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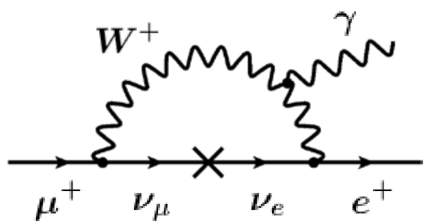
M. Hildebrandt :: Paul Scherrer Institut
on behalf of the CDCH team of the MEG II Collaboration

The ultra-light Drift Chamber of the MEG II Experiment

Vienna Conference on Instrumentation VCI2019, Vienna, February 20, 2019

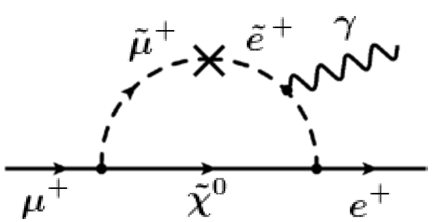
charged Lepton Flavour Violation

- 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})

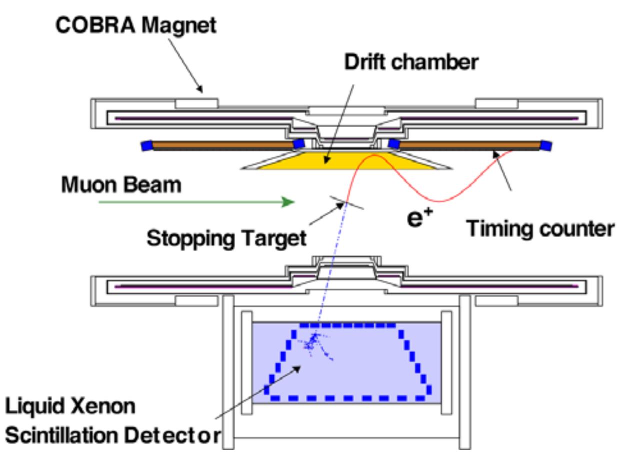
→ experimental observation of $\mu^+ \rightarrow e^+ \gamma$ is clear signature of “New Physics” beyond the SM

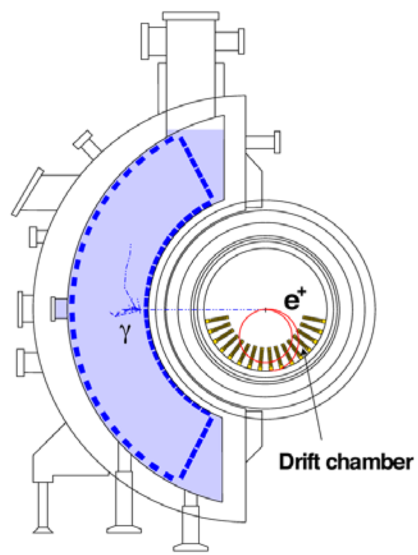
MEG Experiment

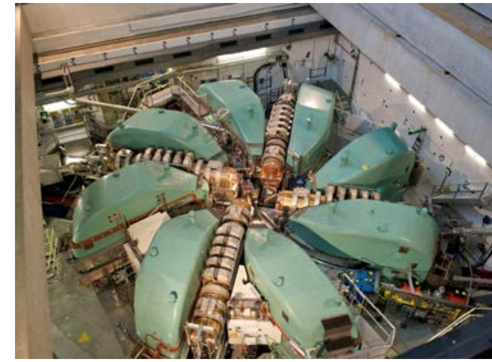
- located at the Paul Scherrer Institut (PSI)
  - p-cyclotron: 590 MeV, 2.4 mA (→1.4 MW)
  - most intense DC low momentum (28 MeV/c) muon beam in the world: intensity $O(10^8\ \mu/s)$
- dedicated detector to measure the observables characterising the $\mu^+ \to e^+ \gamma$ event (E_γ, E_e, $t_{e\gamma}$,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

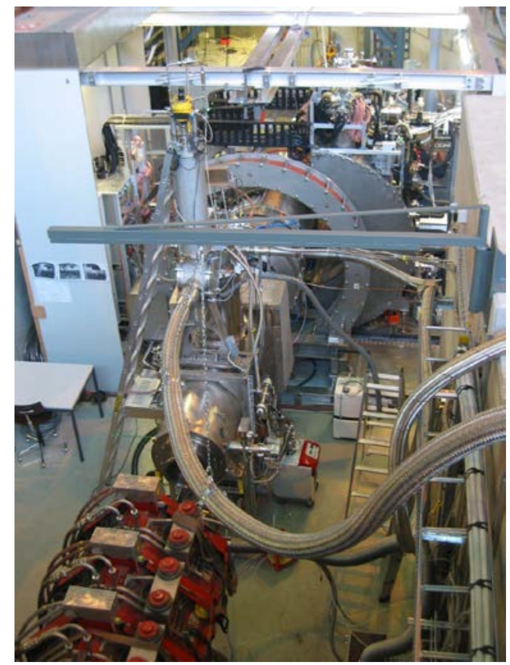
$$\mathbf{BR\ (\mu^+ \to e^+ \gamma)\ <\ 4.2 \cdot 10^{-13}}\ \ (90\%\ \mathrm{CL})$$

→ factor ~30 improvement compared to MEGA experiment









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)

$$\mathbf{SES} = \frac{1}{\underset{\text{beam rate}}{\mathbf{R}} \cdot \underset{\text{acquisition time}}{\mathbf{T}} \cdot \underset{\text{geometrical acceptance}}{\mathbf{A_g}} \cdot \underbrace{\varepsilon(\mathbf{e^+}) \cdot \varepsilon(\gamma) \cdot \varepsilon(\mathbf{TRG})}_{\text{detector efficiency}} \cdot \underset{\text{selection efficiency}}{\varepsilon(\mathbf{sel})}}$$

- reduce the background

$$\mathbf{B_{acc}} \sim \mathbf{R} \cdot \underset{e^+\text{ energy resolution}}{\Delta \mathbf{E_e}} \cdot \underset{\gamma\text{ energy resolution}}{(\Delta \mathbf{E_\gamma})^2} \cdot \underset{\text{relative timing resolution}}{\Delta \mathbf{T_{e\gamma}}} \cdot \underset{\text{relative angular resolution}}{(\Delta \Theta_{e\gamma})^2}$$

- 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)

$$\text{SES} = \frac{1}{\underset{\text{beam rate}}{R} \cdot \underset{\text{acquisition time}}{T} \cdot \underset{\text{geometrical acceptance}}{A_g} \cdot \underbrace{\varepsilon(e^+) \cdot \varepsilon(\gamma) \cdot \varepsilon(\text{TRG})}_{\text{detector efficiency}} \cdot \underset{\text{selection efficiency}}{\varepsilon(\text{sel})}}$$

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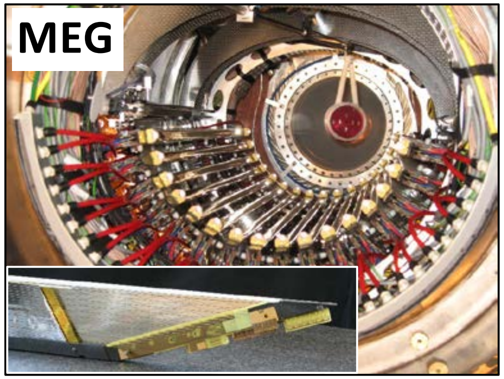
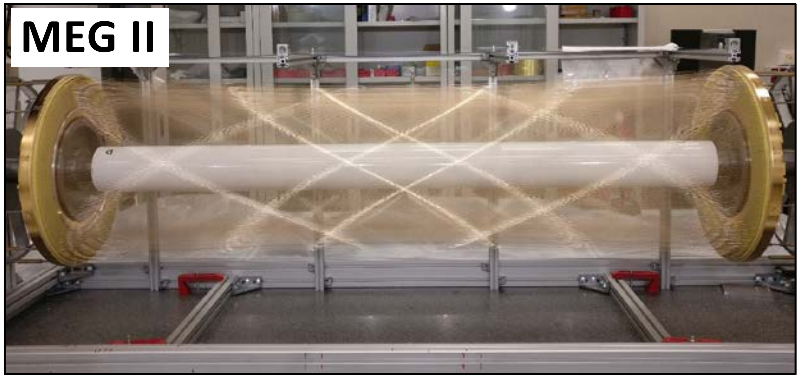


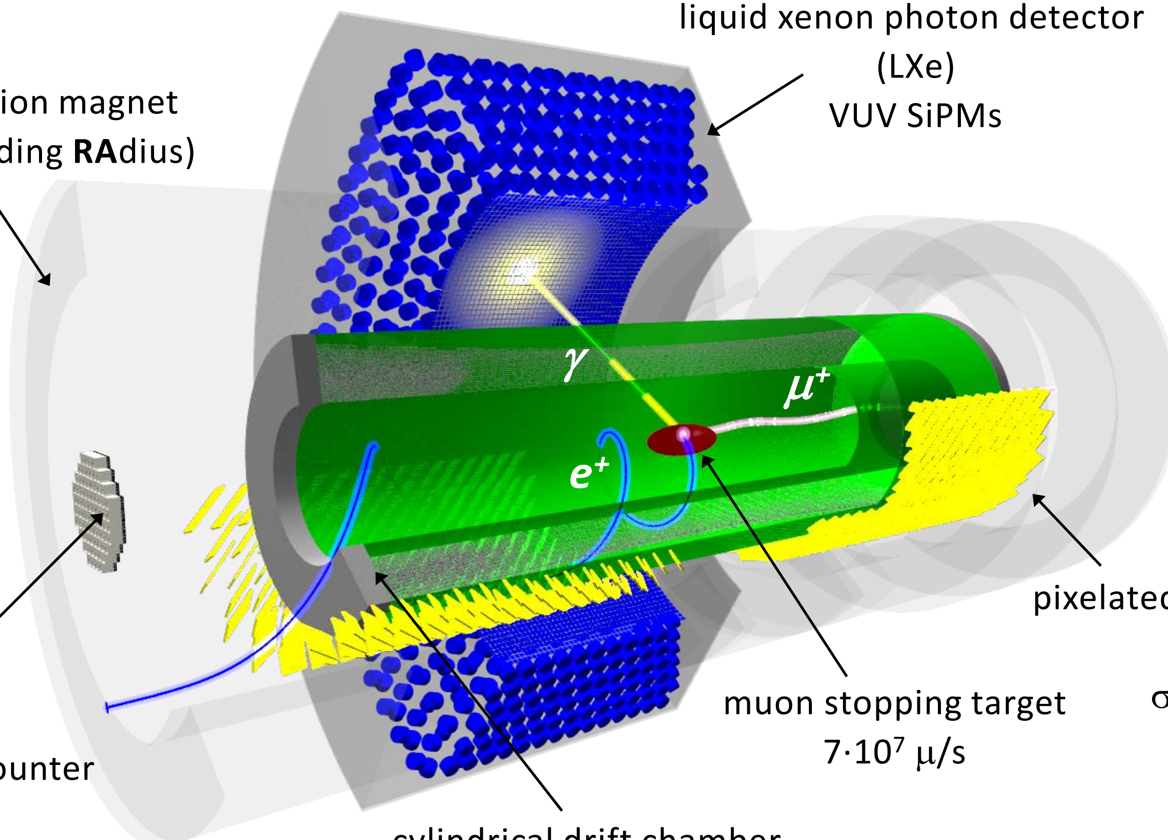
factor 2
improvement



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

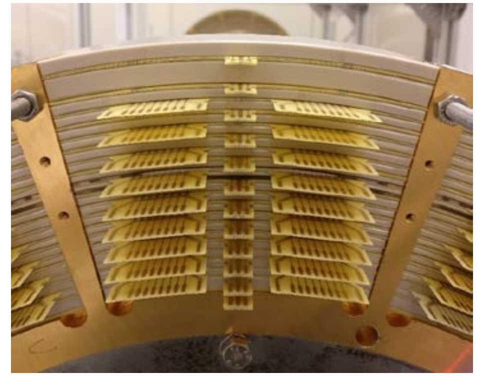
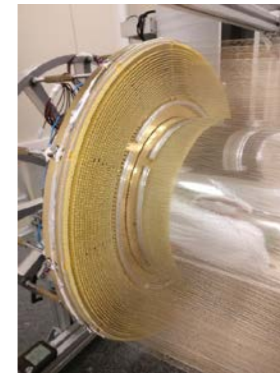
Miki Nishimura
Mon, 18.02., 17:30
plenary talk, ID:607

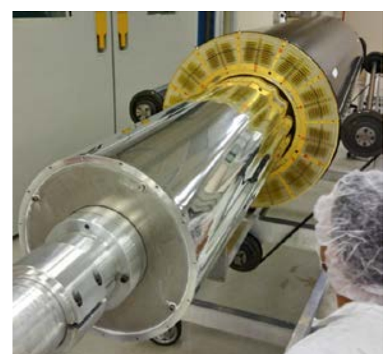
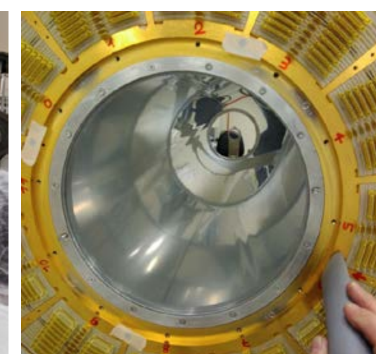


Baldini *et al.*, Eur. Phys. J. C (2018) 78:380

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

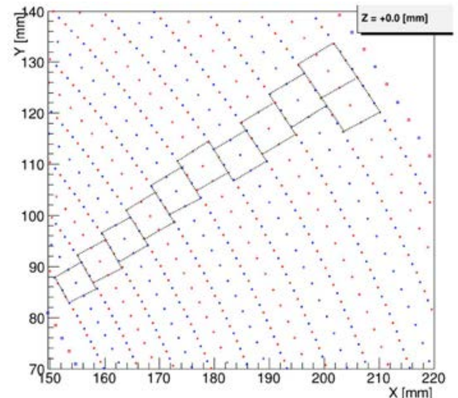



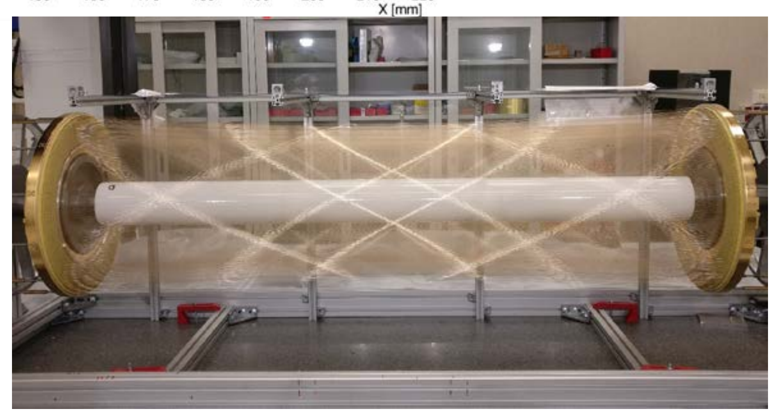



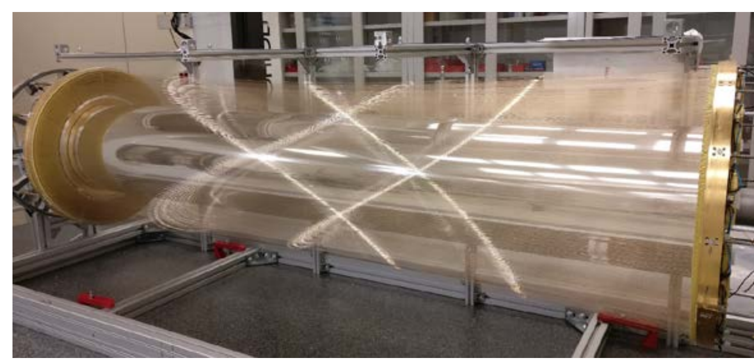
Cylindrical Drift Chamber - 2

- 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)

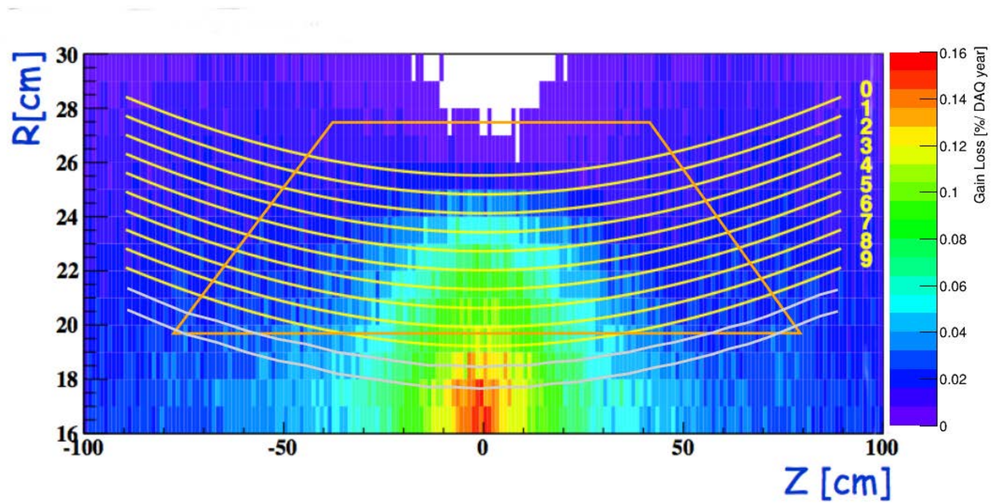


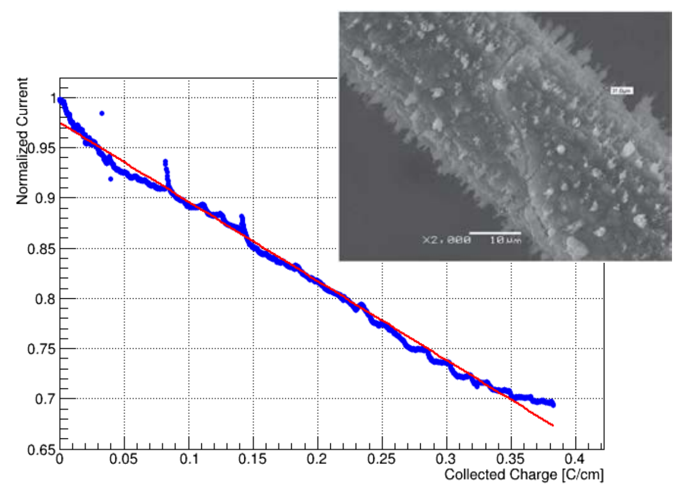




Counting Gas – Ageing

- 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

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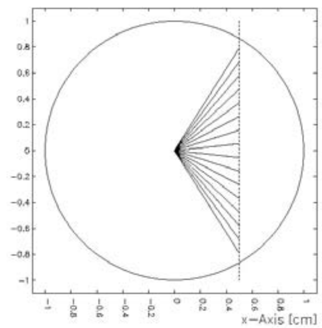
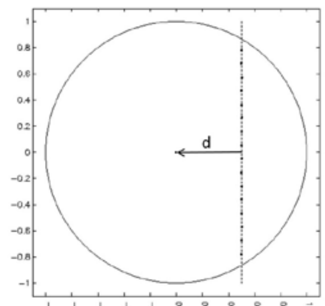
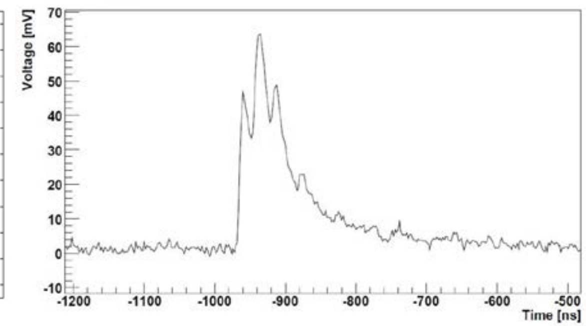
Counting Gas – Cluster Counting Technique

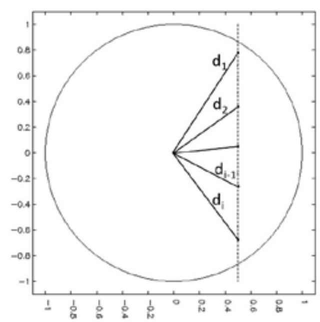
- primary ionisation
  - ~13 e$^-$/cm (n_p dominated by W_{He} = 41 eV)
  - large spacing between the individual clusters → cluster counting and timing technique
    - «traditional»

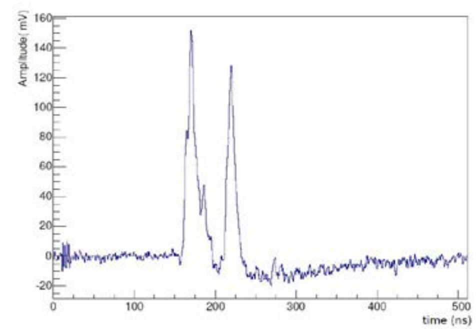






    - cluster counting timing technique
      - → increased number of supporting points along particle trajectory
      - → improved track fitting accuracy and momentum determination





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

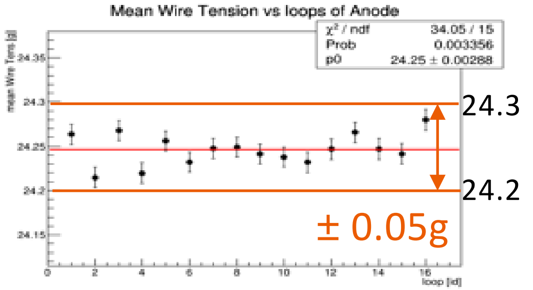
- performance (resolution, σ):

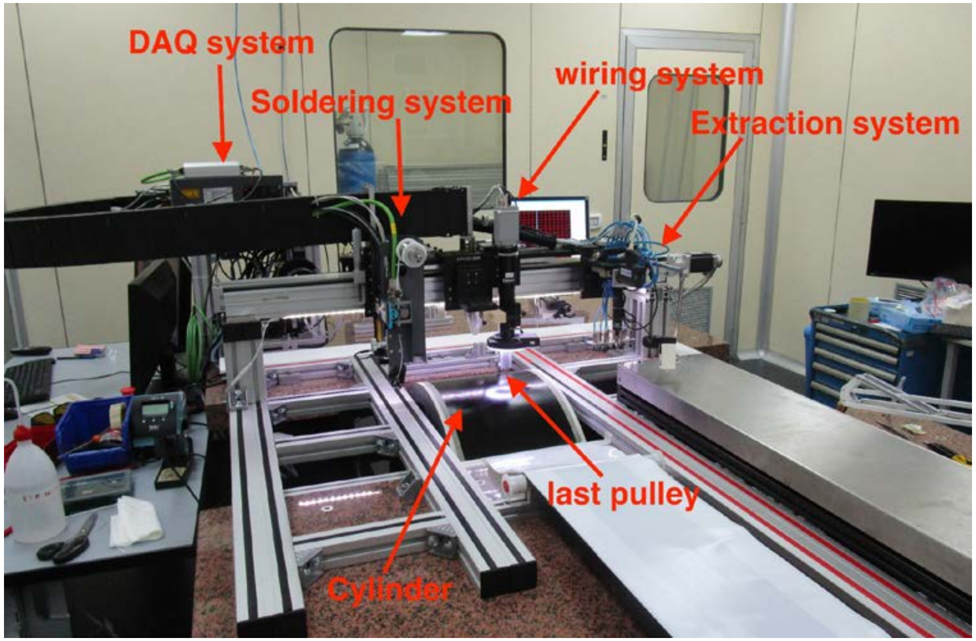
single hit (prototype) ~110 µm in r-direction
momentum (MC) ~110 keV/c (@52.8 MeV/c)
angular (MC) ~5.7 mrad in θ, ~6.0 mrad in ϕ

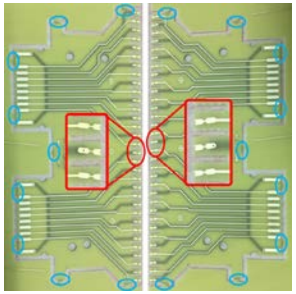
Signorelli, D'Onofrio, Venturini, NIM A 824 (2016) 581-583
Baldini *et al.*, 2016 JINST 11 P07011

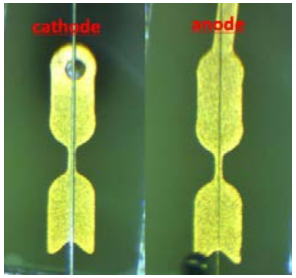
Wiring Technique

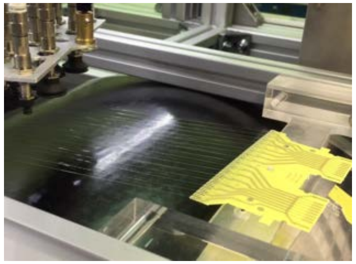
- semi-automatic wiring robot
  - to string continuously variable wire pitch and stereo angle configurations
  - to apply a pre-defined mechanical tension to the wires, constant and uniform (± 0.05g)
  - to monitor the wire locations and their alignment (~20 μm)
  - to monitor the soldering quality on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











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

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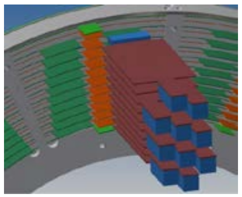
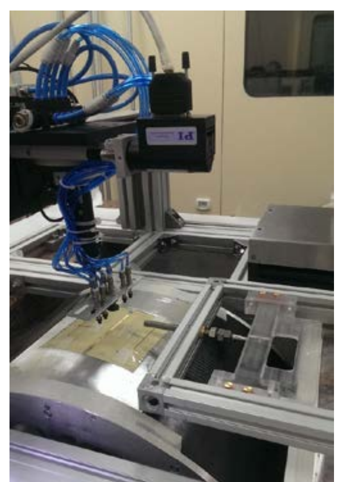
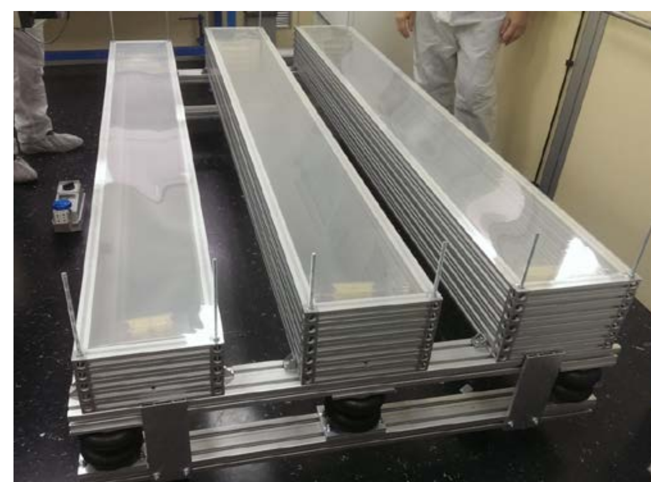
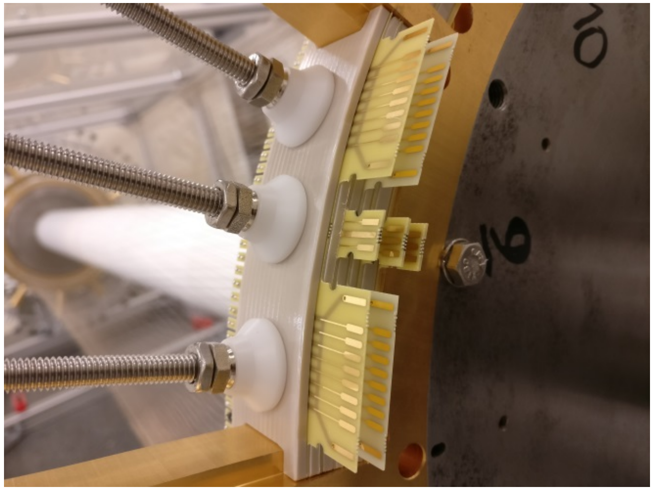
Construction Work - 1

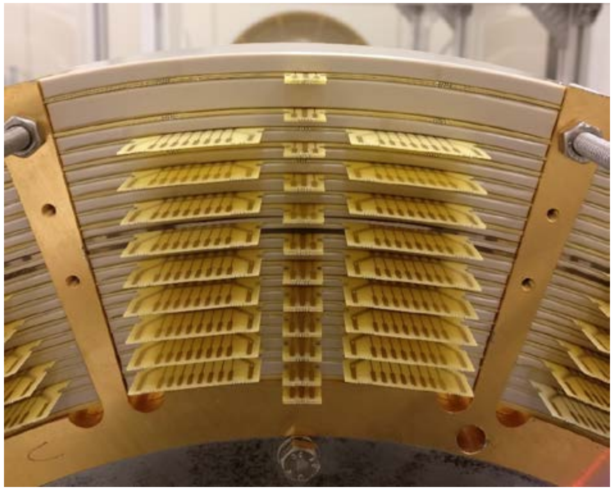


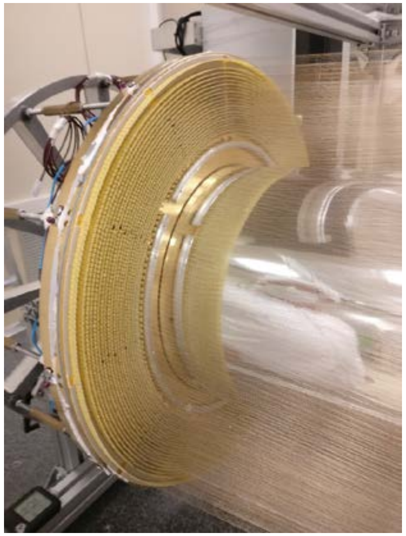


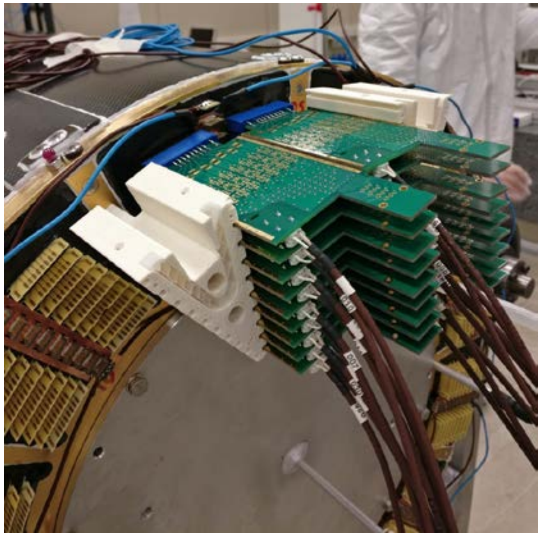


Construction Work - 2









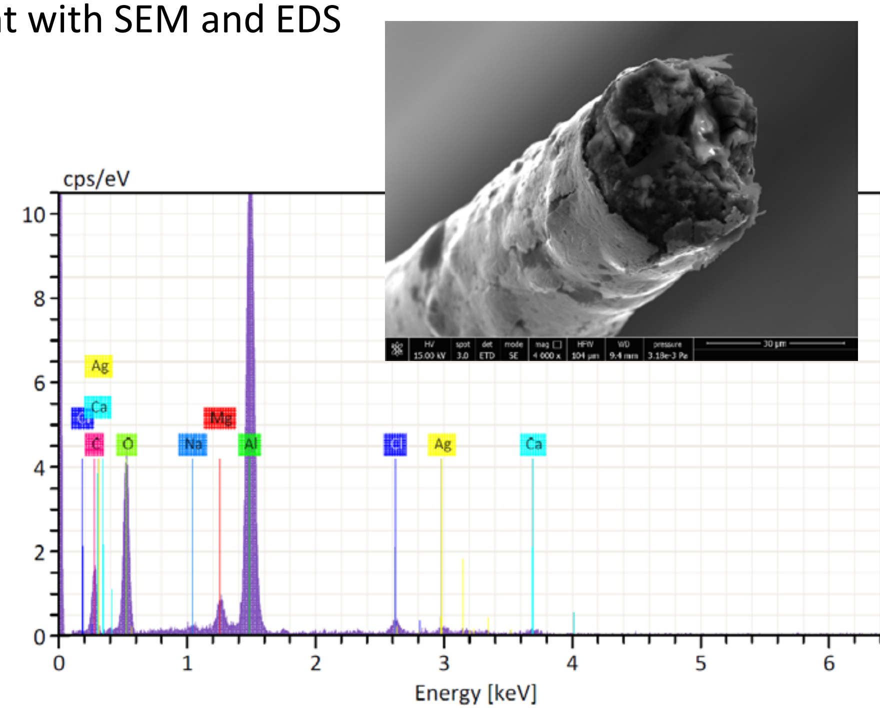
Humidity and Corrosion of Al Wires - 1

- observation: during assembly in 2016 and 2017 several silver-coated 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

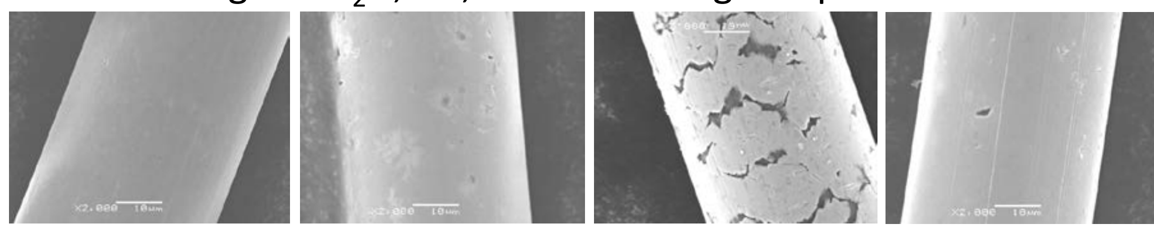


- «fear»: mechanical stress could enhance the corrosion, known as Stress Corrosion Cracking (*status 2019: this seems not(!) to be the case*)

Humidity and Corrosion of Al Wires - 2

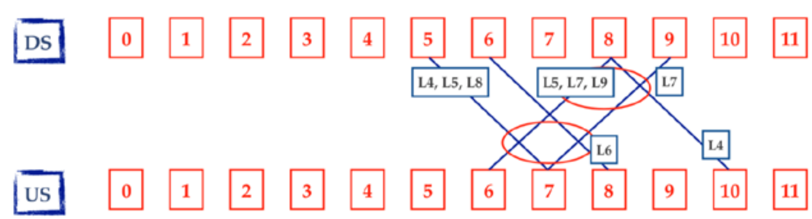
- conclusion: silver-coated Al wire (Al alloy 5056, Ag layer for soldering purposes), is very sensitive to corrosion induced by humidity, in particular in the presence of NaCl

→ 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…

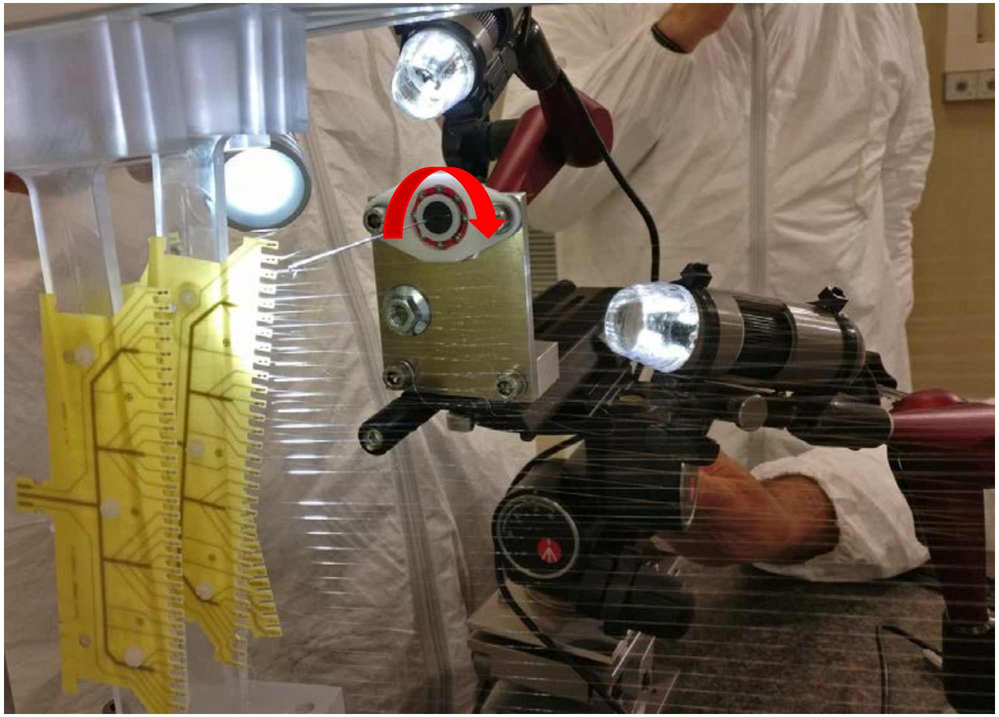
- …but unfortunately end of 2018 during pre-commissioning run: signature/combination of short-circuited segments indicate broken wire

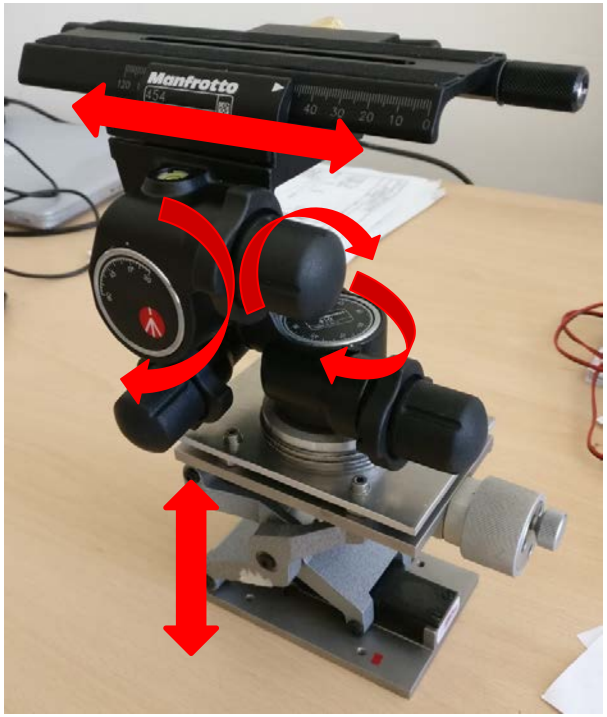


→ drift chamber will be re-opened and inspected

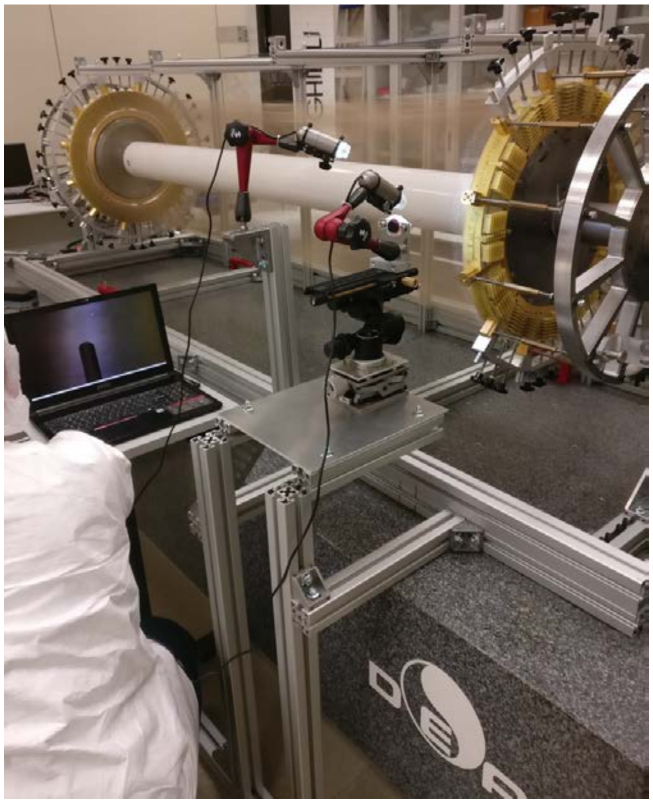
Removal of broken Wire - 1

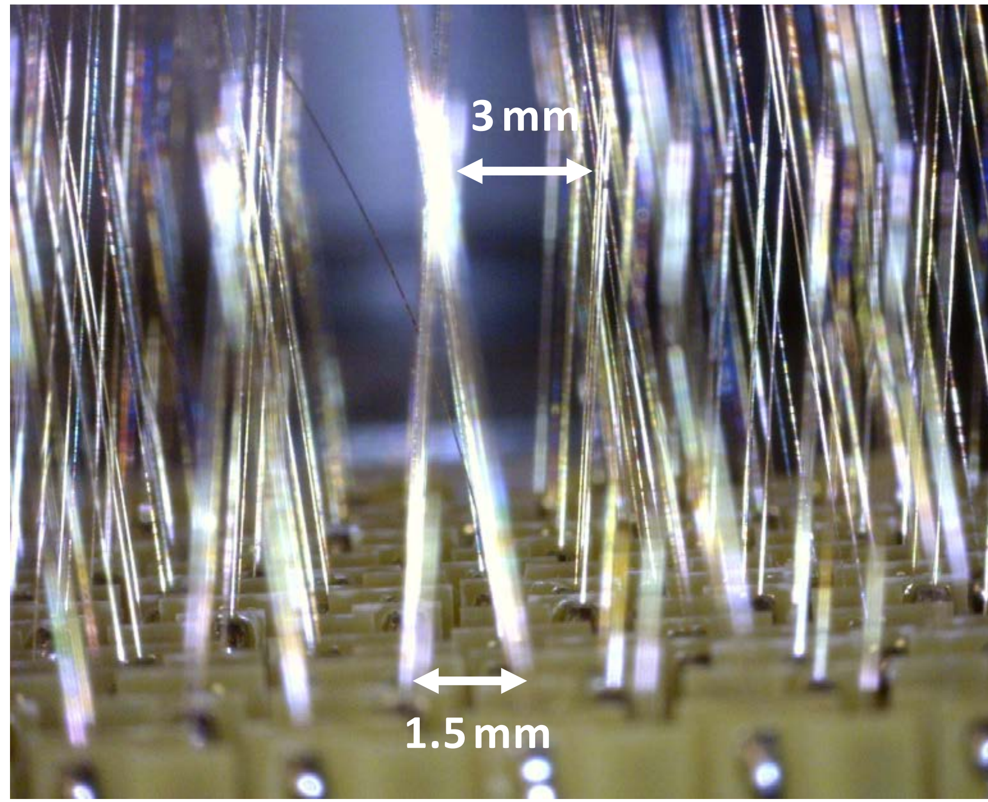
- proven strategy to remove broken wire
  - 1 mm stainless steal rod with 1.5 mm hook
  - support with 5(+1) independent axes with micrometric manual control





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

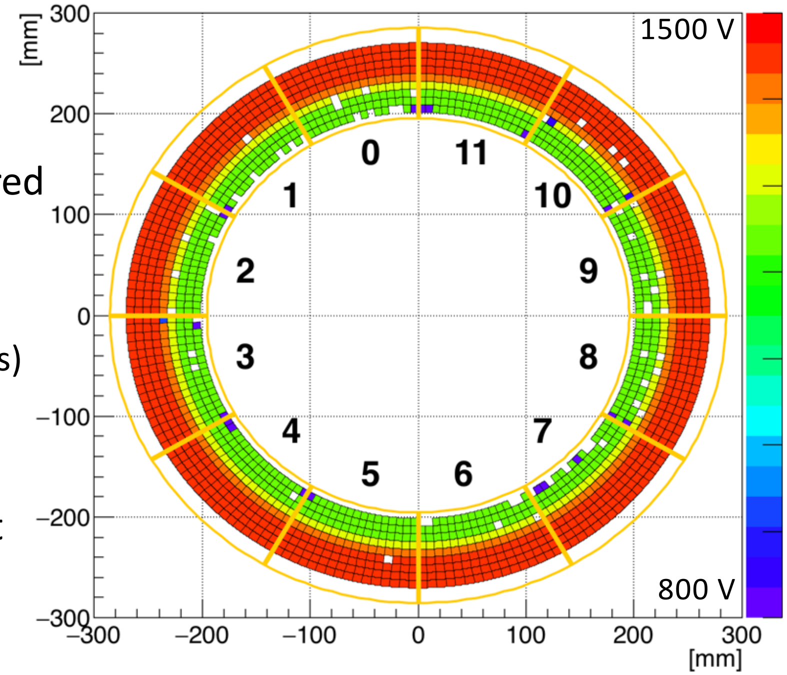
  taking into account - drift cell size and

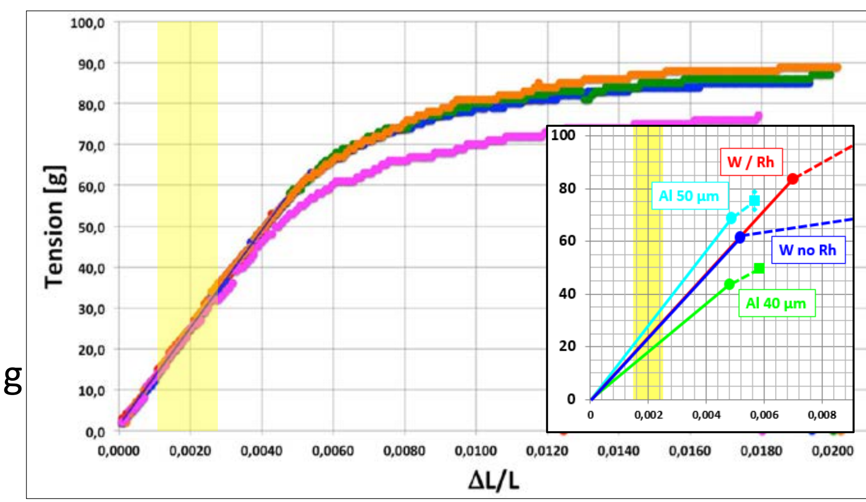
  - wire positioning accuracy

  → wire tension needs to be increased!

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

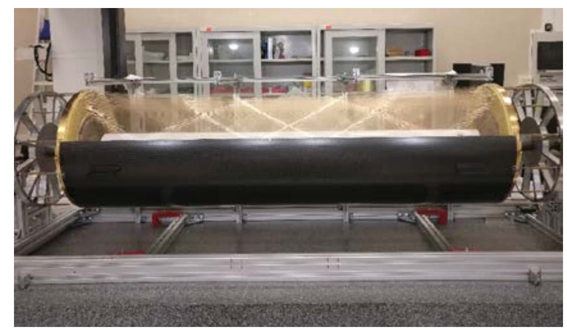
↔ «fear» of enhanced wire breaking in case of Stress Corrosion Cracking (*status 2019: fear not confirmed*)

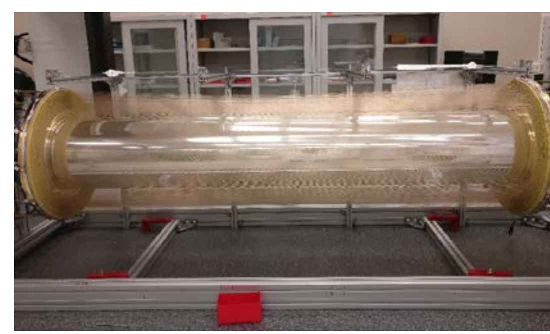




Stretching of Drift Chamber

- 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

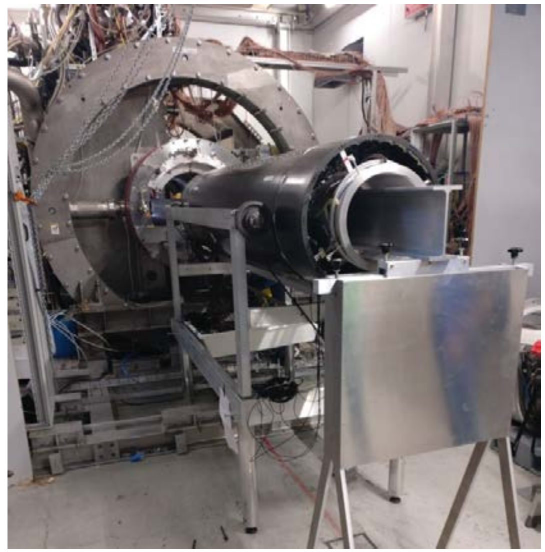


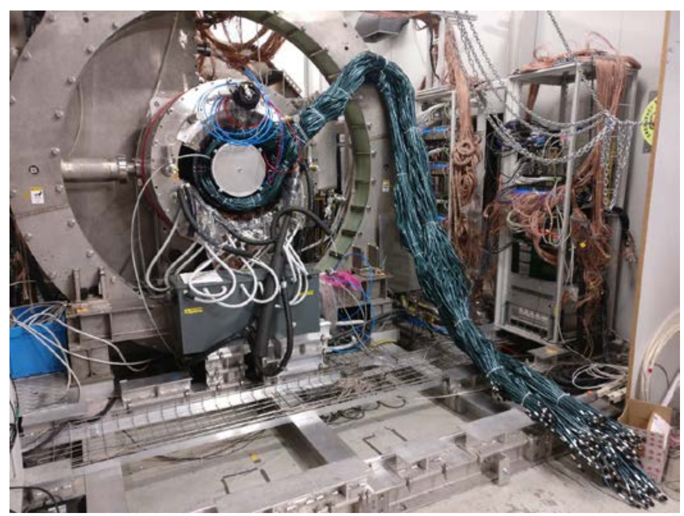


- *remark*: parallelism on the level of <50 μm
  (reminder geometry: length 2 m, diameter 60 cm, applied force 280 kg)

Installation

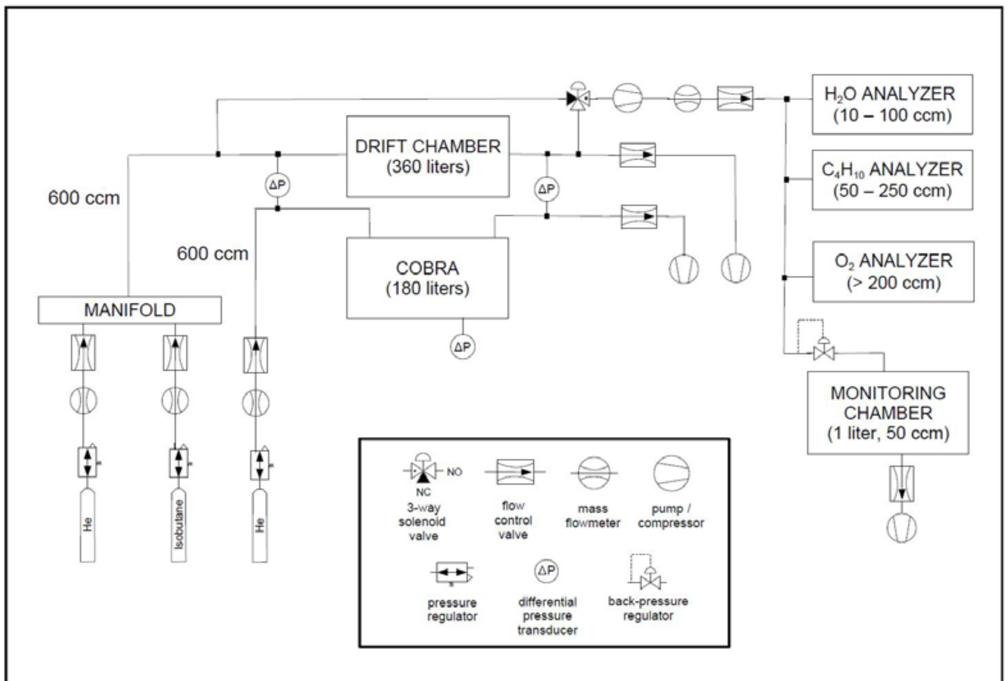
- October 2018: installation, survey, cabling, etc.

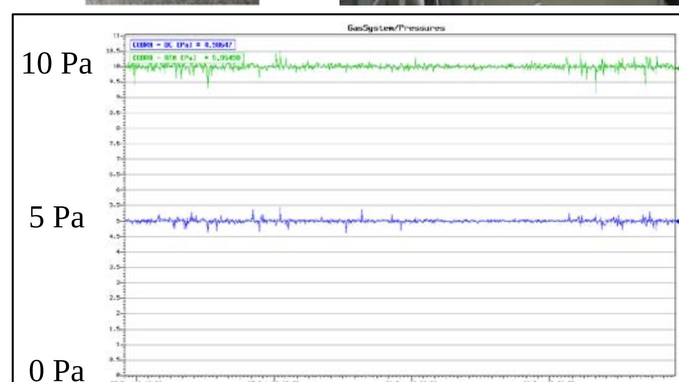




Pressure Regulation & Gas Monitoring System

- 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



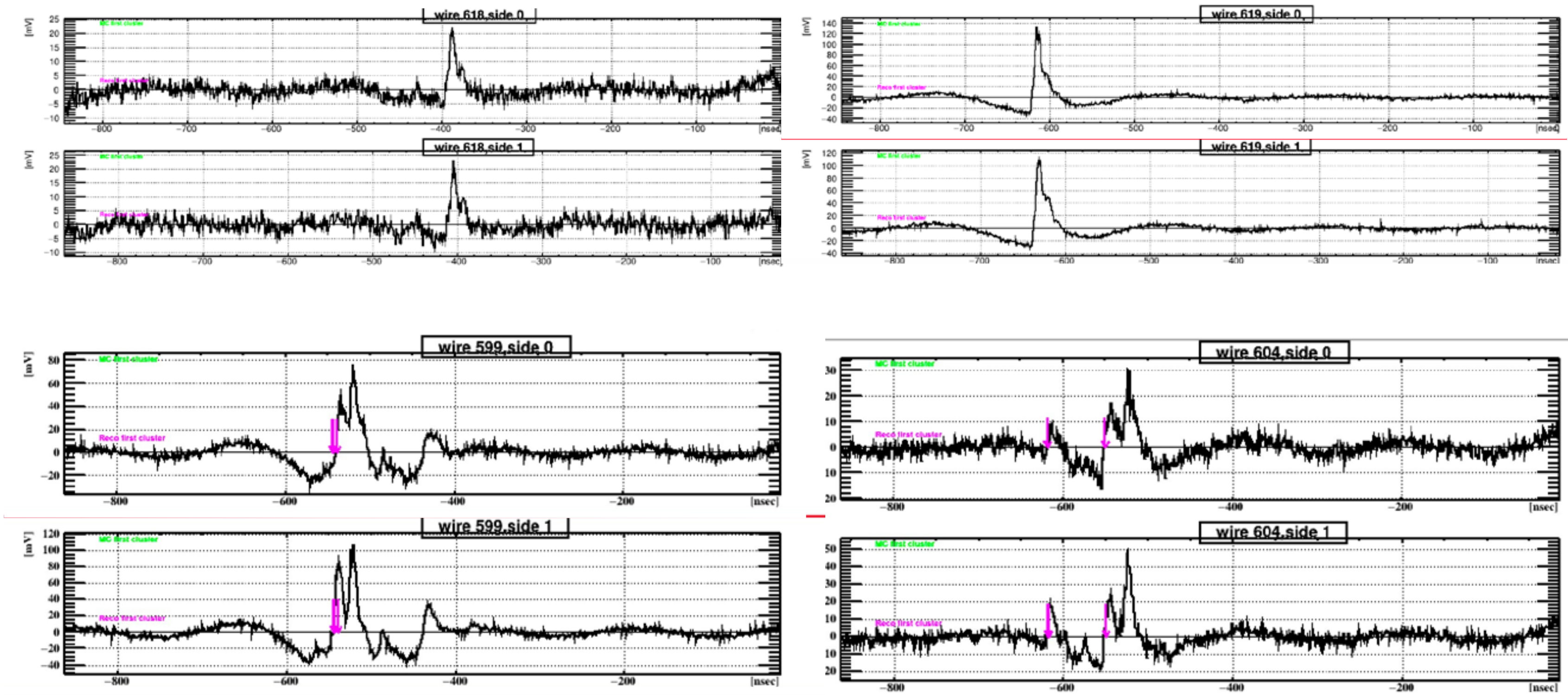
Baldini *et al.*, 2018 JINST 13 P06018



Performance – First Glimpse

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

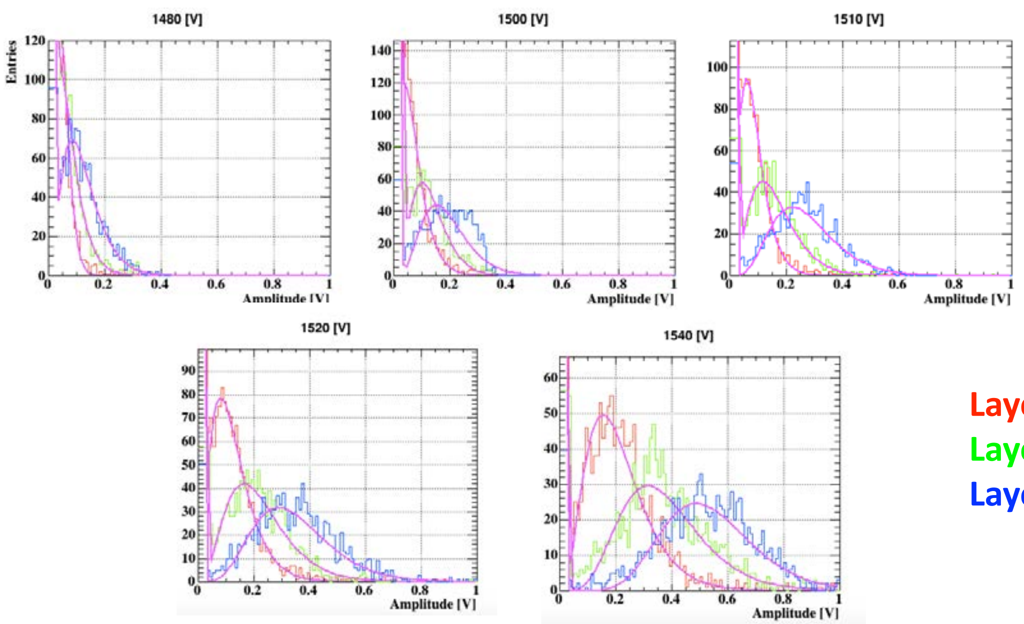
    remark: 1.2 GSPS, but transmission limited to 400 MHz bandwidth,
    consequently: individual clusters hardly resolvable…



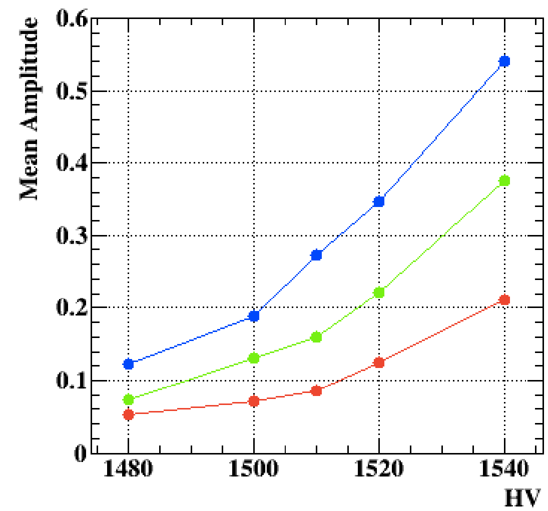
Performance – First Glimpse

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

  - amplitude distributions vs HV



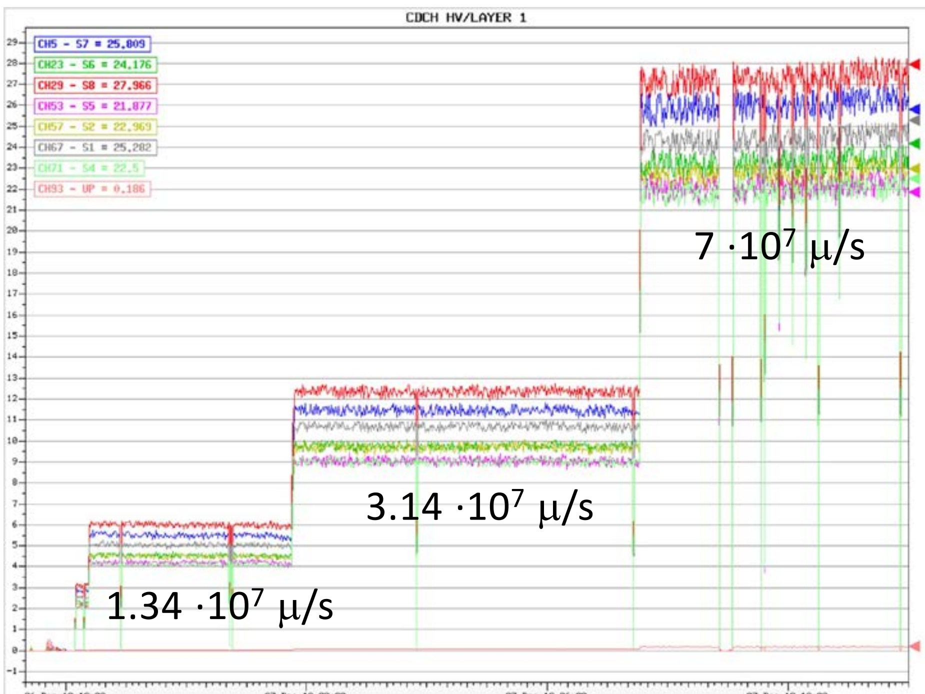
  - gain vs HV (arbitrary units)

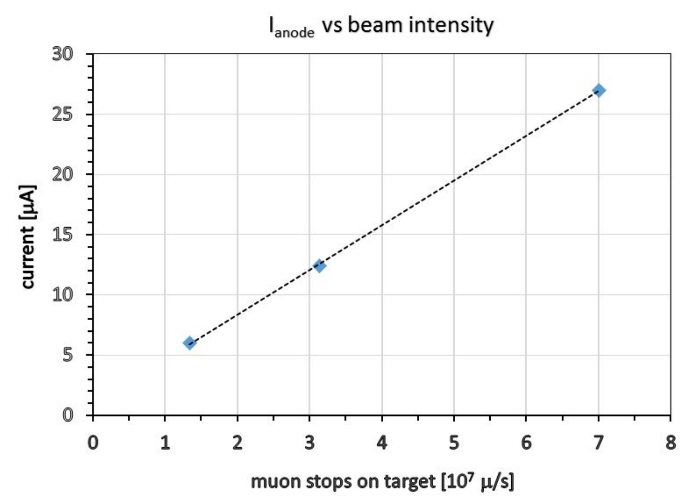


Layer 1
Layer 2
Layer 3

Performance – First Glimpse

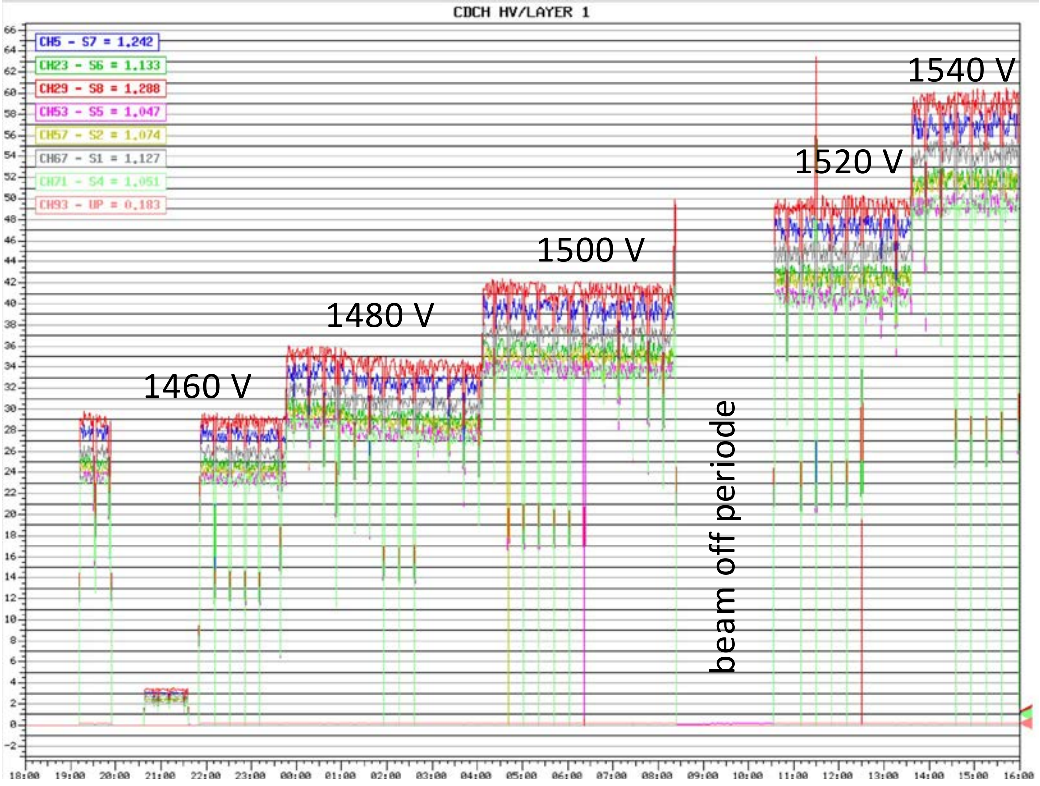
- December 2018: cosmics and Michel e^+ events at muon beam intensities of up to 10^8 μ/s
  - scan with fixed HV at different beam intensities





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



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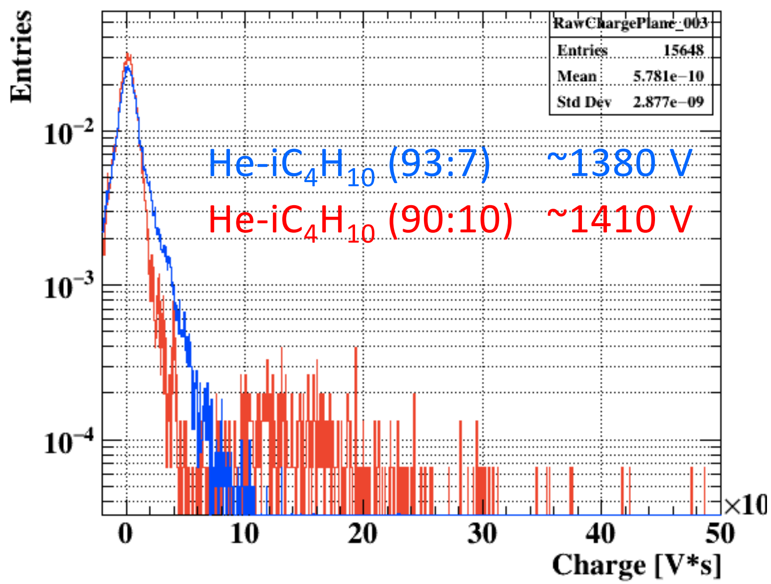
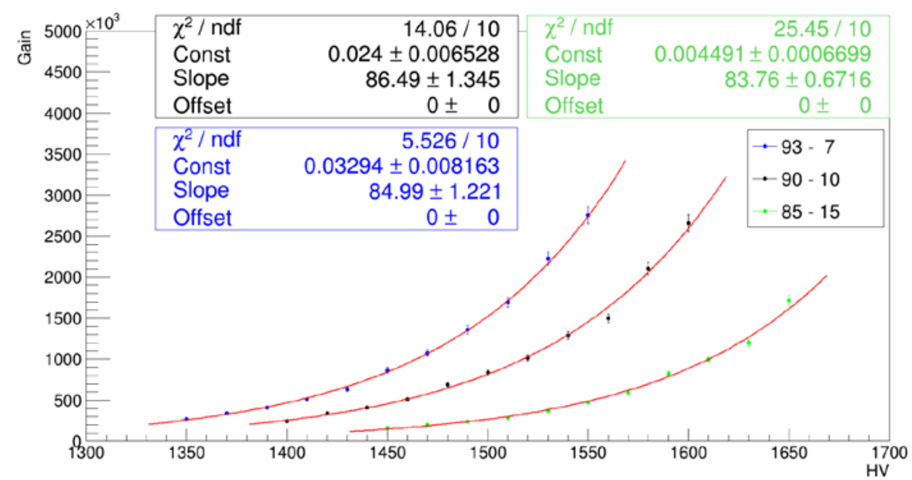
Performance – First Glimpse

- 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)



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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 wire will be removed
  - chamber length will be increased

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

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

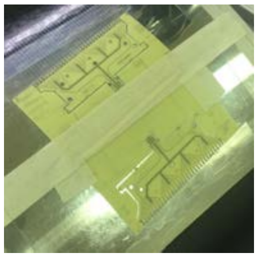
- Fabrizio Cei
- Franco Grancagnolo
- Donato Nicolo
- Angela Papa
- Francesco Tassieli

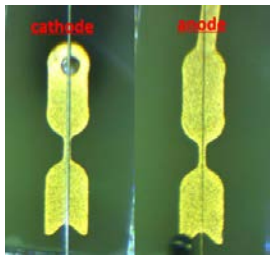
- Dieter Fahrni
- Andreas Hofer
- M.H.

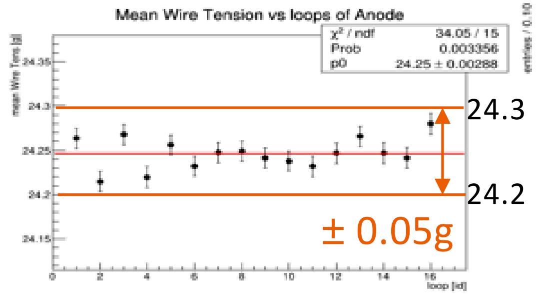
- Alexander Kolenikov
- Vladimir Malyshev

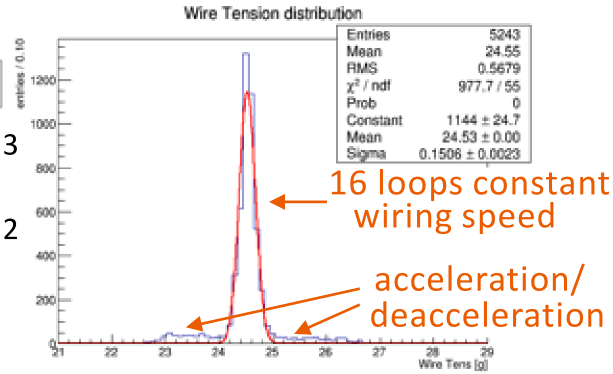
Wiring Technique

- semi-automatic wiring robot
  - wiring system



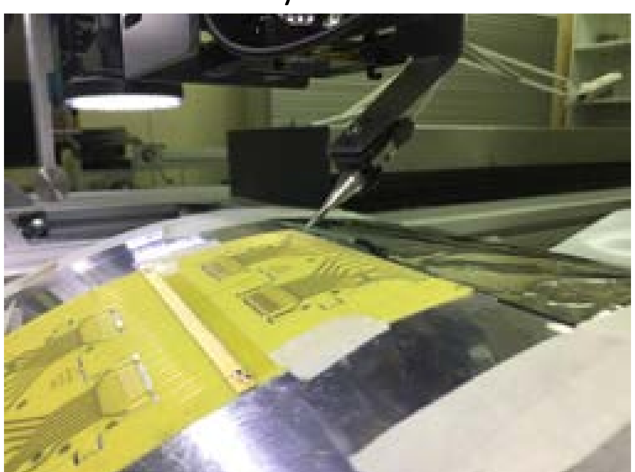






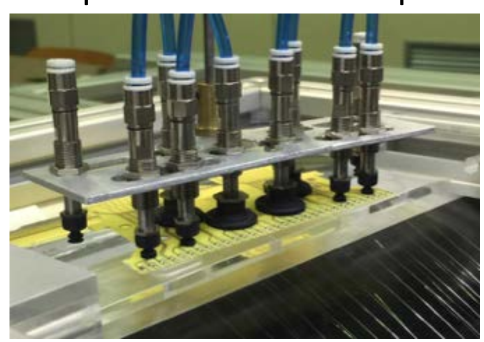
  - soldering system

LASCON Hybrid IR laser

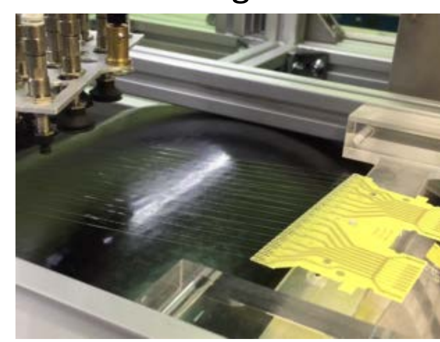


  - extraction system

lifting up of pcb with vacuum operated suction cups



unrolling from winding drum



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

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