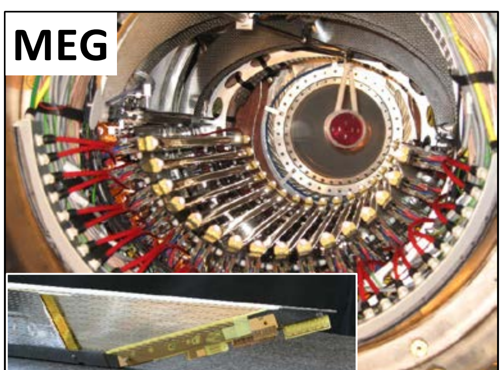
beam rate (R), acquisition time (T), geometrical acceptance (A_g), detector efficiency ($\varepsilon(e^+) \cdot \varepsilon(\gamma) \cdot \varepsilon(TRG)$), selection efficiency ($\varepsilon(sel)$)

- reduce the background

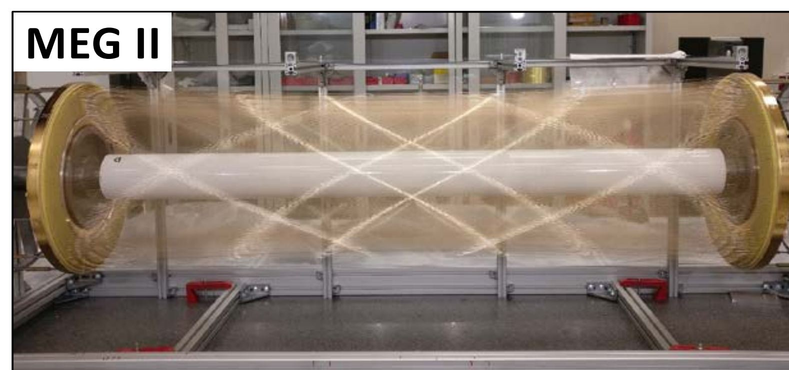
$$B_{acc} \sim R \cdot \Delta E_e \cdot (\Delta E_\gamma)^2 \cdot \Delta T_{e\gamma} \cdot (\Delta\Theta_{e\gamma})^2$$

e^+ energy resolution (ΔE_e)

relative angular resolution ($(\Delta\Theta_{e\gamma})^2$)

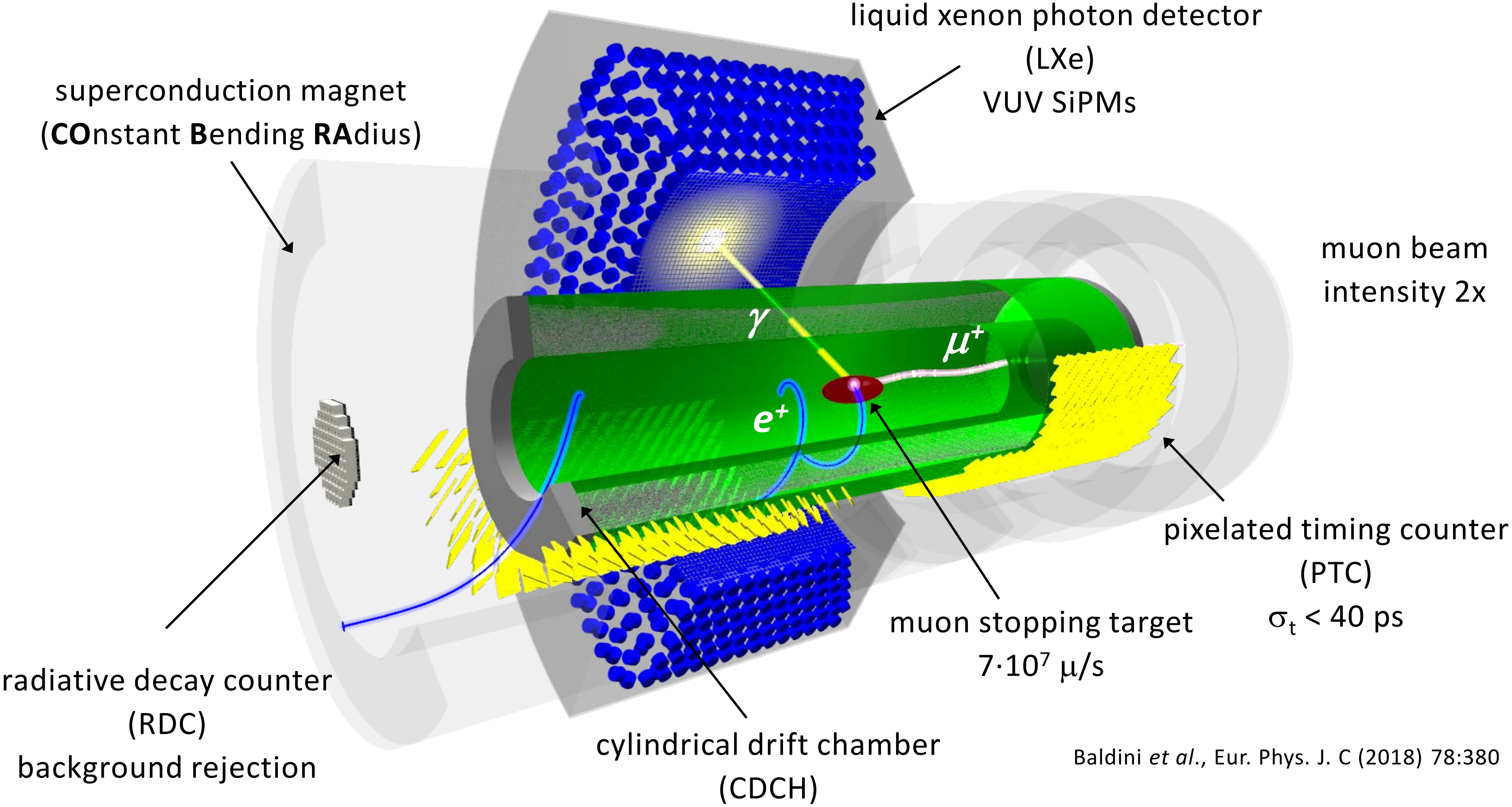


factor 2 improvement →



MEG II Experiment

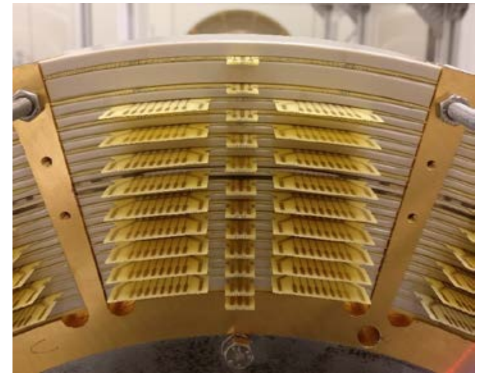
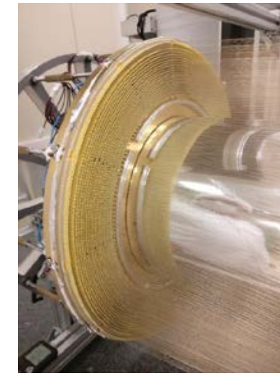
- improved resolutions for all sub-detectors (2x)
- increased beam rate
- new electronics : ~9000 channels at 5GSps (DRS4 based)
- updated and new calibration methods

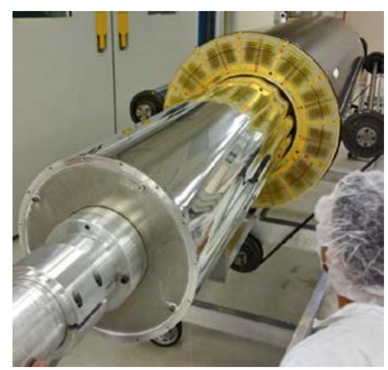
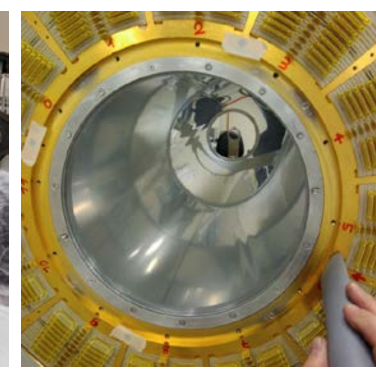


Baldini *et al.*, Eur. Phys. J. C (2018) 78:380

Cylindrical Drift Chamber - 1

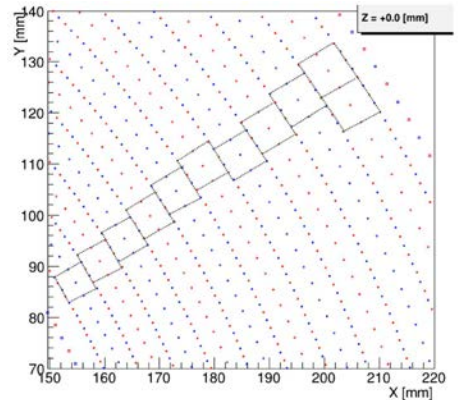
- designed to measure 52.8 MeV/c e^+
  - single volume detector
  - high transparency
  - low multiple scattering contribution $1.58 \cdot 10^{-3}$ X_0 along e^+ track
- mechanics
  - length = 200 cm, $\varnothing_{outer}$ = 60 cm
  - sensitive region 29 cm < $r_{sensitive}$ < 17 cm corresponding to the bending radius of 52.8 MeV/c e^+ in the magnet
  - carbon fiber support structure (1.76 mm thick) consisting of two half-shells
  - endplates with stacked pcbs and PEEK spacers
  - aluminized Mylar foil to separate sensitive volume with wires and inner part with μ-beam and stopping target

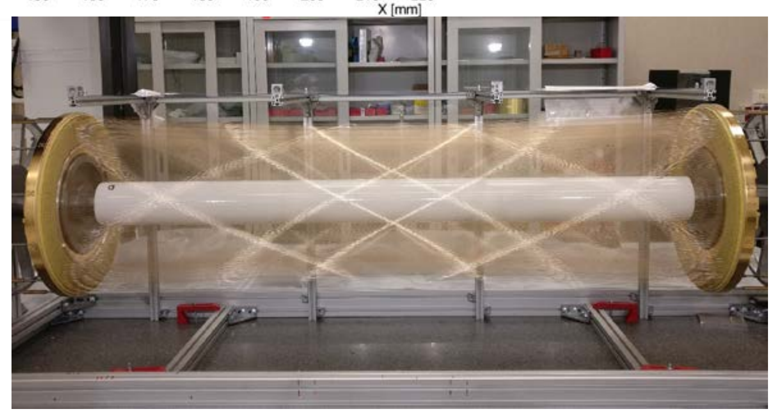



Cylindrical Drift Chamber - 2

- wiring
  - stereo angle geometry (6.0° to 8.5°)
    → hyperboloid volume
  - 10 concentric drift cell layers (original design)
    realised: 9 layers
  - 2 guard wire layers
  - (approximately) squared drift cell size
    $\pm z_{max}$: 6.7 mm (inner) – 8.7 mm (outer)
    z = 0: 5.8 mm (inner) – 7.5 mm (outer)
  - 20 μm gold-plated W wires
    40 μm, 50 μm silver-plated Al wires
    (→ 1728 + 9408 + 768 = 11902 wires with 272 kg)

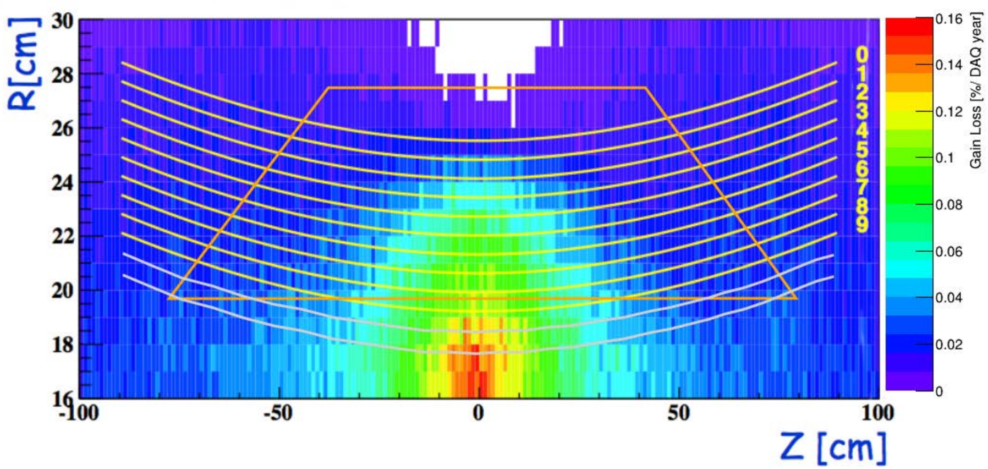


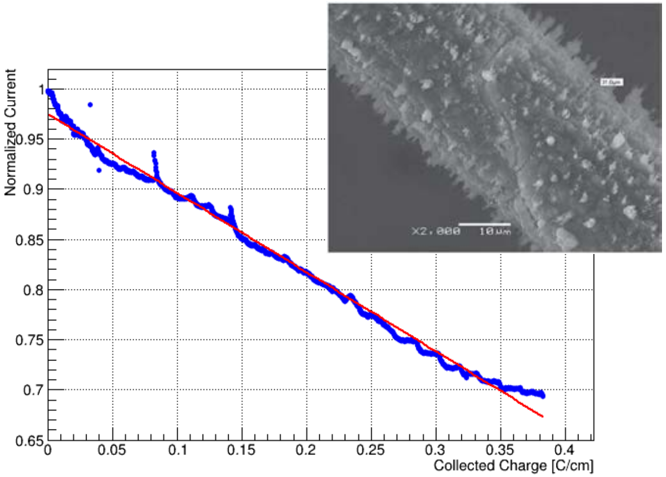


- readout / hit reconstruction principle:
  - stereo angle geometry
  - cluster counting and timing technique
  - double readout for charge division and signal time propagation difference (DRS4)

Counting Gas – Ageing

- He-iC_4H_{10} gas mixture, mixing ratio 90:10
  - helium-based gas mixture due to need of long radiation length
    small contribution to multiple scattering important for low momentum measurement
  - isobutane added as quencher to increase HV stability
- ageing tests (performed with He-iC_4H_{10}, 85:15)
  - laboratory tests with x-ray source, acceleration factor 20x
  - «hottest» spot: central region of innermost anode wire
    ~30 kHz e^+/cm → 0.5 C/cm in 3 years (@ $2\cdot10^5$ gas gain) → ~15% gain loss/year
  - in general: < 10% gain loss/year

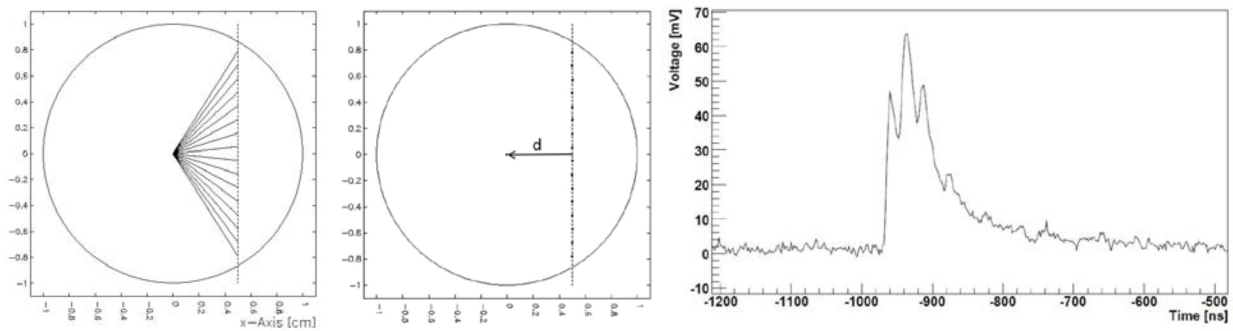




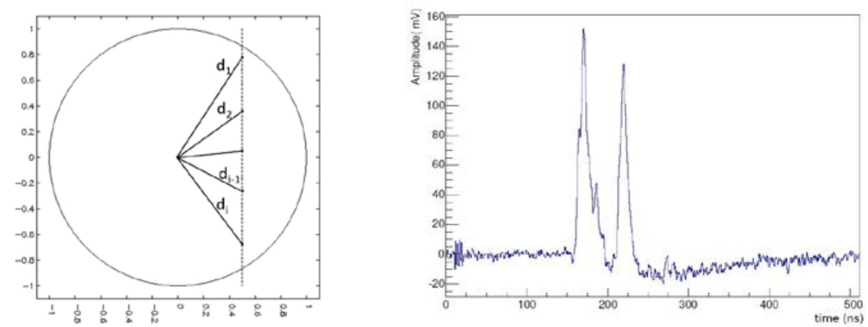
Venturini, Il Nuovo Cimento 38 C (2015) 22

Counting Gas – Cluster Counting Technique

- primary ionisation
  - ~13 e^-/cm (n_p dominated by W_{He} = 41 eV)
  - large spacing between the individual clusters → cluster counting and timing technique
    - «traditional»



- cluster counting timing technique
  - → increased number of supporting points along particle trajectory
  - → improved track fitting accuracy and momentum determination



Cataldi, Grancagnolo, Spagnolo, NIM A 386 (1997) 458-469
Tassielli, Grancagnolo, Spagnolo, NIM A 572 (2007) 198-200

- performance (resolution, σ):

single hit (prototype)	~110 µm in r-direction
momentum (MC)	~110 keV/c (@52.8 MeV/c)
angular (MC)	~5.7 mrad in θ, ~6.0 mrad in ϕ

Signorelli, D'Onofrio, Venturini, NIM A 824 (2016) 581-583
Baldini *et al.*, 2016 JINST 11 P07011

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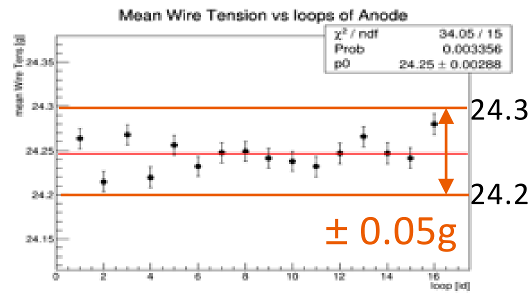
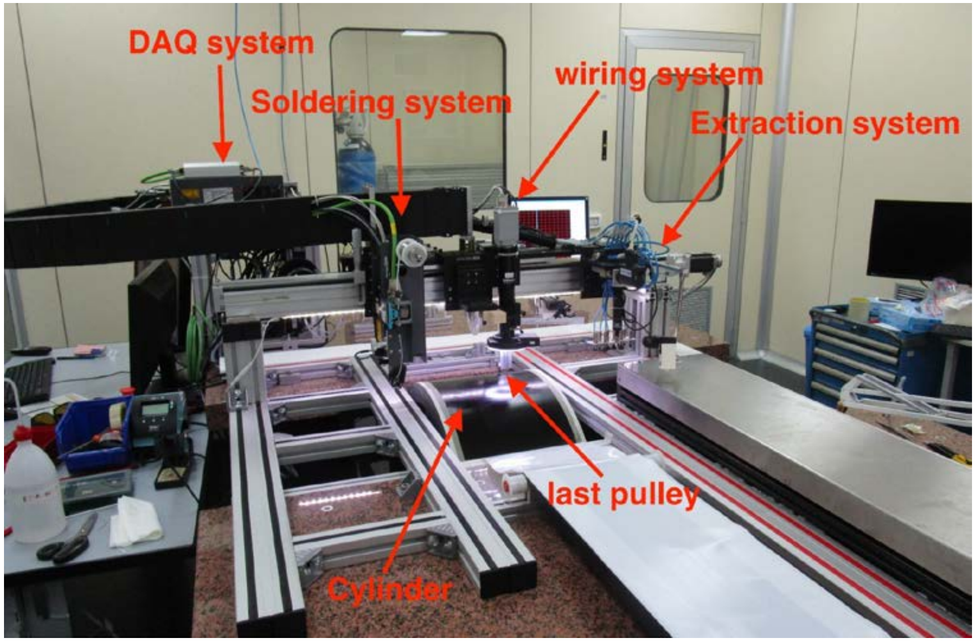
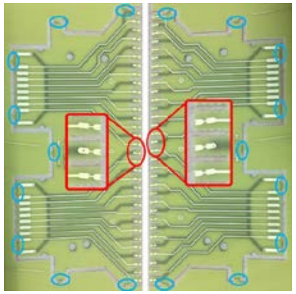
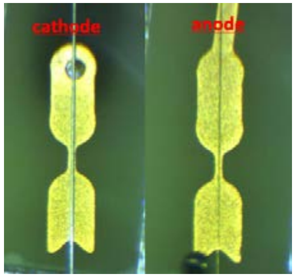
Wiring Technique

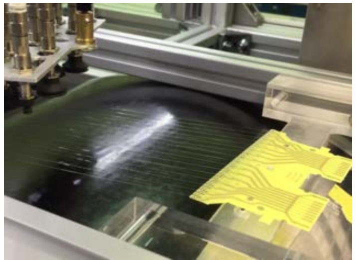
- semi-automatic wiring robot
  - to string continuously variable wire pitch and stereo angle configurations
  - to apply a pre-defined mechanical tension to the wires, constant and uniform (± 0.05g)
  - to monitor the wire locations and their alignment (~20 μm)
  - to monitor the soldering quality on the pcb





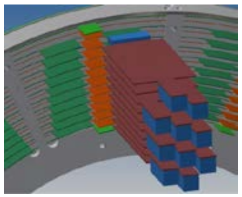


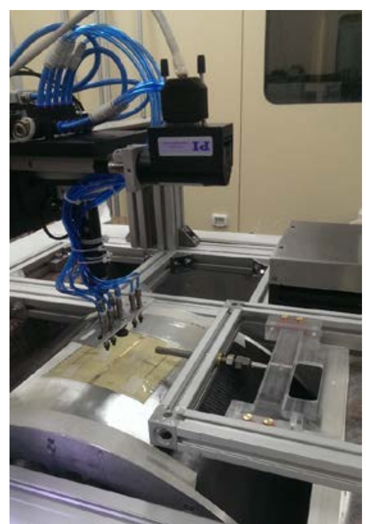


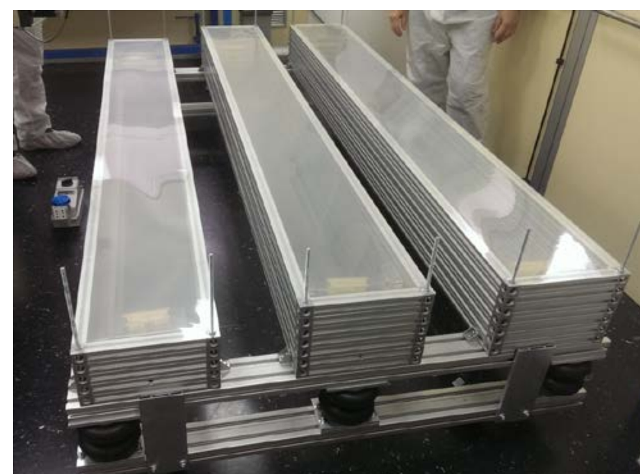


Chiarello *et al.*, NIMA in press, https://doi.org/10.1016/j.nima.2018.10.112

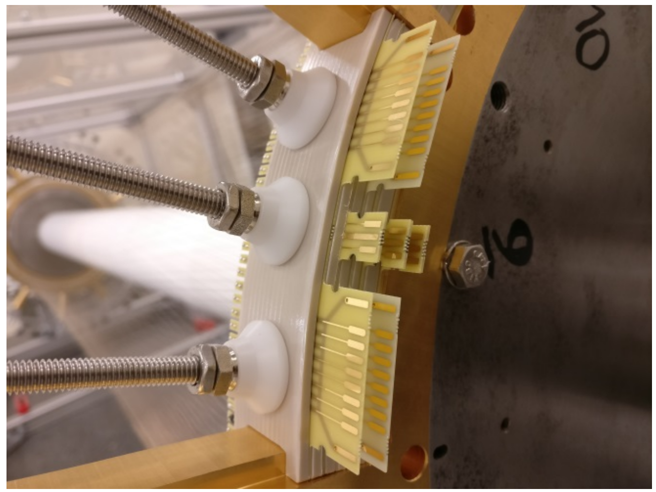
Construction Work - 1

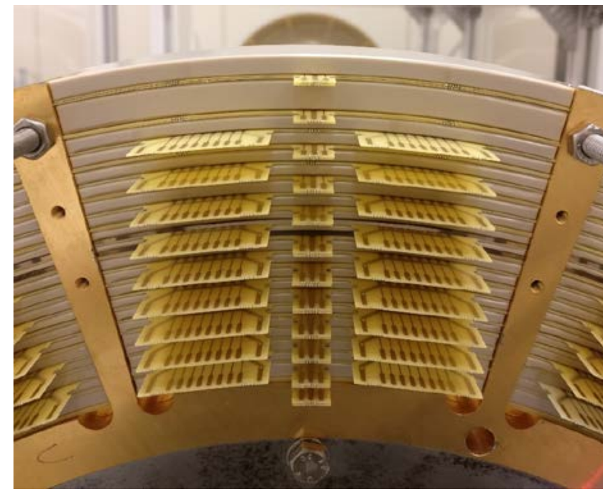


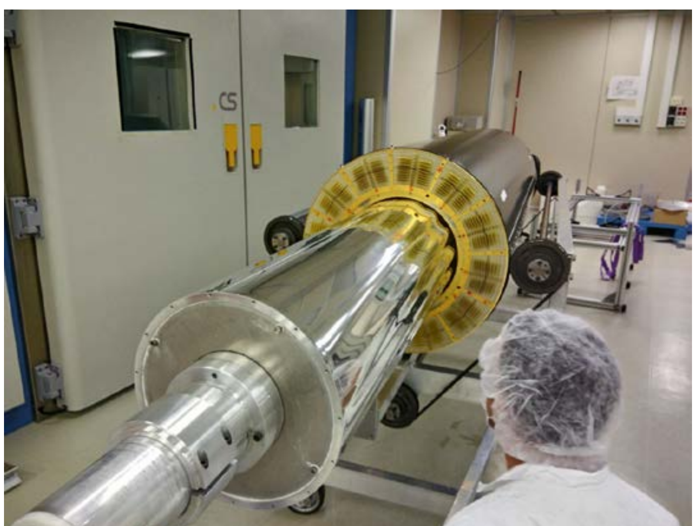


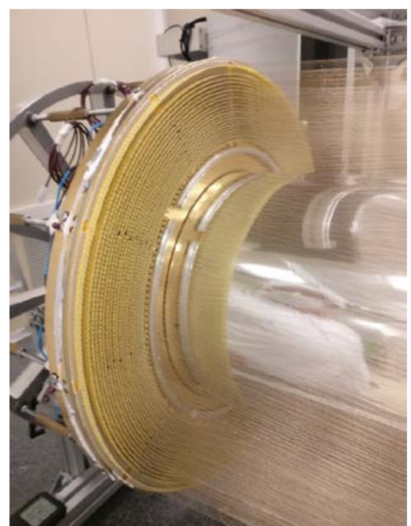


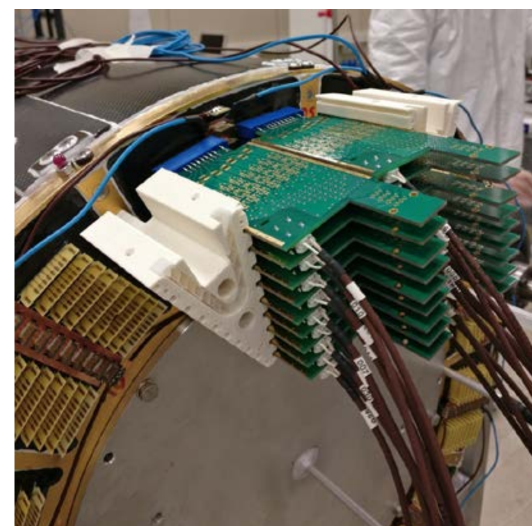
Construction Work - 2







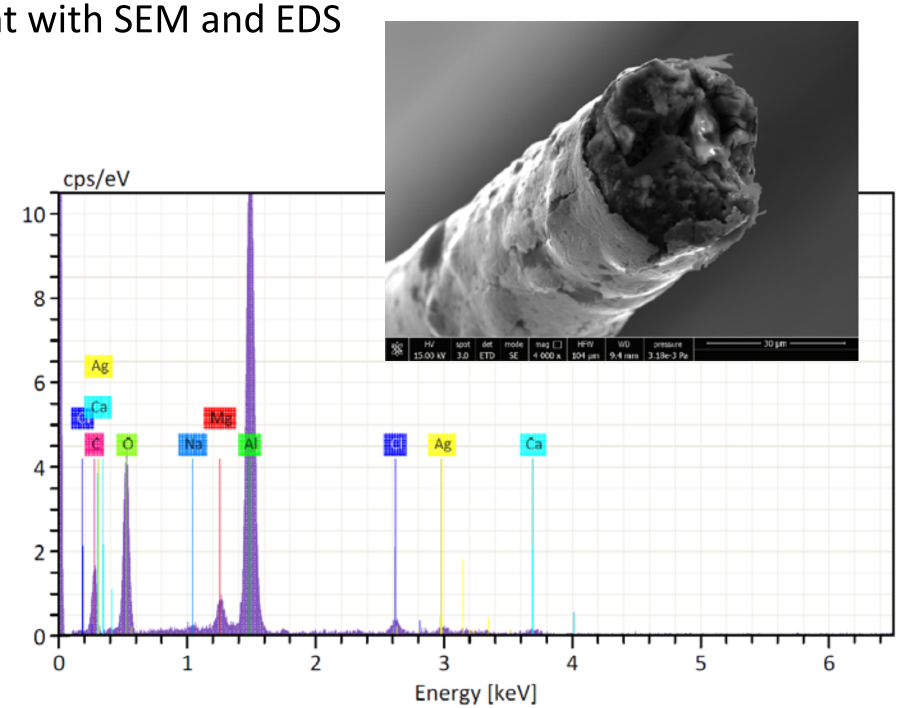




Humidity and Corrosion of Al Wires - 1

- observation: during assembly in 2016 and 2017 several silver-plated Al wires broke
  even
  - the elongation ΔL/L was only at 50% of the elastic limit
  - the wires passed a preceding stretching test during QA procedure (stretching up to 75% of elastic limit)
- intensive examinations of the breaking point with SEM and EDS
  - traces of Na and Cl
- laboratory test:
  - «untouched» wires were immersed or sprayed with water and 3% water solution of NaCl

  → in all cases wire breaking could be induced and breaking point looked identical to broken wires in drift chamber



- «fear»: mechanical stress could enhance the corrosion, known as Stress Corrosion Cracking (*status 2019: this seems not(!) to be the case*)

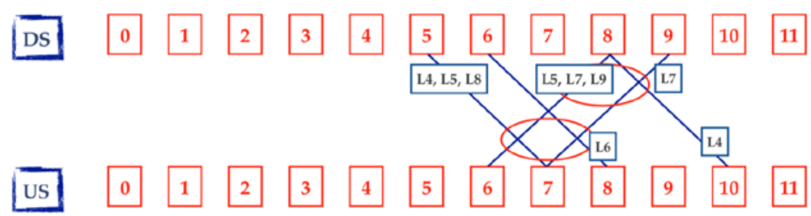
Humidity and Corrosion of Al Wires - 2

- conclusion: silver-plated Al wire (Al alloy 5056, Ag layer for soldering purposes), is very sensitive to corrosion induced by humidity, in particular in the presence of NaCl

→ lessons learned:
- avoid humidity → additional dehumidifier installed in clean room
- avoid Na and Cl ↔ close to Mediterranean Sea
  ↔ Cl traces found even on «untouched» wires from manufacturer
- observations are sign of H_2O, Na, Cl and "Al + Ag composition with cracks"

- due to unique, but potentially bad condition in clean room caused by power cut: construction and assembly restarted from scratch in August 2016 under condition of rel. humidity <55%, since August 2017 (rel. humidity <50%) no further wire breaking occurred…

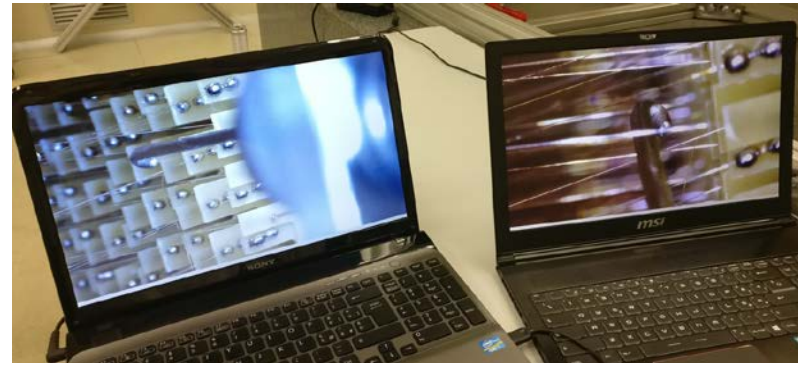
- …but unfortunately end of 2018 during pre-commissioning run: signature/combination of short-circuited segments indicate broken wire

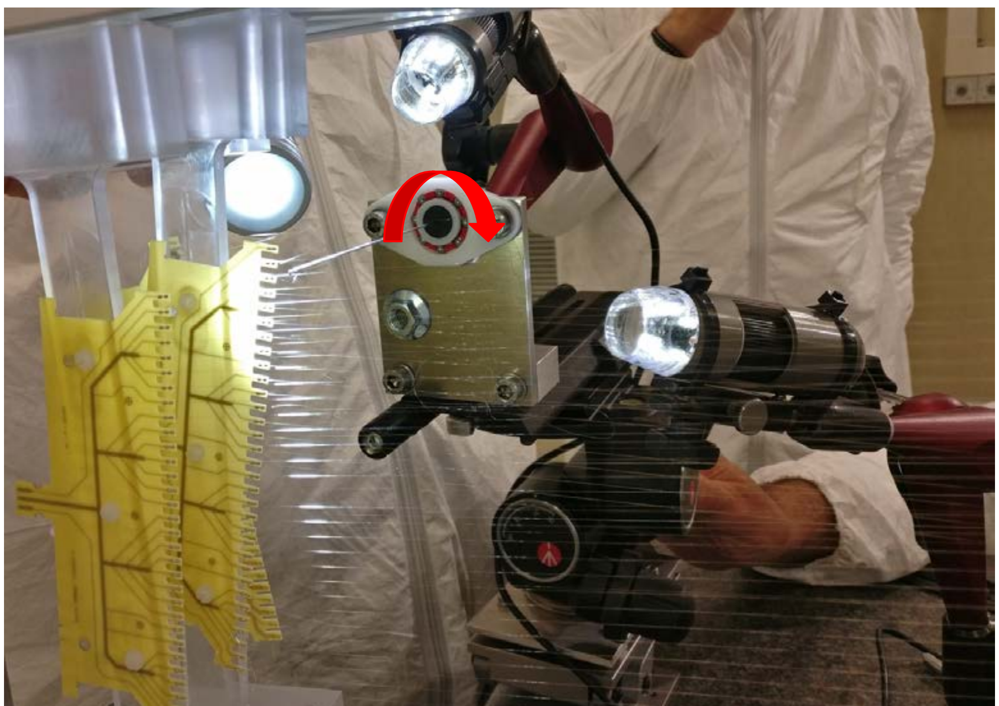


→ drift chamber was re-opened and inspected: 2 broken silver-plated Al wires

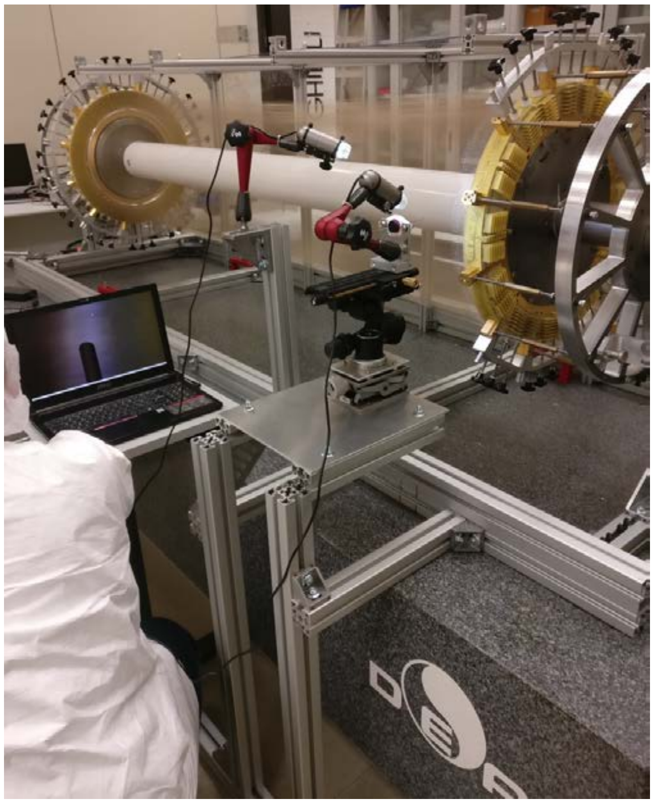
Removal of broken Wire - 1

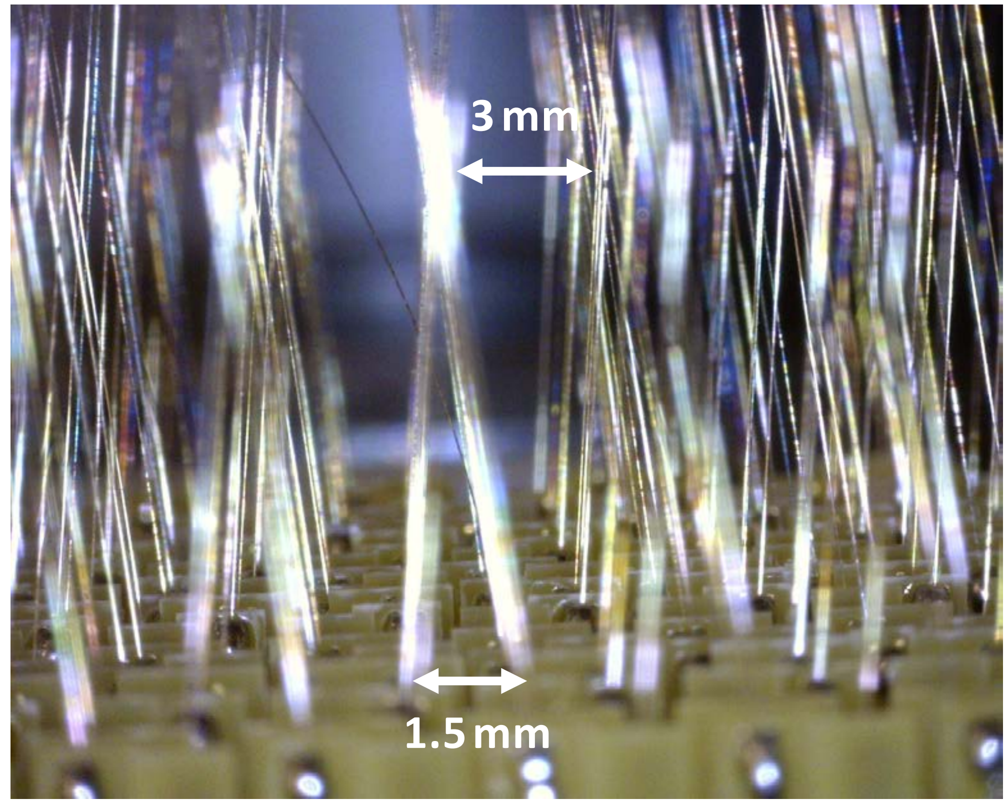
- proven strategy to remove broken wire
  - 1 mm stainless steal rod with 1.5 mm hook
  - support with 5(+1) independent axes with micrometric manual control





Removal of broken Wire - 2



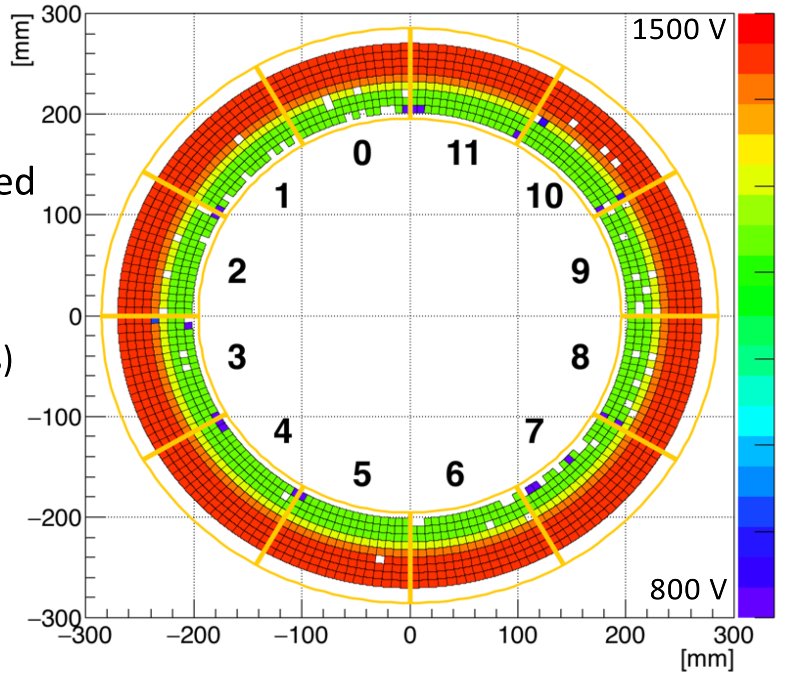


remark: 14 broken wires successfully removed with this procedure in August 2017

HV Stability and Mechanical Wire Tension

- observation during HV conditioning in 2018
  - a few drift cells showed oscillating currents
  - in some cases even a permanent short occurred
  - outer layers: - more stable than inner layers
    - higher voltages can be reached

    (outer layers: larger drift cells = larger wire distances)



- most probable reason:

  mechanical tension of the wires is not sufficient

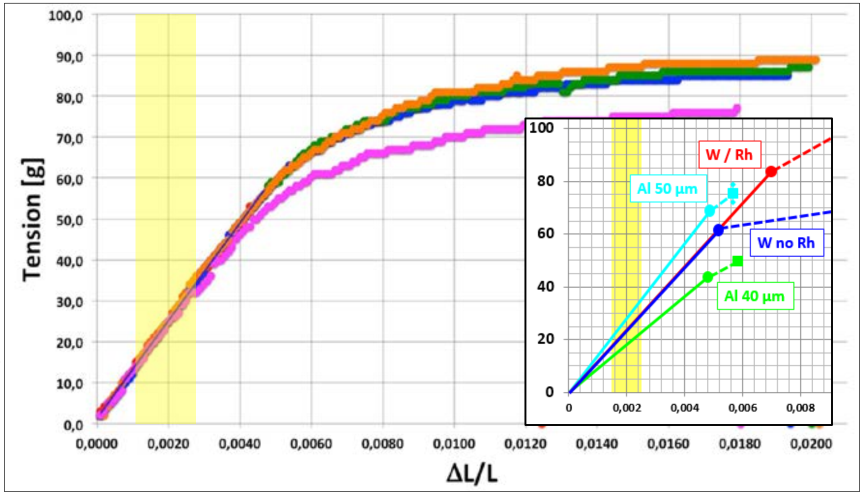
  taking into account - drift cell size and

  - wire positioning accuracy

  → wire tension needs to be increased!

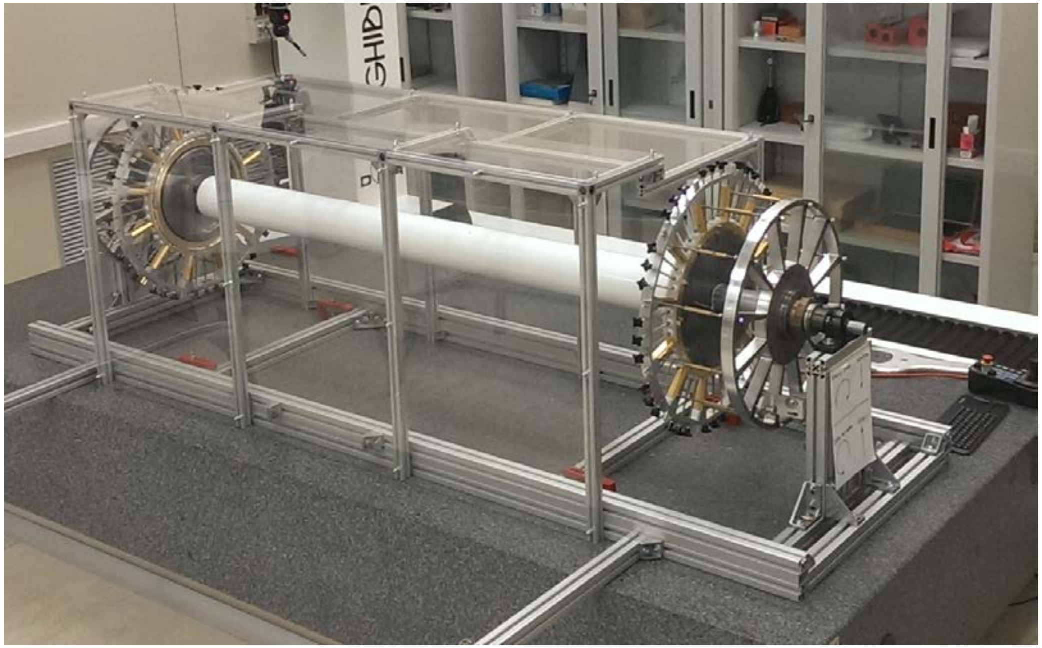
remark: why have we been so «conservative» concerning the wire tension, i.e. 50% of elastic limit?

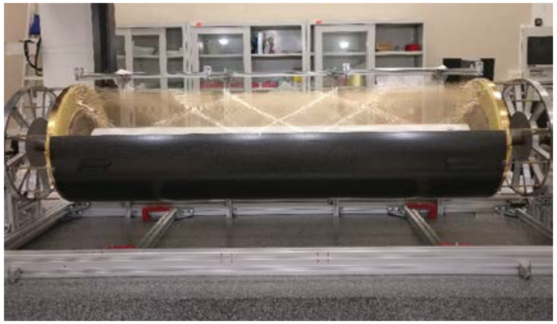
↔ «fear» of enhanced wire breaking in case of Stress Corrosion Cracking (*status 2019: fear not confirmed*)

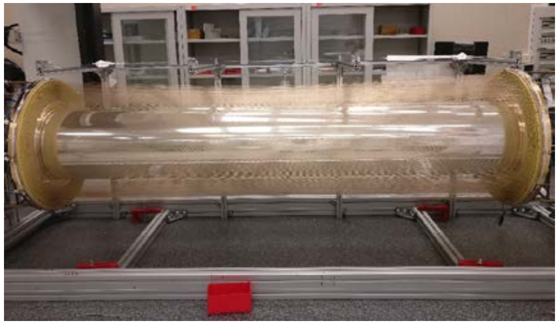


Stretching of Drift Chamber

- proven strategy to re-open and to lengthen the drift chamber
  - dedicated support structure with turnbuckles (used for construction)
  - during stretching procedure additional monitoring with optical or tactile measurements of distance and parallelism of end plates



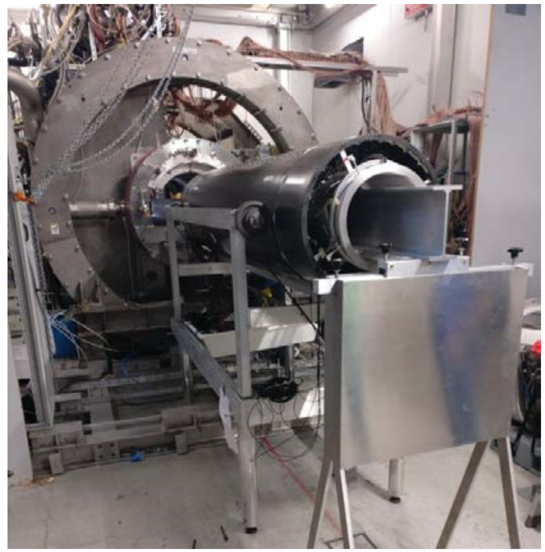
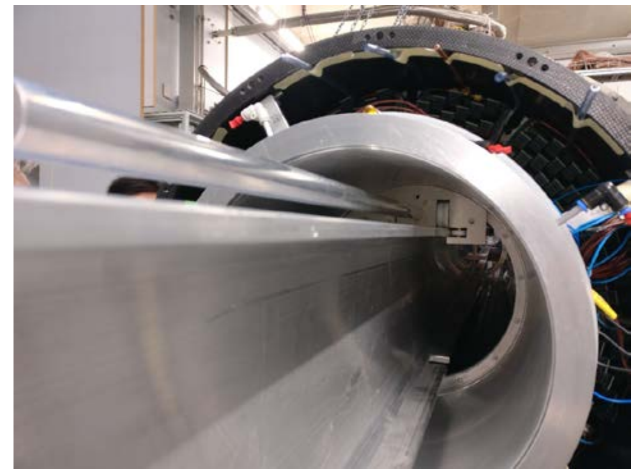


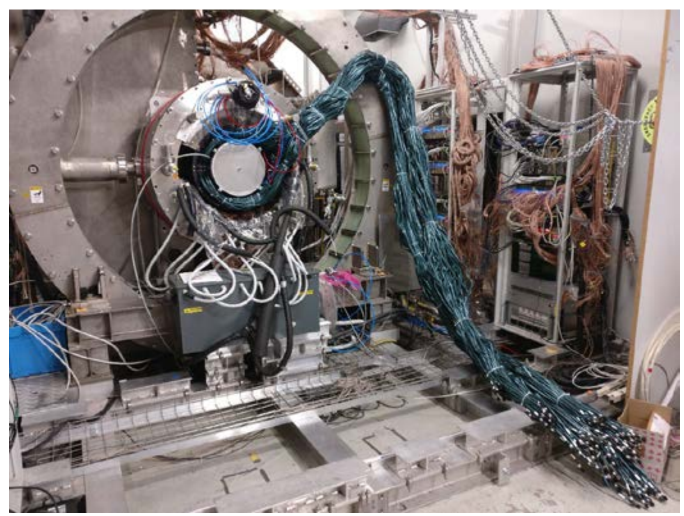
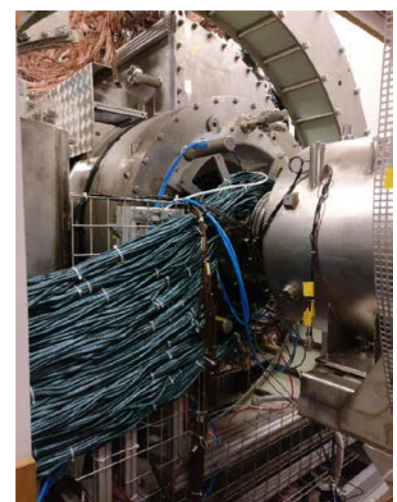


- *remark*: parallelism on the level of <50 μm
  (reminder geometry: length 2 m, diameter 60 cm, applied force 280 kg)

Installation

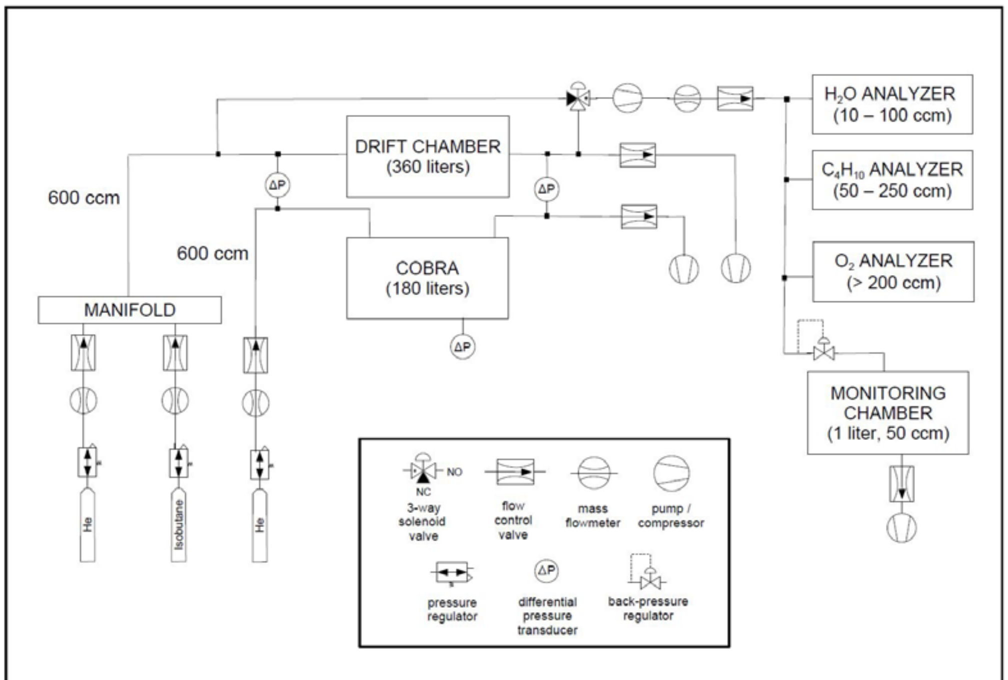
- October 2018: installation, survey, cabling, etc.

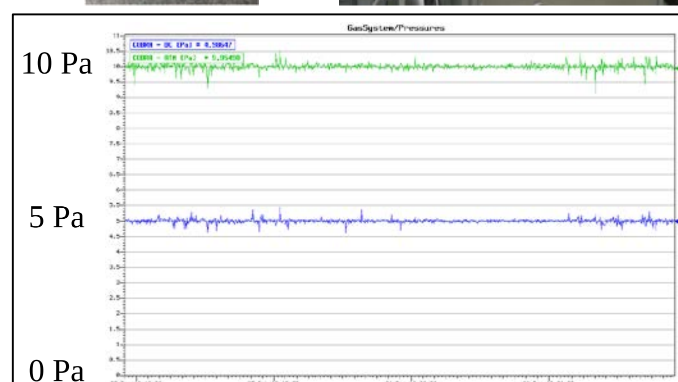



Pressure Regulation & Gas Monitoring System

- gas supply & distribution, pressure control and gas monitoring
- ensures purity to avoid aging and stability of gas mixture for stable electron drift properties
  (3% change of iC_4H_{10} concentration leads to 1% effects on v_d and 5% on gain)
- pressure stability on sub-Pa level achieved during operation
- gas analysis: commercial devices for H_2O, O_2 and iC_4H_{10} (ppm-level)
- monitoring: gain measurement in thin-wall drift tubes using ^{55}Fe



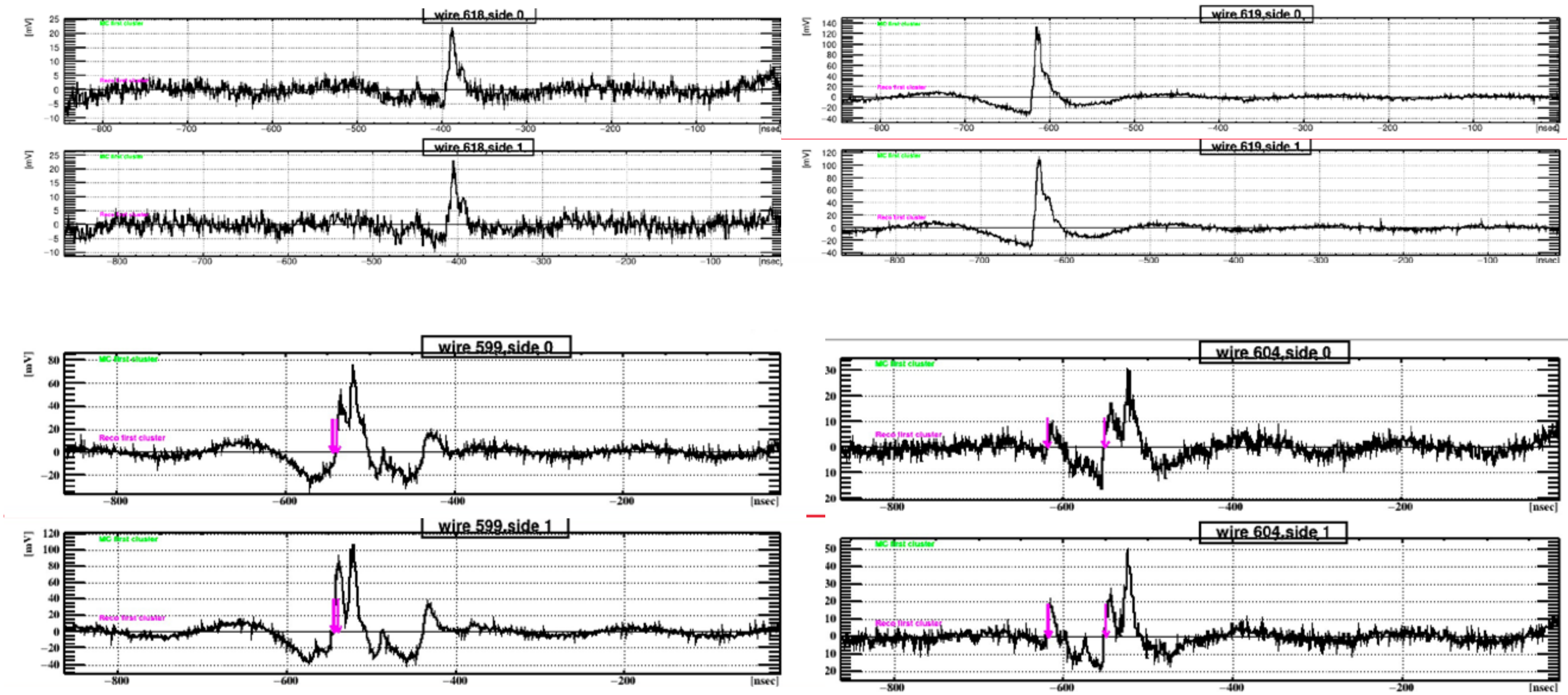
Baldini *et al.*, 2018 JINST 13 P06018



Performance – First Glimpse

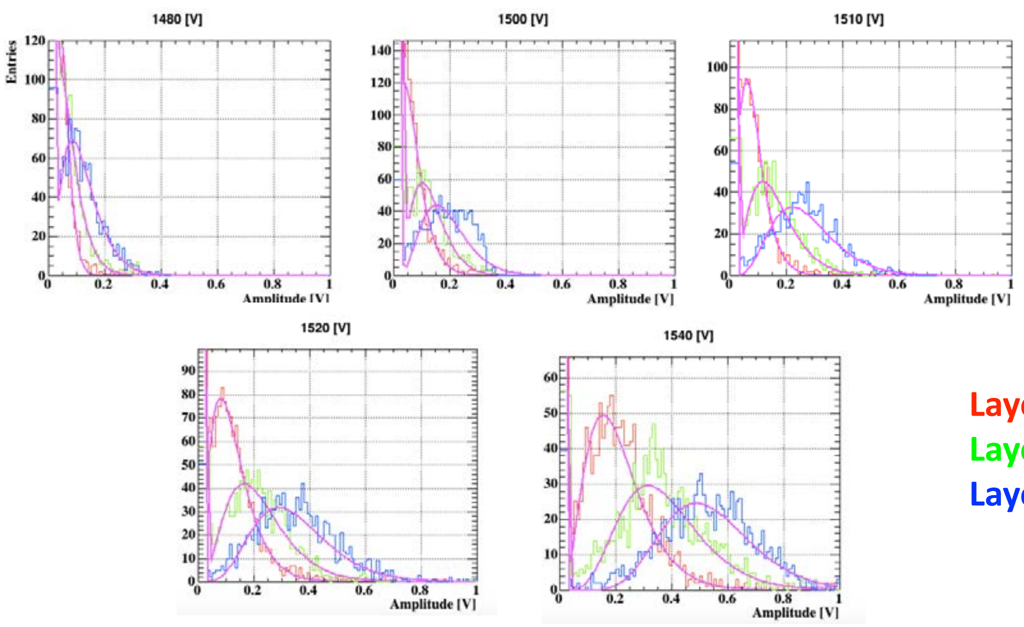
- December 2018: cosmics and Michel e^+ events at muon beam intensities of up to 10^8 μ/s
  - waveforms

    remark: 1.2 GSPS, but transmission limited to 400 MHz bandwidth,
    consequently: individual clusters hardly resolvable…

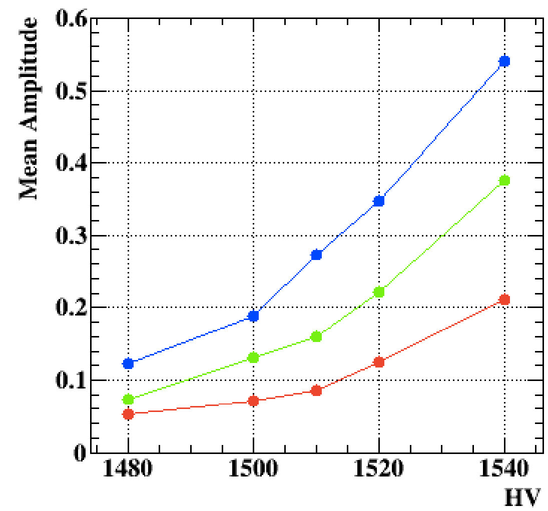


Performance – First Glimpse

- December 2018: cosmics and Michel e^{+} events at muon beam intensities of up to 10^{8} μ/s
  - amplitude distributions vs HV
  - gain vs HV (arbitrary units)

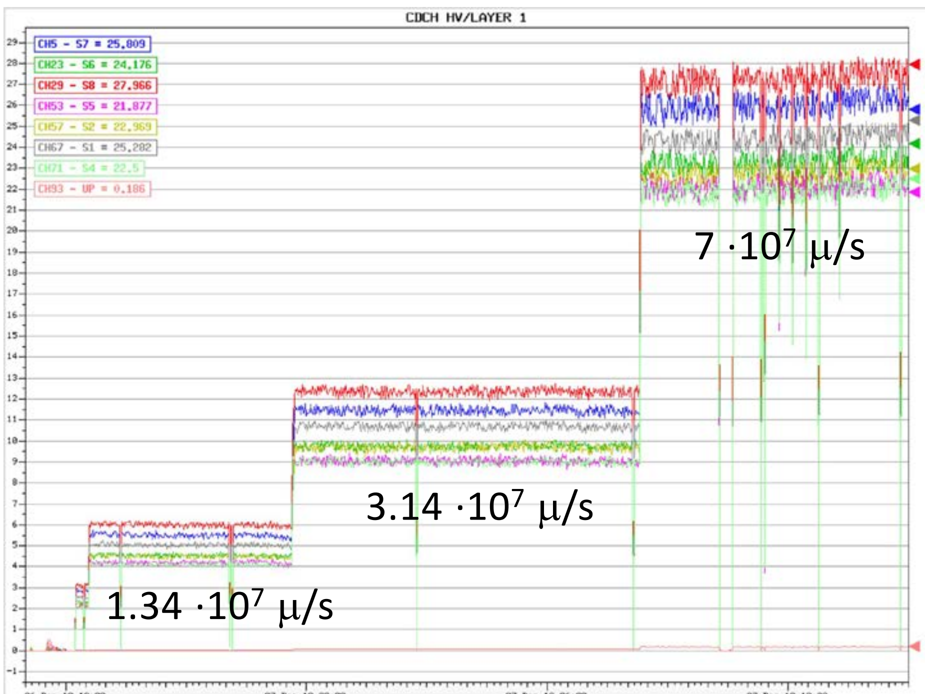


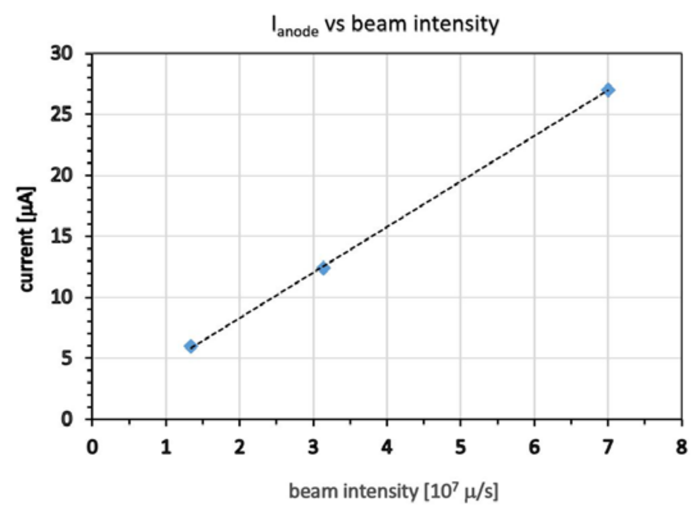
Layer 1
Layer 2
Layer 3



Performance – First Glimpse

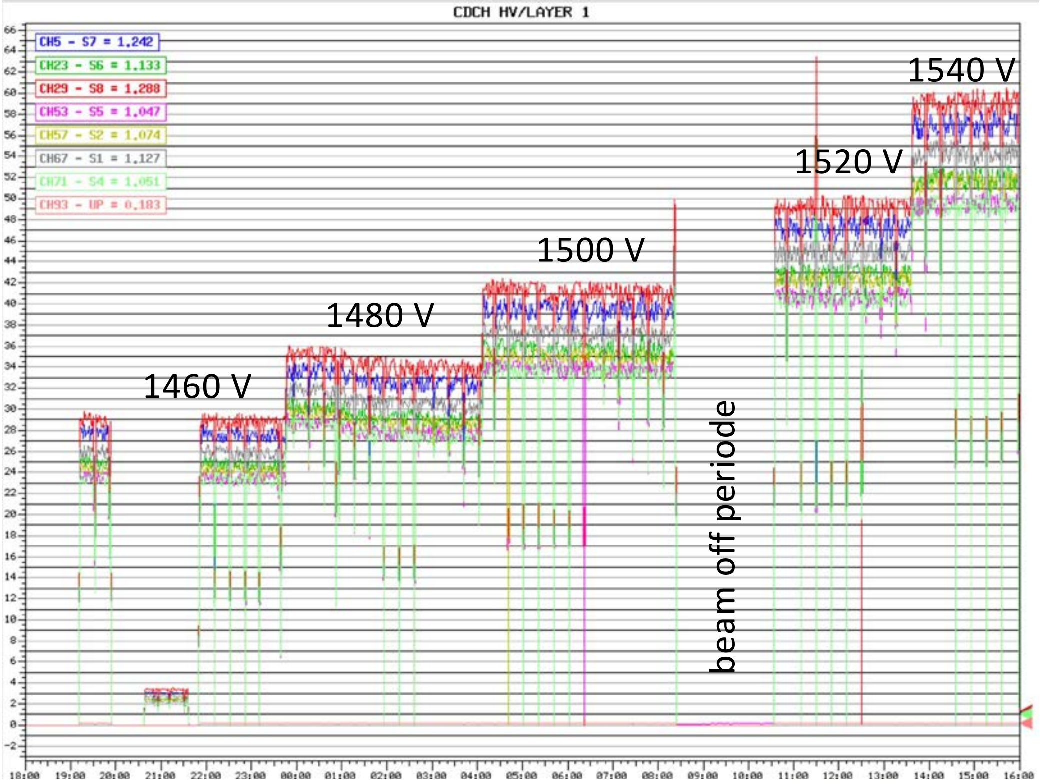
- December 2018: cosmics and Michel e^+ events at muon beam intensities of up to 10^8 μ/s
  - scan with fixed HV at different beam intensities





Performance – First Glimpse

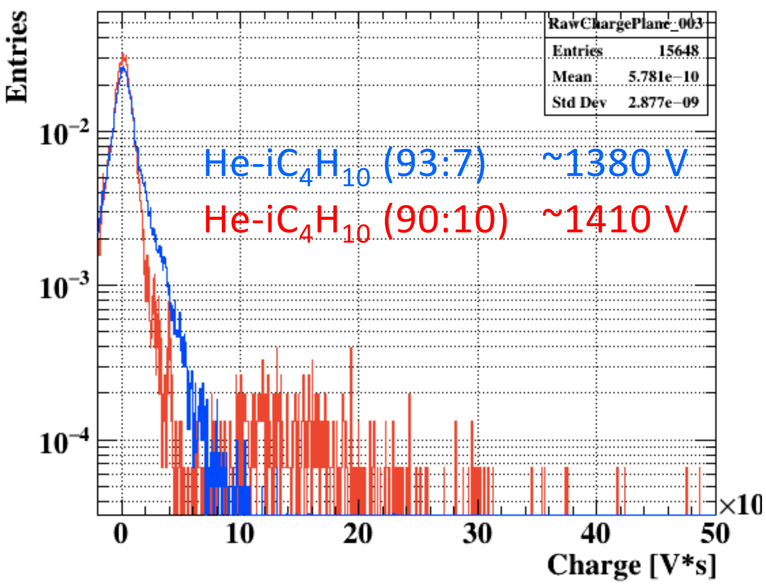
- December 2018: cosmics and Michel e^+ events at muon beam intensities of up to 10^8 μ/s
  - HV scan at full beam intensity



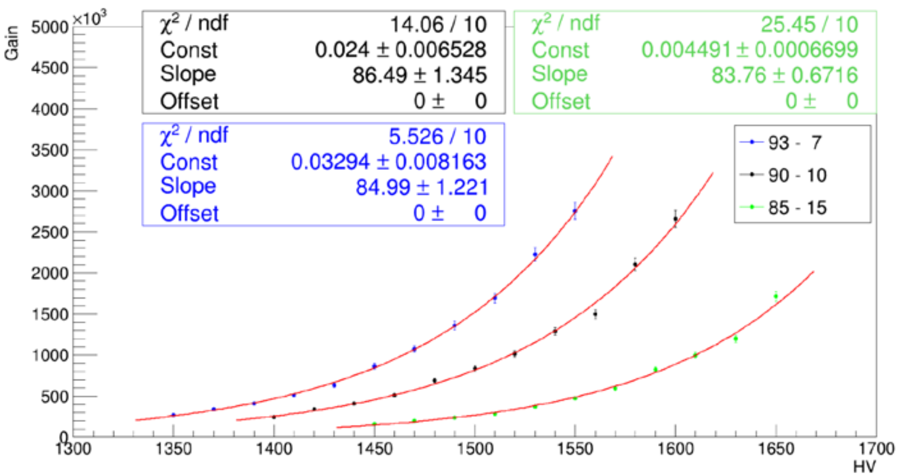
Performance – First Glimpse

- December 2018: cosmics and Michel e^+ events at muon beam intensities of up to 10^8 μ/s
  - comparison of He-iC_4H_{10} in mixing ratios 90:10 and 93:7 and HV values for equivalent gas gain

measurement (layer 3)



simulation (layer 1)



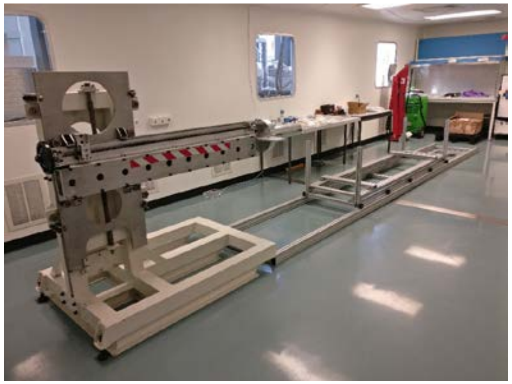
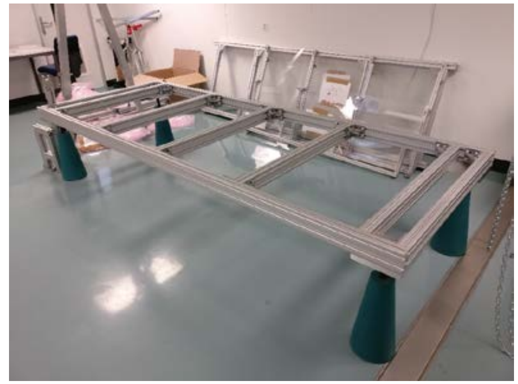
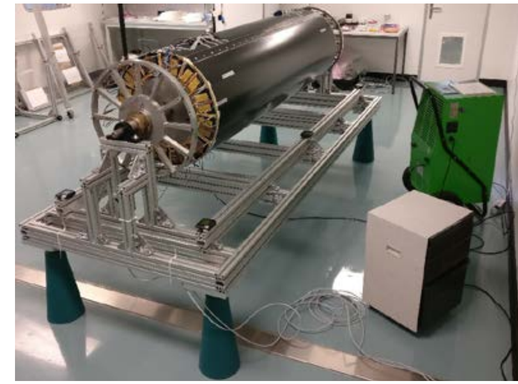
Shutdown 2019 – Experimental Hall

- extraction from COBRA

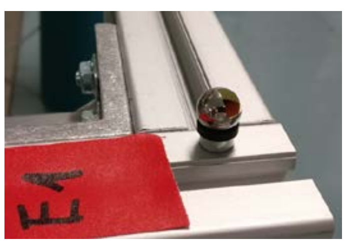
- LEVI-Transport to PSI east side

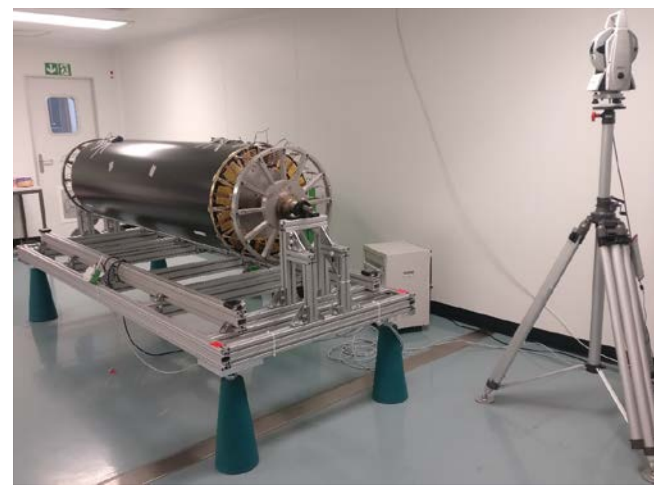
Shutdown 2019 – Clean Room

- preparation of clean room

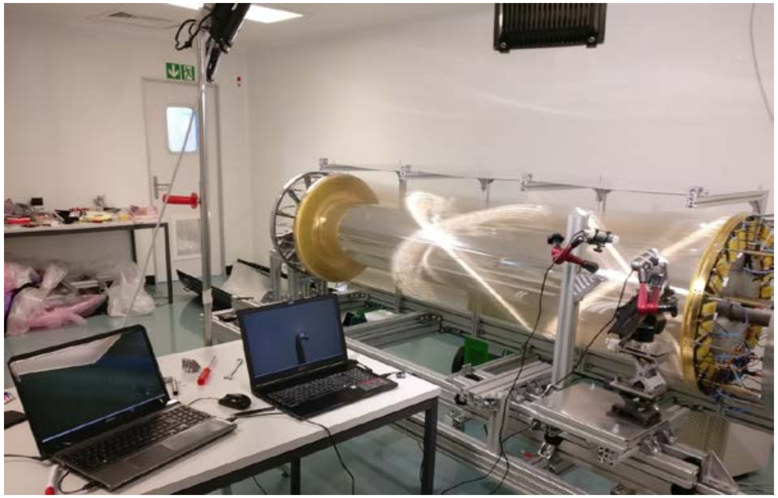
- survey of drift chamber before opening

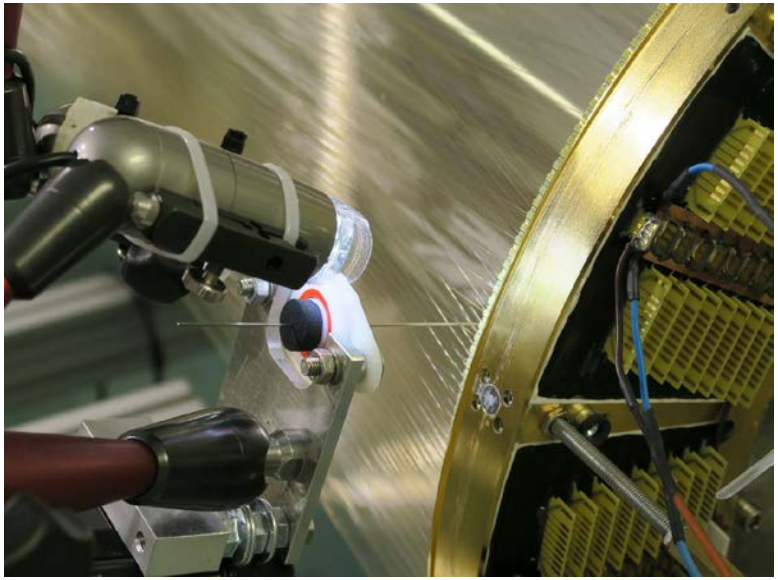




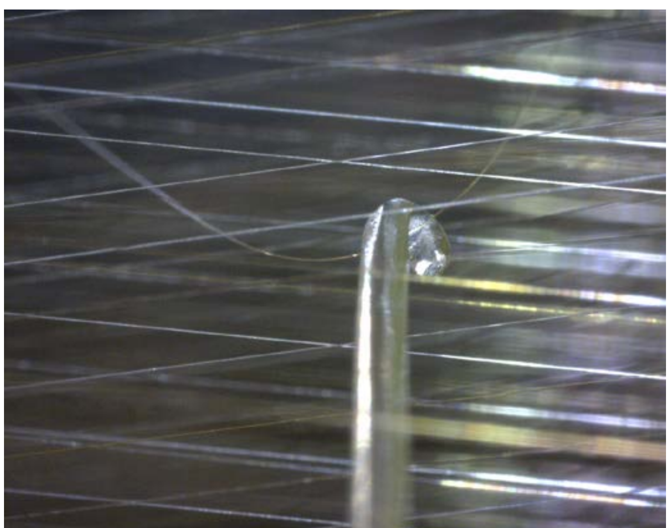
→ length: 1992.855 mm ↔ 1992.840 mm (summer 2018, Pisa)
parallelism: 0.006° → Δ ≈ 30 μm at outer endplate, compatible with measurement in Pisa

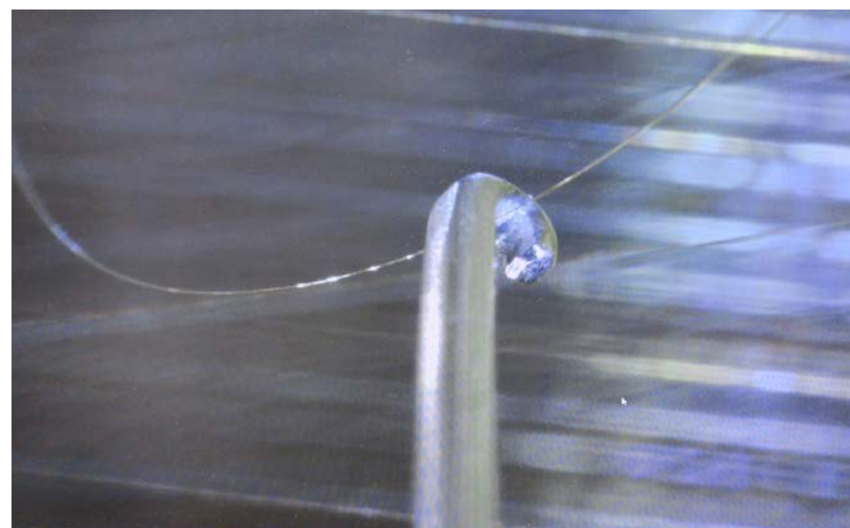
Shutdown 2019 – Removal of 2 broken Wires





Shutdown 2019 – Removal of 2 broken Wires



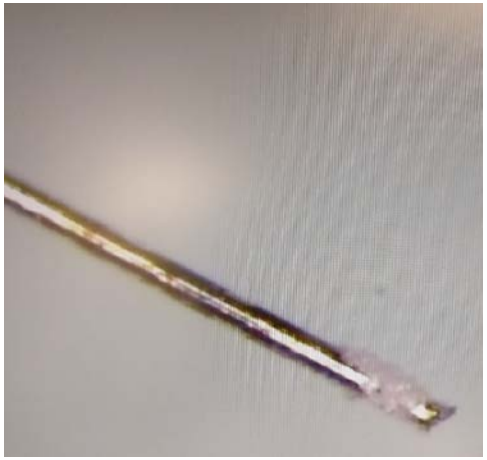


Status and next Steps

- both broken wires: 40 μm silver-plated Al cathode wires

- breaking points of wires give hint to «Al corrosion» as observed in 2016 and 2017
  - flat wire ends
  - crystalline structures close to breaking points

  → needs to be confirmed by metallurgy analysis



- since 10 days:
  - drift chamber temporarily closed, sealed and flushed with N_2 to avoid any humidity
  - stretched by +500 μm compared to Run 2018 (final goal: 1000 – 1500 μm)

- next steps:
  - stretch to reach good electrostatic stability at working point
  - overstretch for certain time period to find (potentially) «weak» wires

  → both activities will be monitored online with laser tracker surveys
  - full HV test, closing, sealing, insertion in COBRA and successful Run 2019 !

Summary

- MEG II experiment
  - seeks for the cLFV decay $\mu^+ \rightarrow e^+ \gamma$
  - aims for a sensitivity of 10^{-14}
- new cylindrical Drift Chamber (CDCH)
  - low-mass construction ($1.58 \cdot 10^{-3}$ X_0)
  - improved resolutions (2x) compared to previous drift chamber system
- construction phase finished summer 2018, although facing some wire breakings and severe issue of Al corrosion
- first commissioning December 2018
  - basic operation principles proven
  - HV instabilities limited operation
- annual PSI accelerator shutdown
  - broken wires have been removed
  - chamber length will be increased

→ confidence that the Drift Chamber will fulfil the experiment's requirements

PAUL SCHERRER INSTITUT

Teams and Support

collaborative effort:

- Universities/INFNs in Pisa, Lecce and Rome (I)
- Paul Scherrer Institut, Villigen (CH)
- JINR, Dubna (RUS)

- Marco Chiappini
- Gianluigi Chiarello
- Marco Francesconi

- Gabriela Balestri
- Alessandro Bianucci
- Giulio Petragnani
- Fabrizio Raffaelli

- Alessandro Baldini
- Luca Galli
- Marco Grassi
- Marco Panareo
- Francesco Renga
- Cecilia Voena

- Fabrizio Cei
- Franco Grancagnolo
- Donato Nicolo
- Angela Papa
- Francesco Tassieli

- Dieter Fahrni
- Andreas Hofer
- M.H.

- Alexander Kolenikov
- Vladimir Malyshev

Measurement of Wire Tension

- based on measurement of resonance frequency
  - $f = \frac{1}{2L}\sqrt{\frac{T}{\rho}}$ where f fundamental resonance frequency
    T wire tension
    L wire length
    ρ linear mass density
  - capacitive coupling of two adjacent wires: $C_{ww} = \frac{\pi\varepsilon}{ln\frac{2D}{d}}$

$$|\partial f| = \frac{C_{ww}}{2\pi C\sqrt{LC}} \cdot \frac{2/3}{\ln\left(2D/d\right)} \cdot \frac{dD}{D}$$

where d wire diameter
D wire distance
L, C inductance , capacitance of auto-oscillating circuit