Gaseous Detectors for Preclinical Proton Beam Monitoring, Characterization and Imaging

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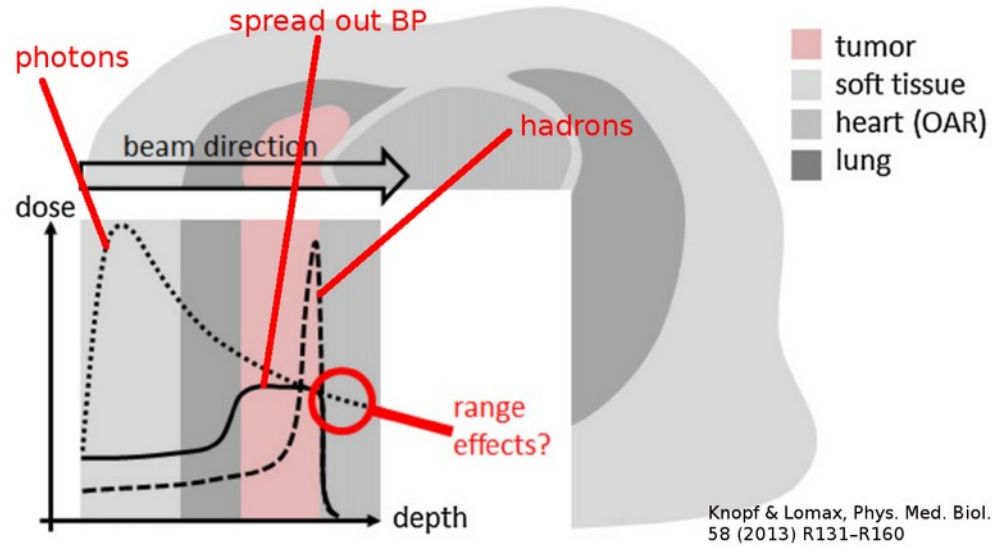
7th International Conference on Micro Pattern Gaseous Detectors – Rehovot, Israel
December 16, 2022

Context: Particle Therapy

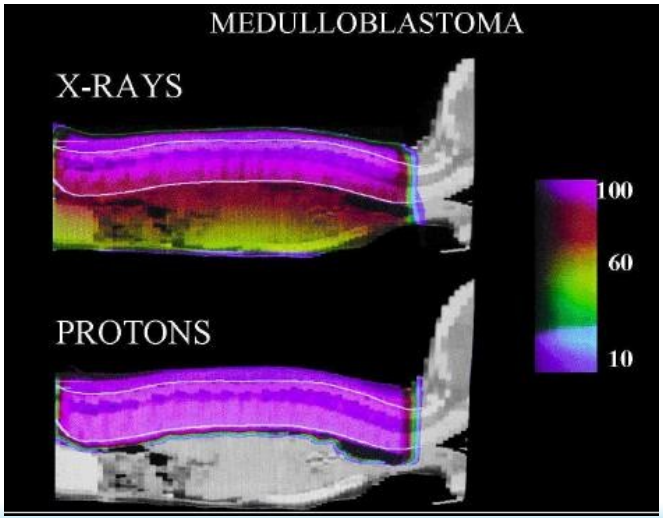
low energy ions: $dE/dx \sim 1/\beta^2$
→ favorable depth-dose:

- none behind tumor
- low in entrance



Knopf & Lomax, Phys. Med. Biol. 58 (2013) R131–R160

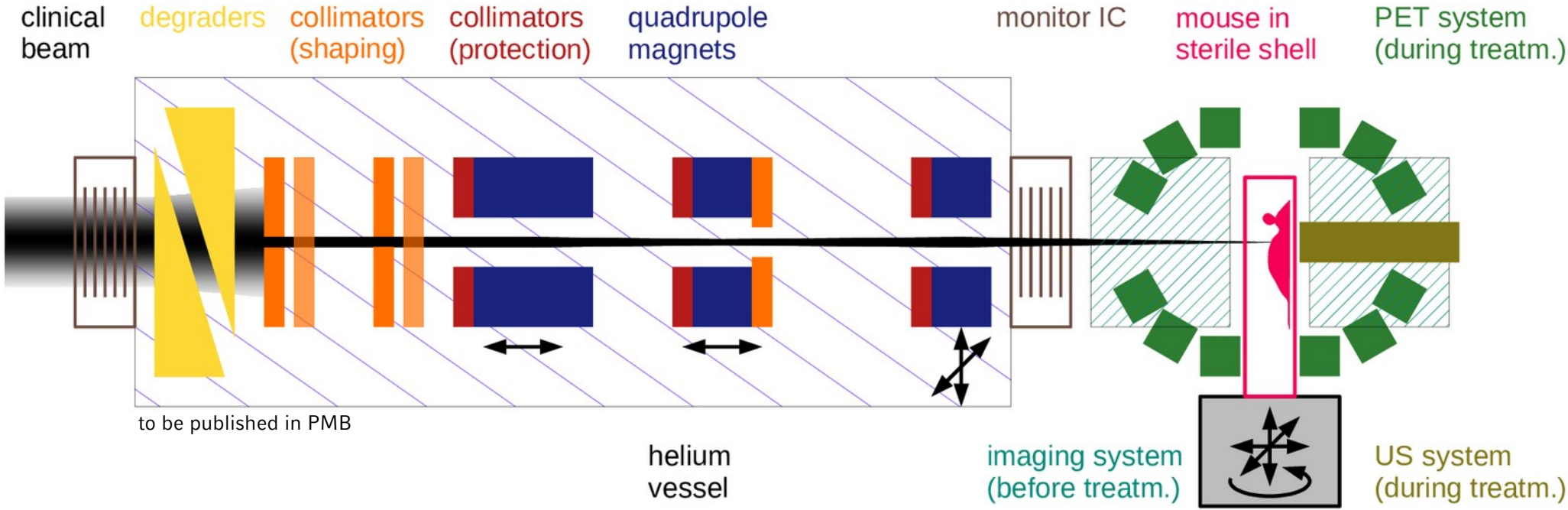
better tumor conformality → low out-of-field dose



ballistic advantages obvious BUT
therapeutical advantages not fully demonstrated

Small Animal Proton Irradiator SIRMIO

portable platform, installed at clinical facility: ERC, 2017 – 2022, PI K. Parodi, lmu.de/sirmio



to be published in PMB

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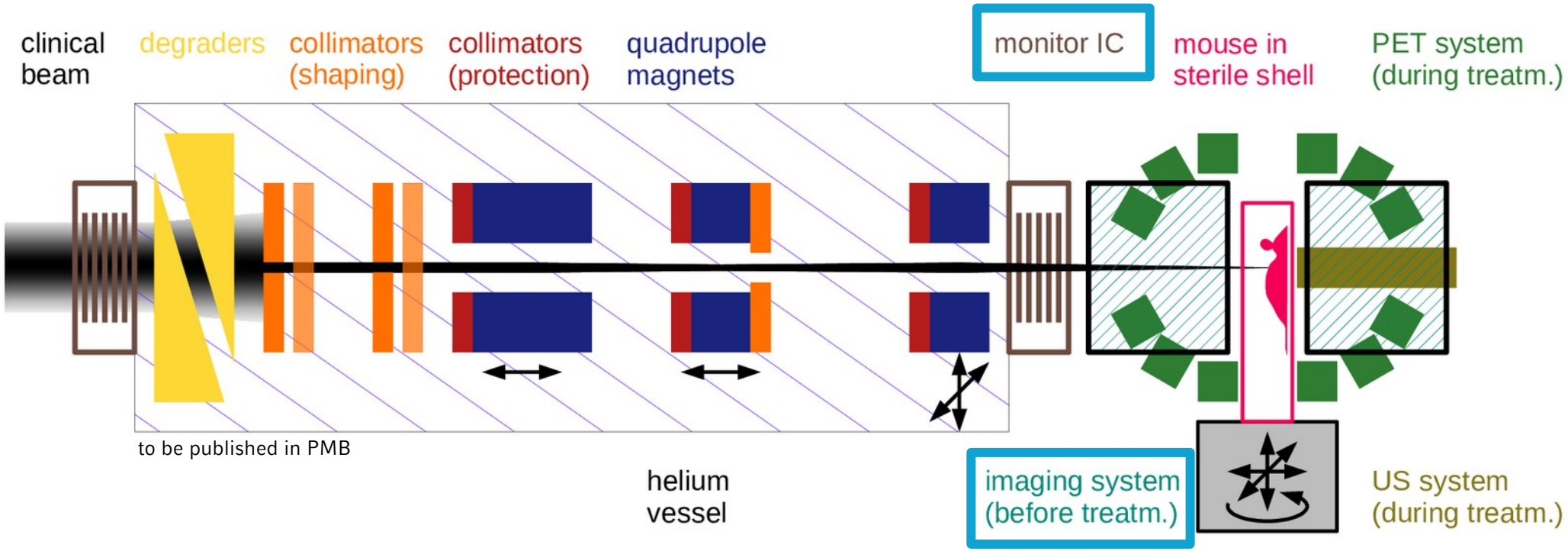
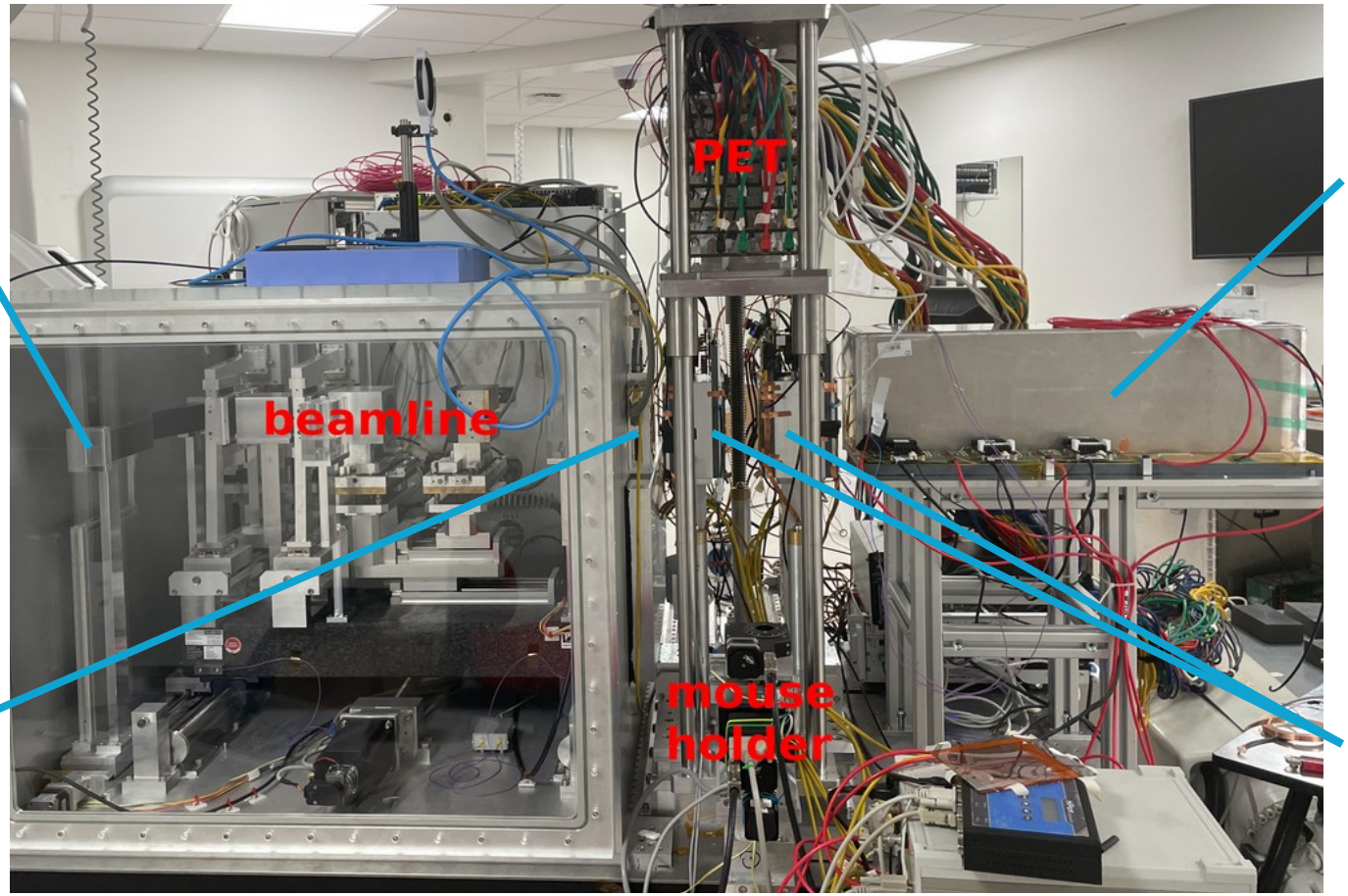


First Full System Test @ DCPT in Sept. 22

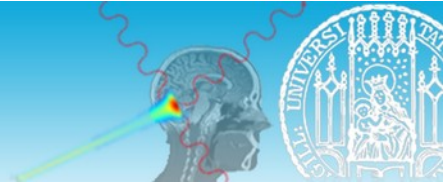


monitor: front IC

monitor: rear IC

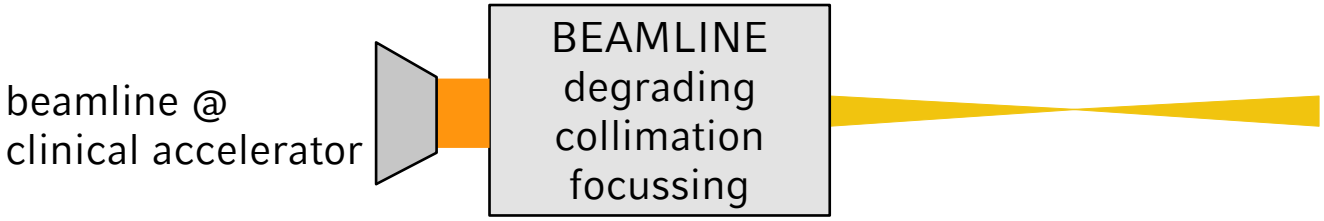
pCT: TPC

pCT: Micromegas Trackers



Proton Beam Characterization

Beam Profile QA System

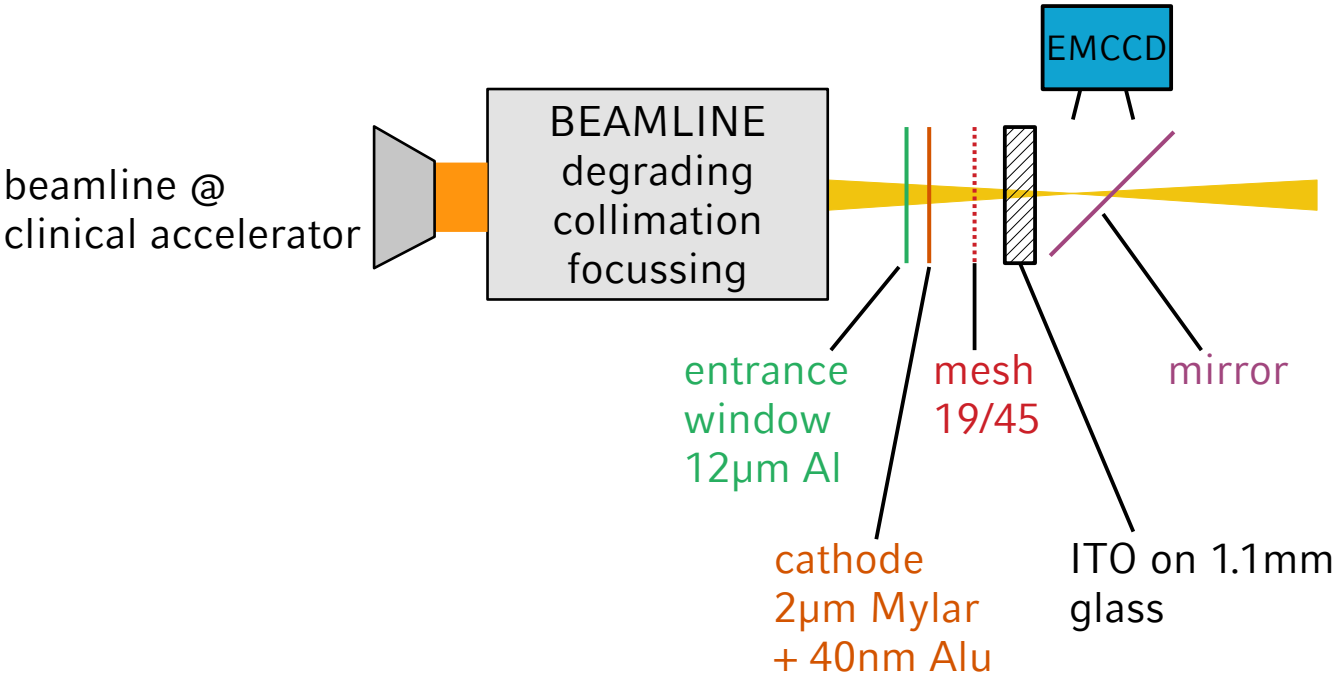


requirement: scan beam profile (20mm → 0.5mm) and position longitudinally prior to irradiation → beam parameters for treatment planning

constraints

- good 2d resolution → pixels
- no beam distortion before measurement (~20-50MeV)
- large dynamic range

Beam Profile QA System



ITO: indium tin oxide
EMCCD: Electron-Multiplying CCD

requirement: scan beam profile (20mm → 0.5mm) and position longitudinally prior to irradiation
→ beam parameters for treatment planning

constraints

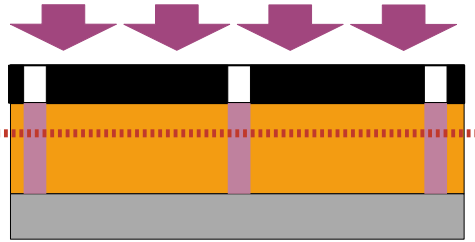
- good 2d resolution → pixels
- no beam distortion before measurement (~20-50MeV)
- large dynamic range

solution (inspired by Brunbauer et al. 2018 JINST 13 T02006 & Iguaz, RD51 CM 2018)
→ Glass Micromegas with optical readout
→ mounted on linear stage

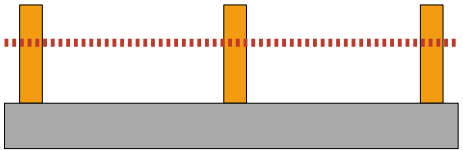
In-House Production: Optical Bulk Micromegas

I. lamination of 2 layers photo-imageable coverlay on ITO glass

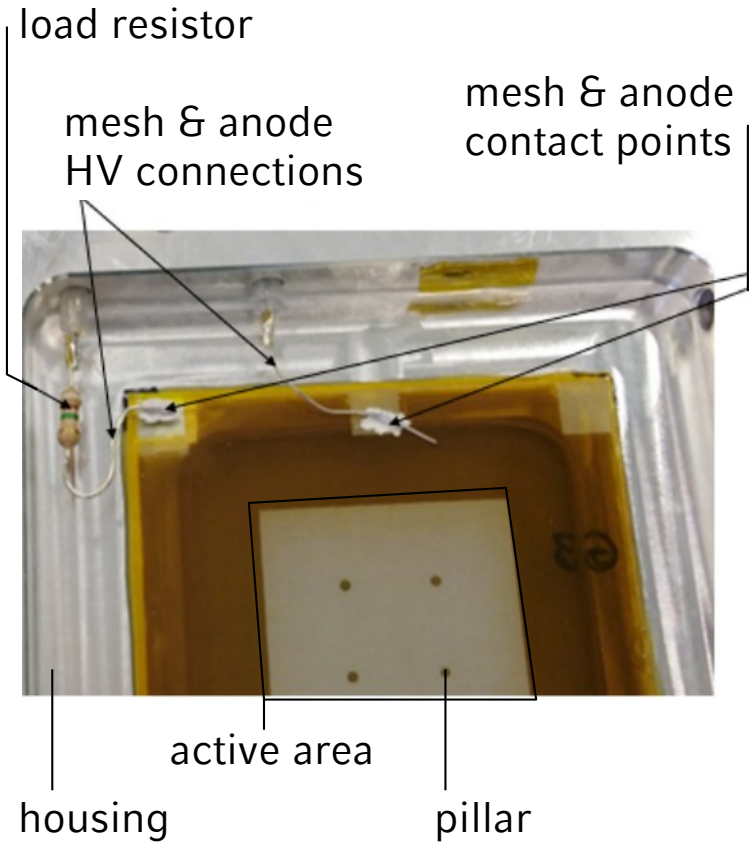
II. stretched mesh on top and lamination of 3rd layer coverlay



III. UV exposure with suitable mask: pillars & rim

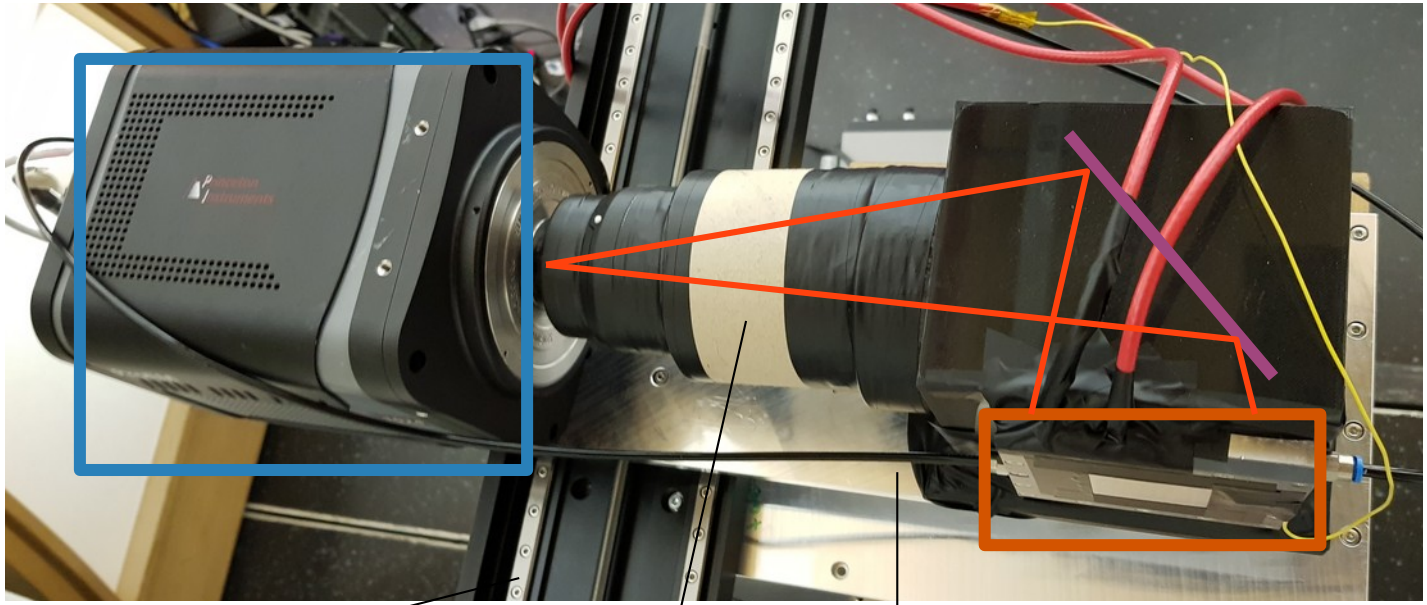


IV. wet development, washing & curing



BSc Belker, Frenzel

Optical Micromegas Beam-Profiler Unit

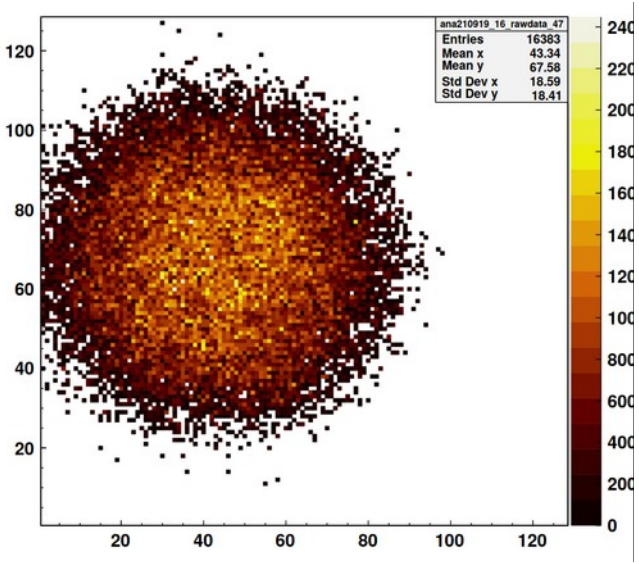


unit mounted on linear stage

fully light tight enclosure

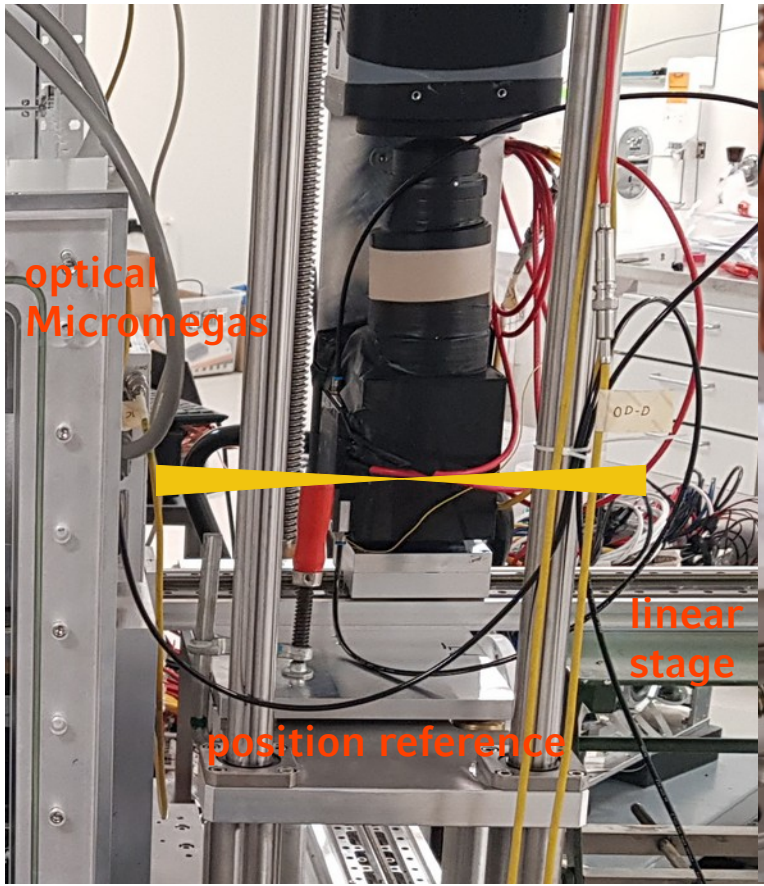
components mounted on common base

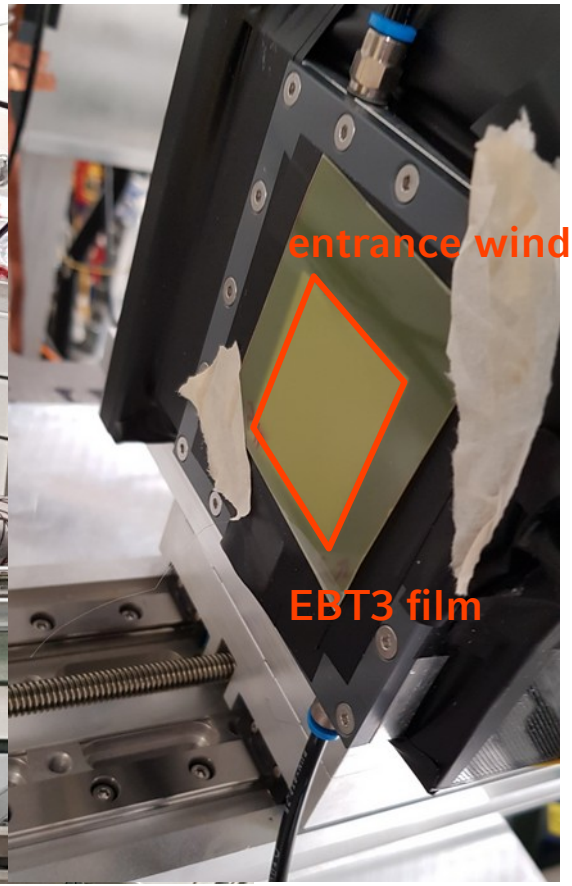
detector tests @ HZB, 68MeV p

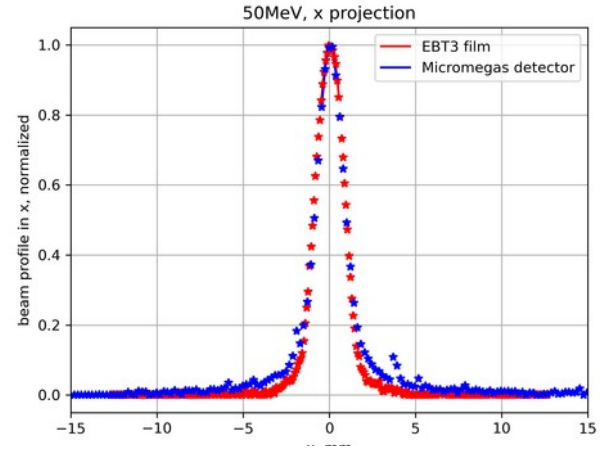


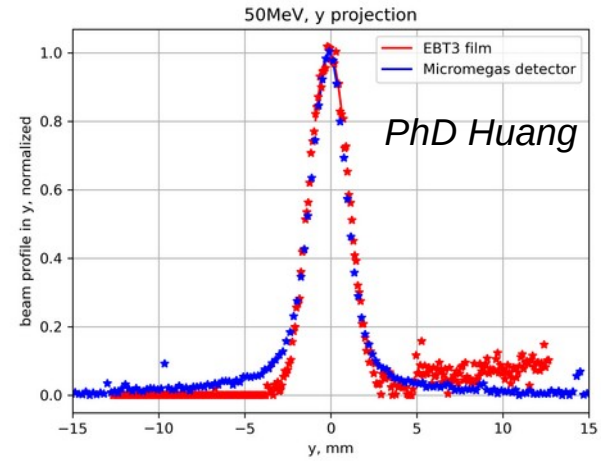
proton rate 2×10^3 – 3×10^5Hz
→ larger currents always possible

Profiling of SIRMIO Beam @ DCPT

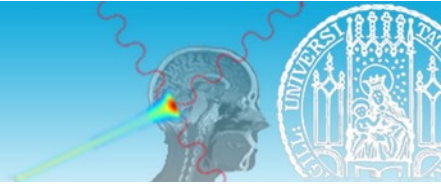






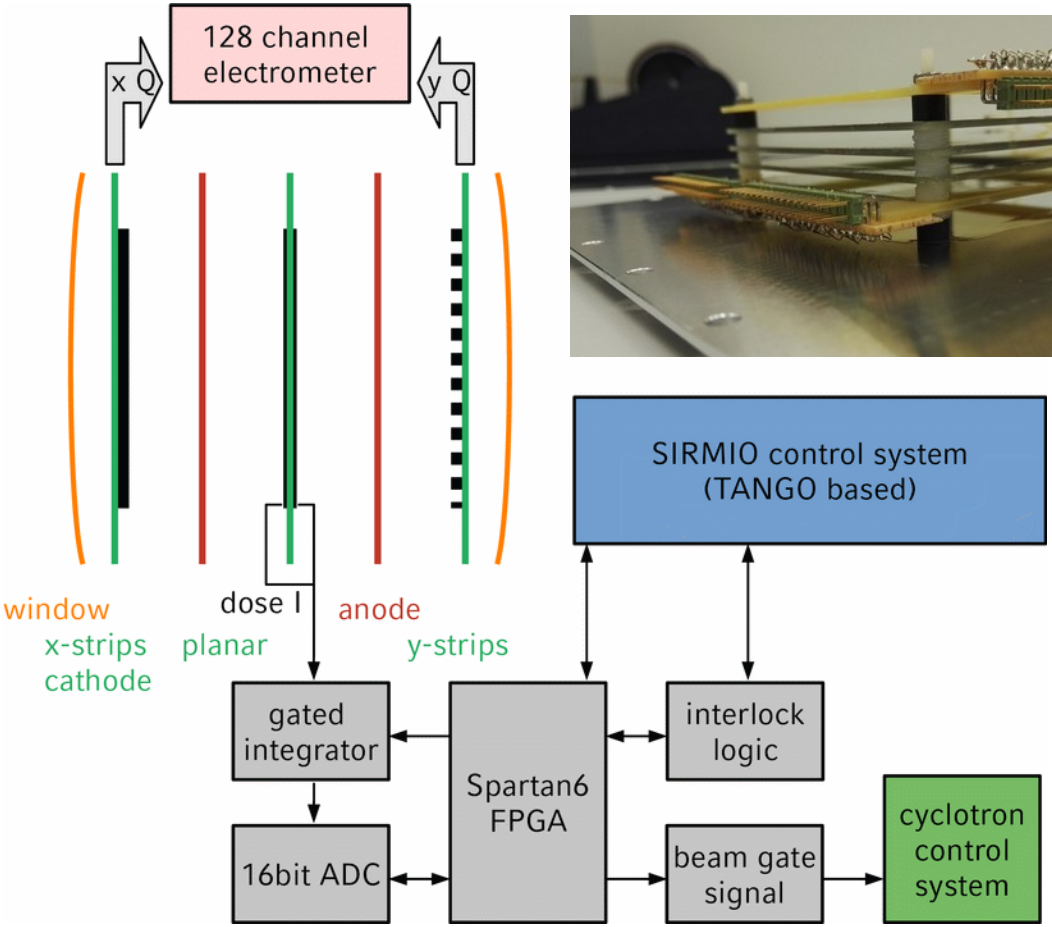


successfully used in beam line characterization @ PSI (2021) & DCPT (2022)



Proton Beam Monitoring

Ultra-Thin Beam Monitor Chambers



two monitor chambers

- active area 64x64mm²
- 2 strip planes (64 strips, 40nm Alu on 10µm Kapton)
- 1 dose gap (unsegmented, 40nm Alu on 2µm Mylar)

custom monitor chamber DAQ

- register charge/integration cycle

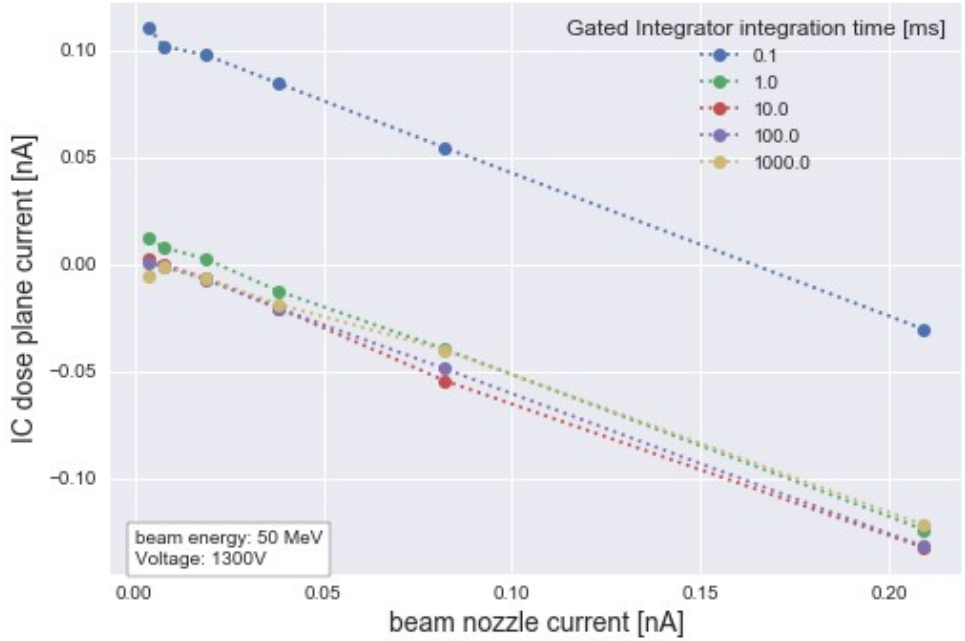
custom DAQ & beam control system

- enable beam & disable beam after target dose was reached
- real time → FPGA

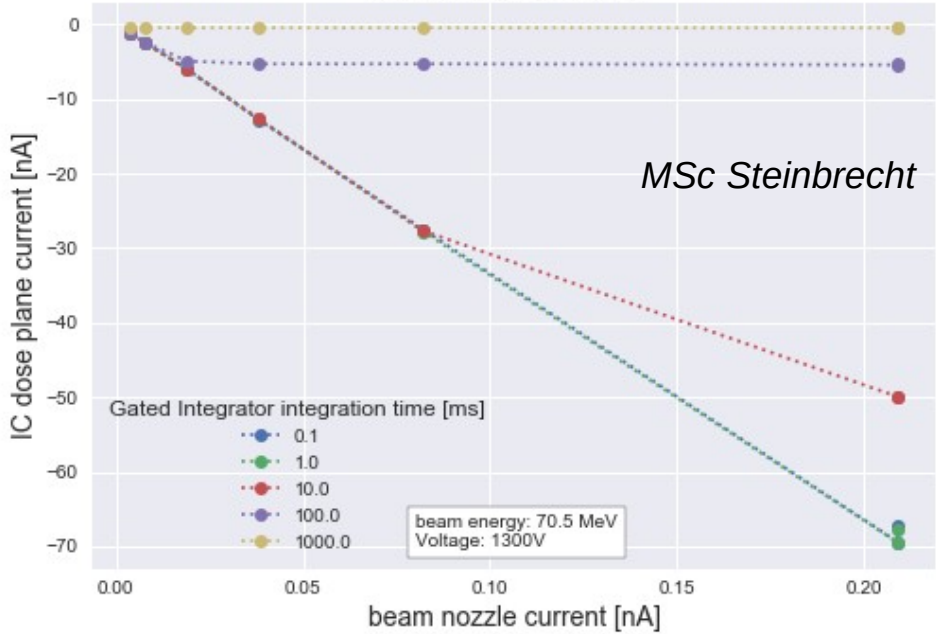
MSc Steinbrecht & Lämmer, PostDoc Gebhard, Englbrecht, Pinto

Beam Monitor System Performance

IC dose plane current vs beam current @ downstream IC



IC dose plane current vs beam current @ upstream IC



→ linear rate behavior of monitor ICs and DAQ system over 4 orders of magnitude

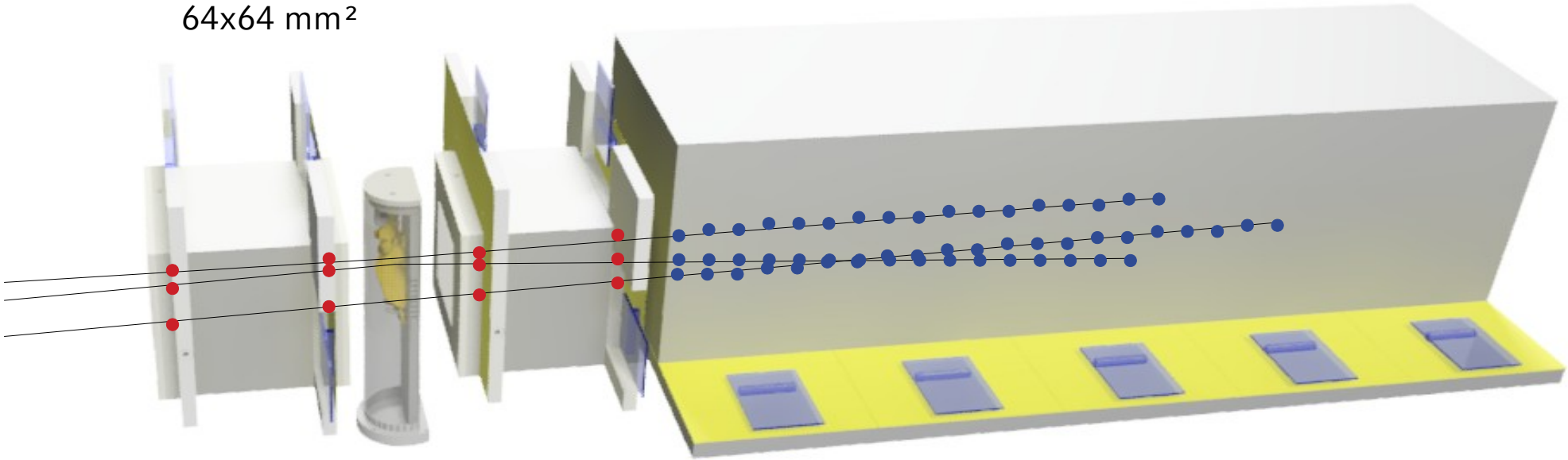
- beam gating works
- this week ongoing @ DCPT: test of treatment plan execution

Proton Imaging

Particle Tracking Proton CT

spatial information from 2d floating strip Micromegas trackers
residual range (→ energy loss) from TPC with vertical absorbers

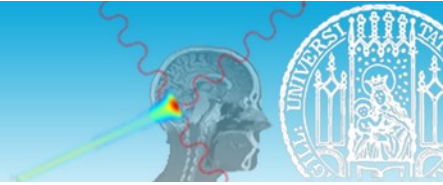
4 aluminum FSM trackers
dual strips (x & y)
64x64 mm²



mouse holder
x, y, z, φ movement
sterile environment

Time Projection Chamber range detector
65 absorber foils (600µm Mylar+Kapton)
8mm gaps in between

Experimental and Simulation Studies



FLUKA simulation and iterative **reconstruction** studies **since 2018** (Meyer, Hu, Englbrecht, Würl): detector and system parameters, reconstruction speed & accuracy

R&D and optimization of **in-house production** methods **since 2018**

aluminum Micromegas (Meurer, Holthoff, Schmidt, Lämmer, Marchfelder, Schinzel, Lange)

- 2019: prototype, 22MeV proton beam test with APV25 electronics
- 2020: prototype, 1 week irradiation with ^{90}Sr source ~ 100 tomographies → still alive
- 2021: series detector, 80GeV pion & muon beam test with VMM electronics
- 2022: series detector, 75MeV proton beam test with VMM electronics

TPC range detector (Kähler, Schackmann, Holthoff, Lämmer)

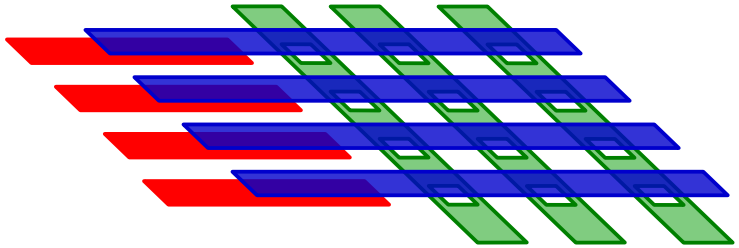
- 2019: prototype with absorbers, 22MeV proton beam tests with APV25 electronics
- 2021: series detector without absorbers, 80GeV pion & muon beam test with VMM electronics

September 2022: system test

all trackers + TPC (13/65 absorbers) + VMM SRS + discharge protection + SIRMIO proton imaging beam

In-house Production:
Aluminum Floating Strip Micromegas

12µm Al anode strips &
y-readout- strips (direct coupling) on
32µm Kapton & glue
→ x-readout strips outside active area
→ 0.15% X_0 per detector (70% from mesh)



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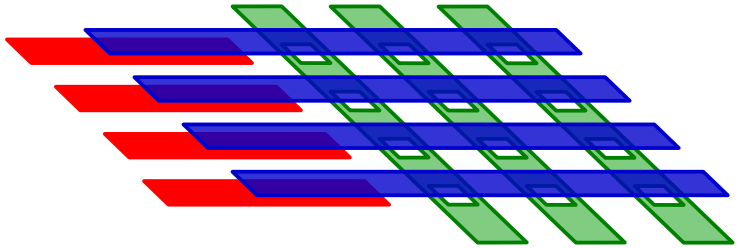
12µm Al anode strips &
y-readout- strips (direct coupling) on
32µm Kapton & glue
→ x-readout strips outside active area
→ 0.15% X_0 per detector (70% from mesh)

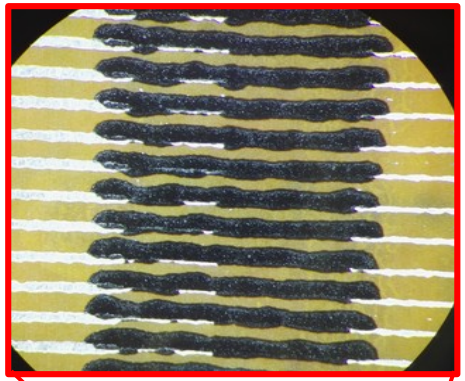
electrodes: photolithography (& etching)

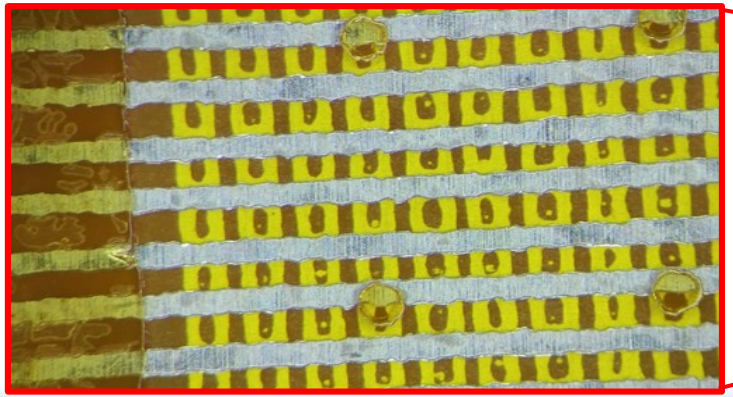
mesh support pillars: photolithography

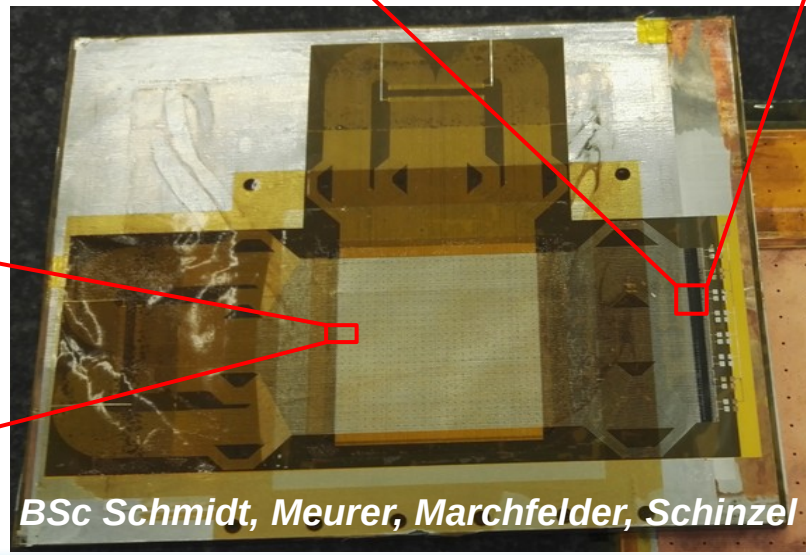
contacts & resistors: screen print

accurately glue on support



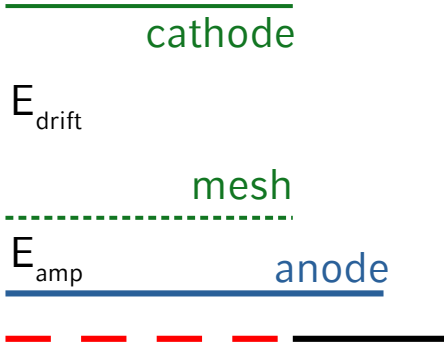




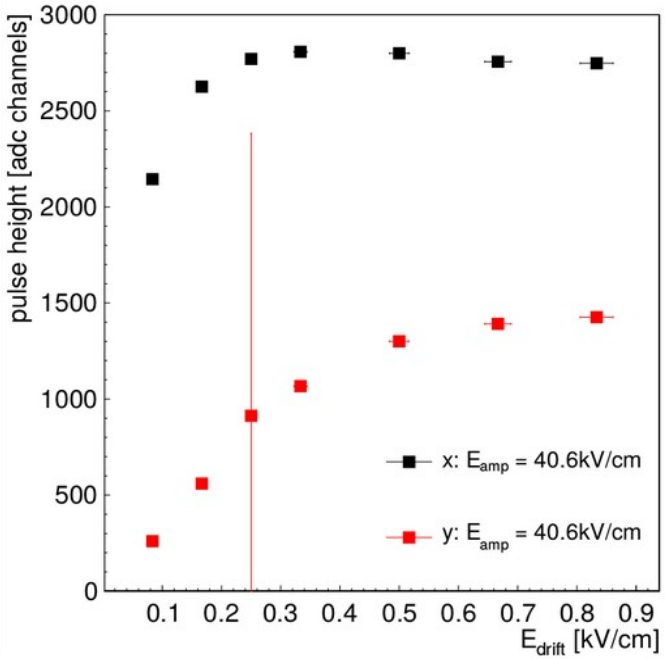


Tracker Prototype @ 22 MeV Protons

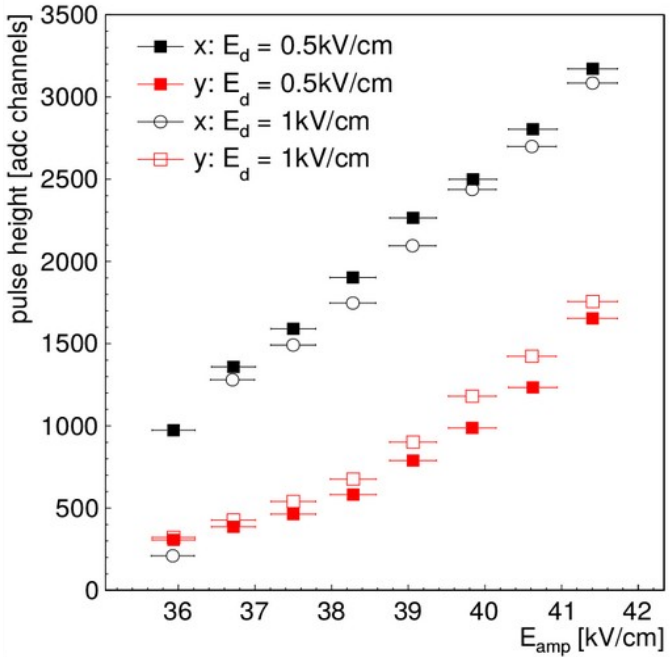
- full size Alu Micromegas
- APV25 DAQ: rate < 1kHz
- Ne:CF_4 80:20 vol. %



pulse height vs E_{drift} @ 40.6kV/cm



pulse height vs E_{amp}



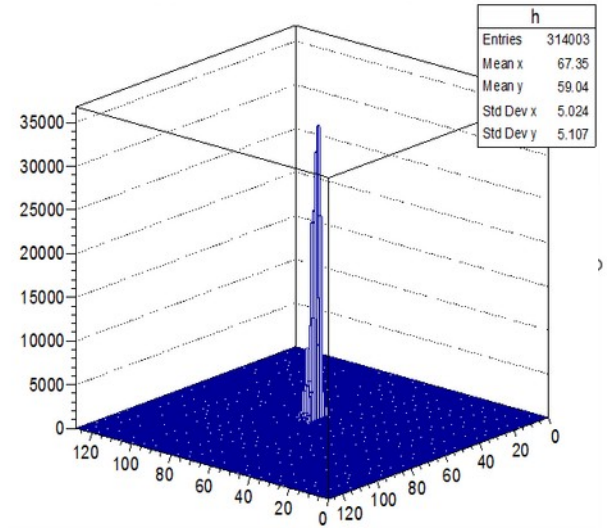
x: typical transparency behavior
y: influence of electron drift velocity → bi-polar signal

pulse height ratio y/x ~ 0.5 → well usable

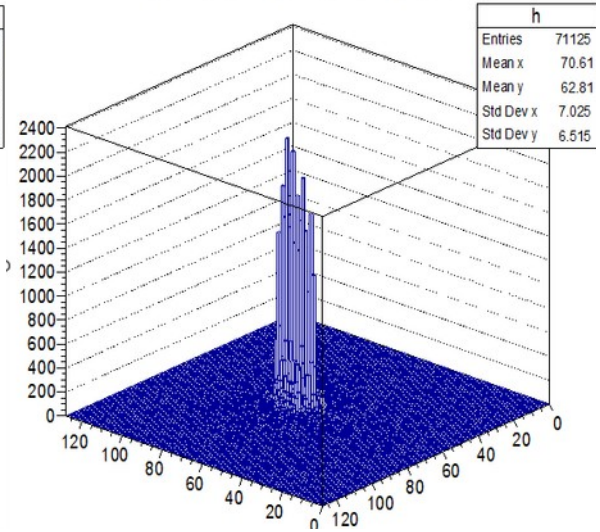
Series Tracker @ 50 MeV Protons

cluster distribution

detector 1

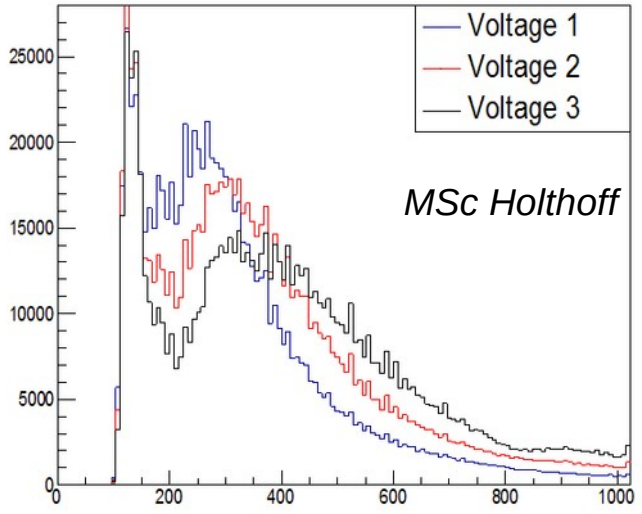


detector 2



pulse height distribution

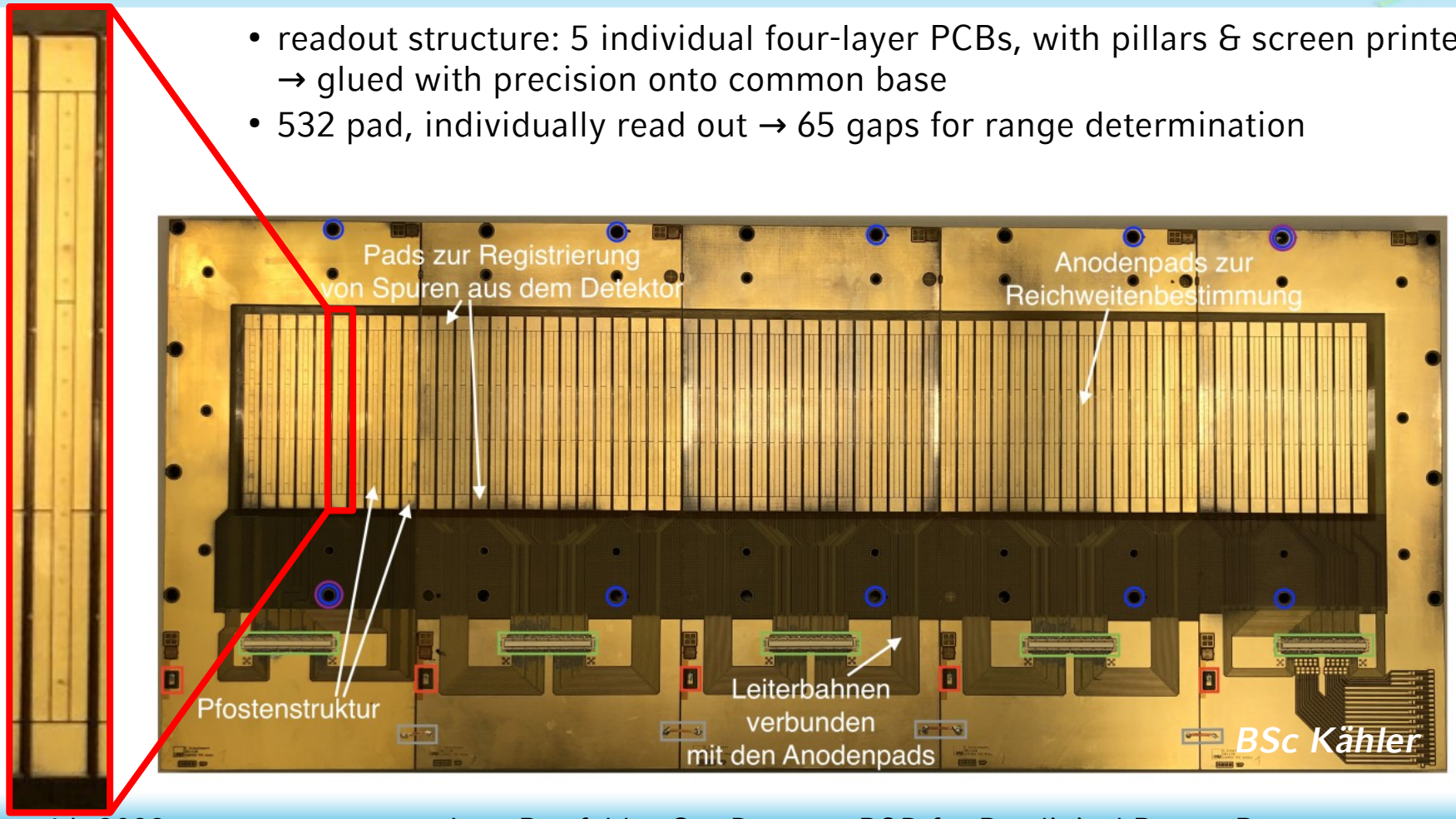
detector 1, x-layer

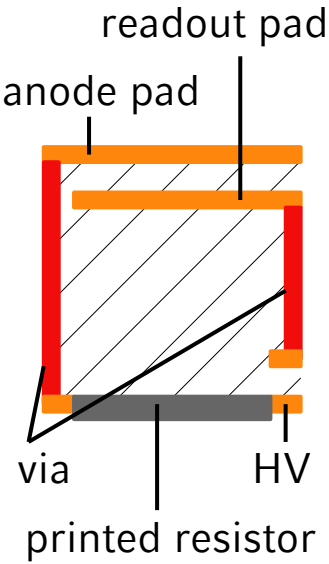


- SRS VMM + external discharge protection circuit → successful operation
- analysis currently ongoing

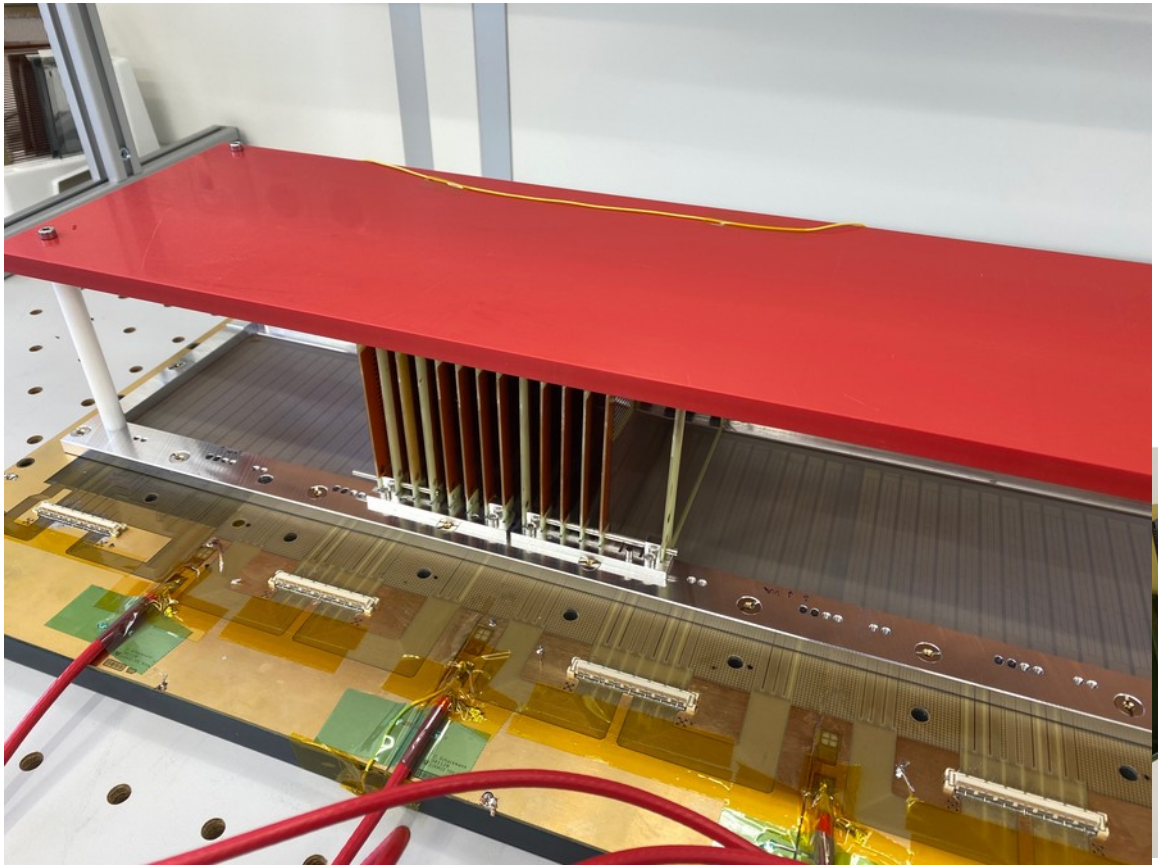
In-house Production: TPC

- readout structure: 5 individual four-layer PCBs, with pillars & screen printed contacts → glued with precision onto common base
- 532 pad, individually read out → 65 gaps for range determination

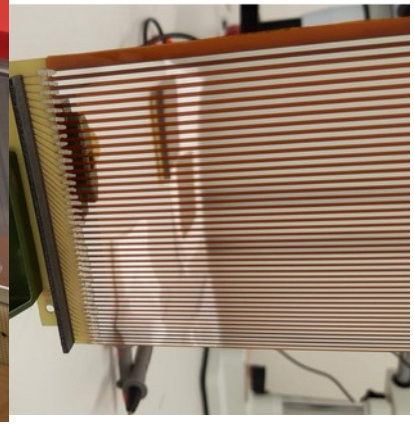


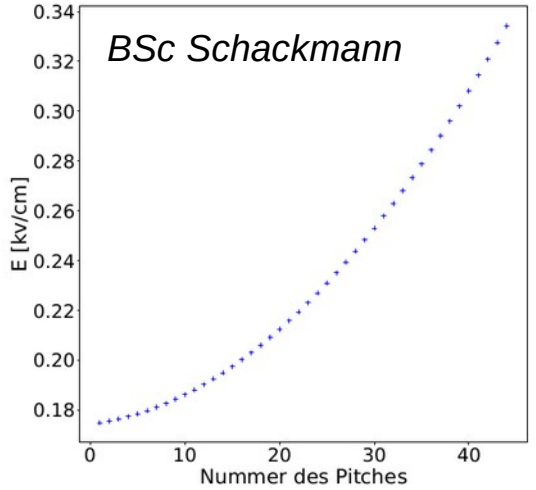


TPC: Field Shaping Absorbers



- 2kV drift field/96mm
- sandwich: 600µm Mylar equivalent thickness
- field-shaping 50nm Aluminum strips, pitch decreasing → drift field increases downwards → efficient extraction of ionization electrons
- production currently ongoing





Summary

- SIRMIO: portable small animal proton irradiator platform for pre-clinical research
- **gaseous detector R&D** program for beam characterization, monitoring & proton imaging
- challenge: **low energy, small beam diameter, high rate**

- **beam-profiler**: optical glass Micromegas
- **beam monitor**: ultra-thin aluminum strip ICs + DAQ & beam control
- **proton CT** system: aluminum Micromegas trackers & TPC range detector

- **in-house production** & assembly
- several **successful measurement campaigns** with prototypes & series detectors

this work received support from: ERC grant 725539 (SIRMIO), H2020 grant 730983 (INSPIRE), H2020 grant 101008548 (HITRIplus)

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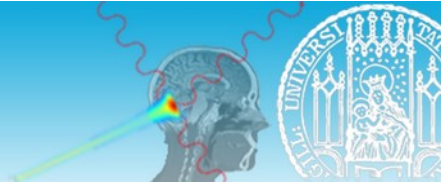

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Thank you!

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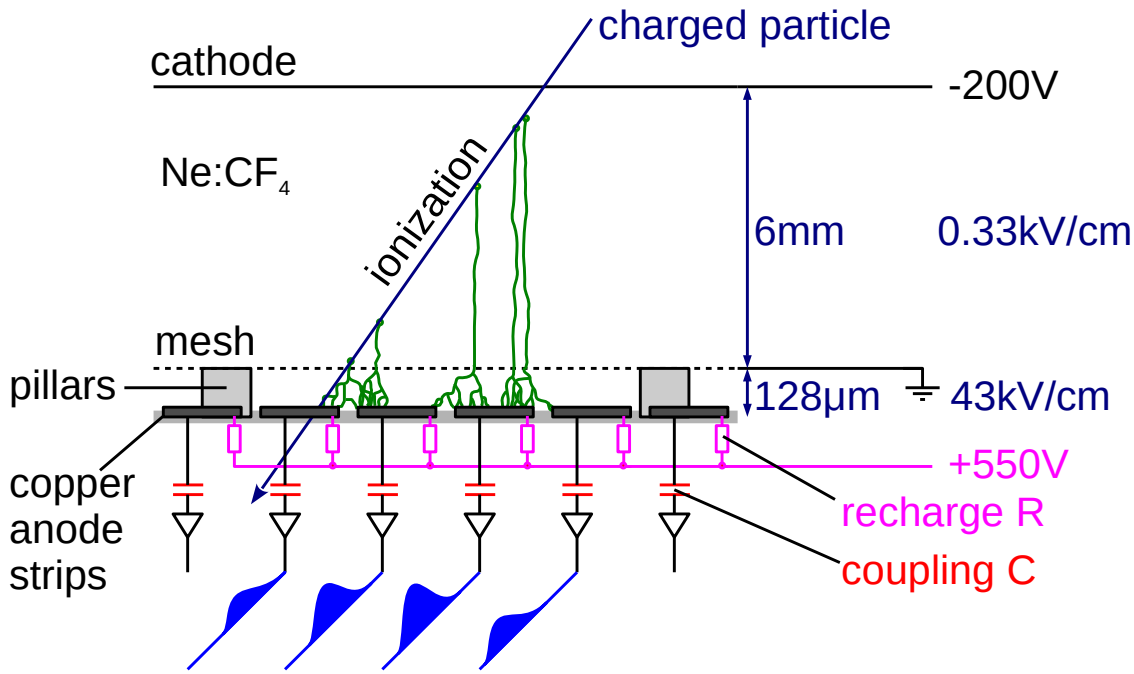
backup

Floating Strip Micromegas Detectors

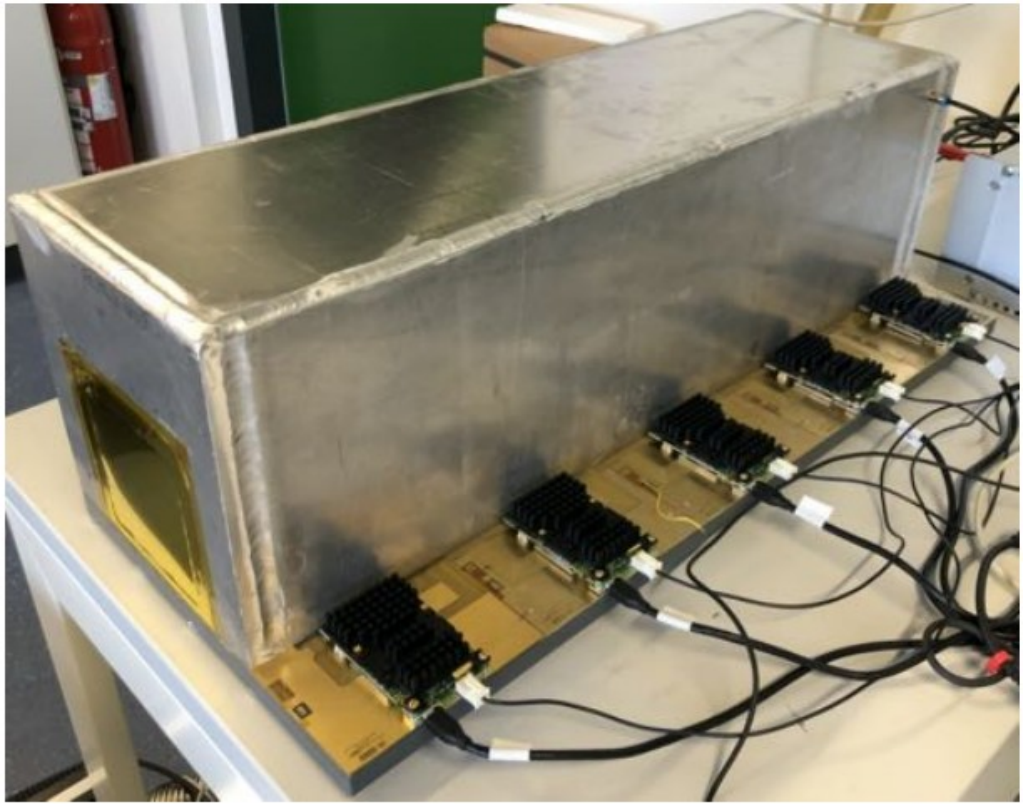
Micromegas detectors

- charged particles → ionization of gas
- amplification of ionization electrons in avalanches
- charge collection on finely segmented readout structures
- discharge mitigation: individual HV connection & capacitive coupling

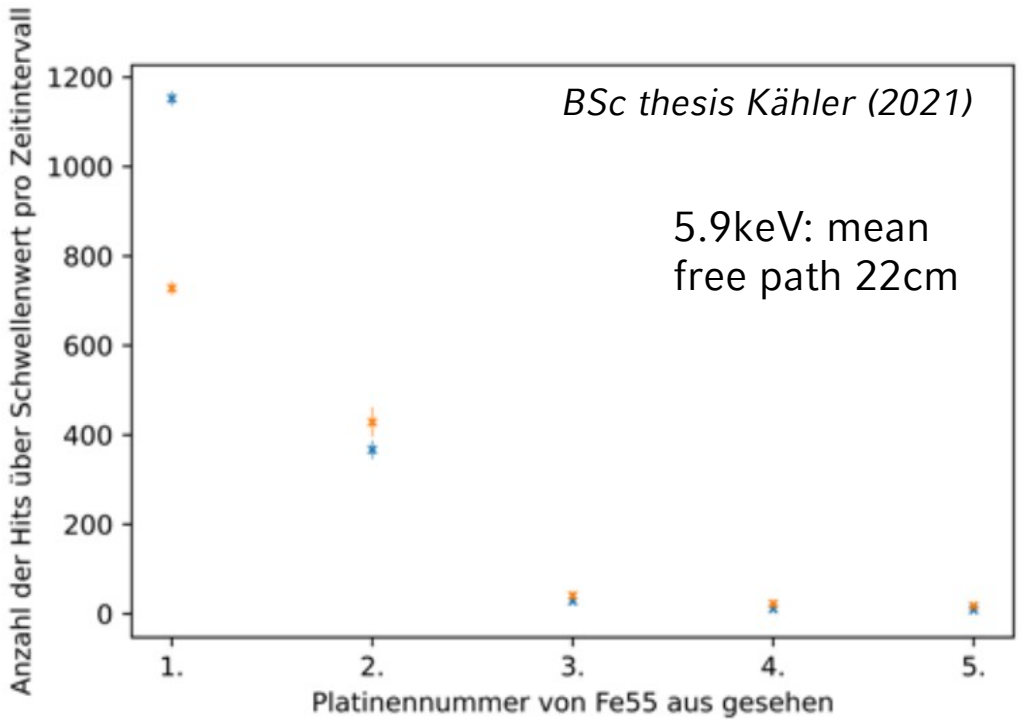
- high-rate capable: > 5MHz/cm²
- good spatial resolution: <80µm
- very low material budget
- capable to produce these detectors in-house → tune according to application



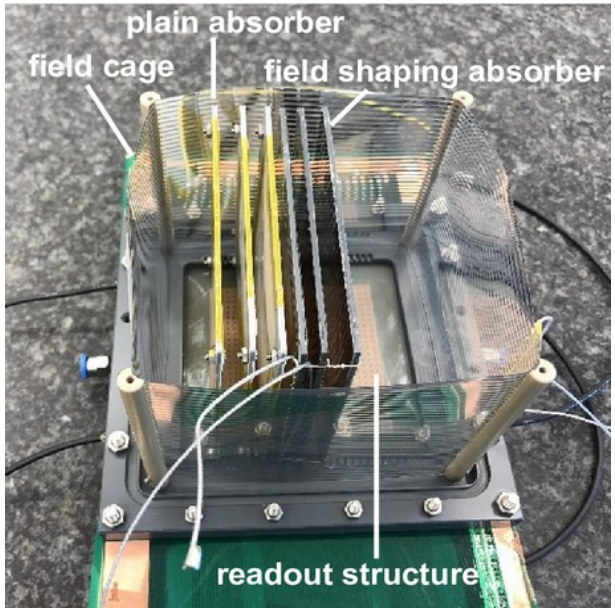
Source Test: TPC with VMM Electronics

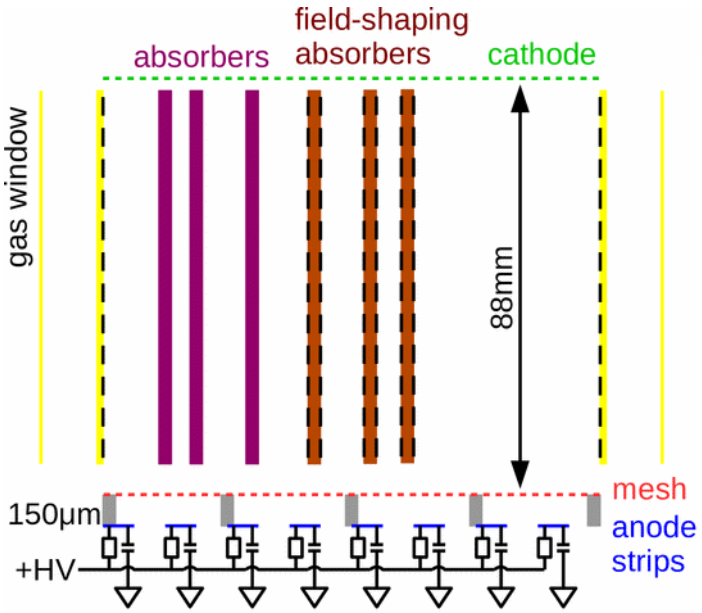


^{55}Fe event rate in TPC vs distance to source

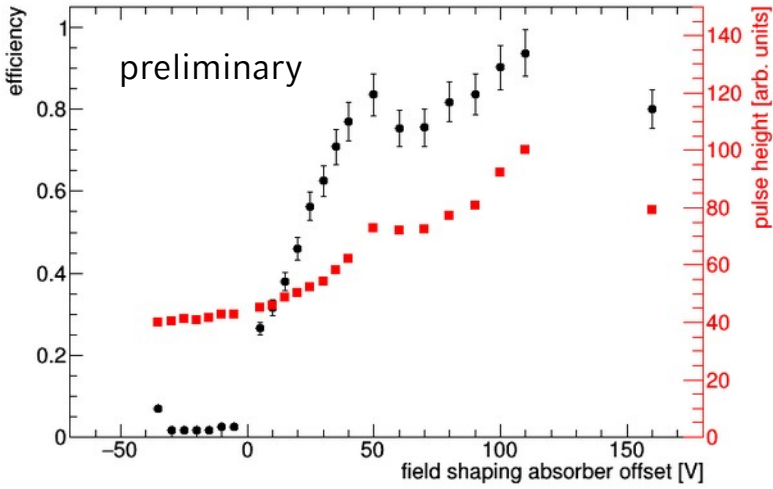


TPC Prototype @ 22MeV Protons



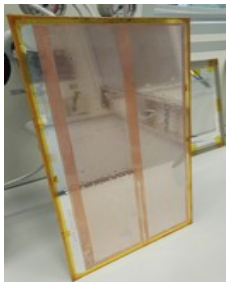


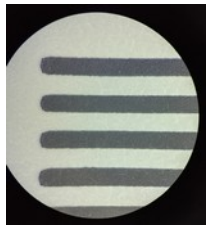
variation of absorber offset voltage @ 54mm electron drift distance



- 88mm drift region
- 64x64mm² strip Micromegas readout structure
- 50µm Mylar field cage
- absorbers: 3 field-shaping, 4 plain (PTFE or Mylar)

beam tests @ 22MeV & 75MeV p
→ understand concept





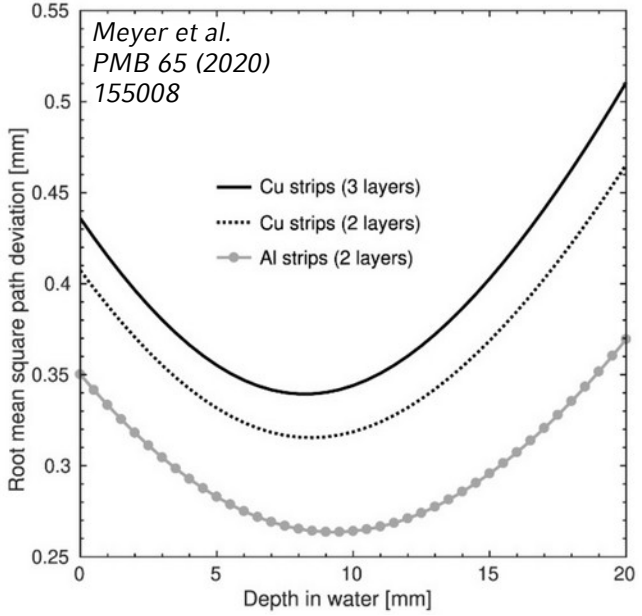
1mm strips
1mm gap

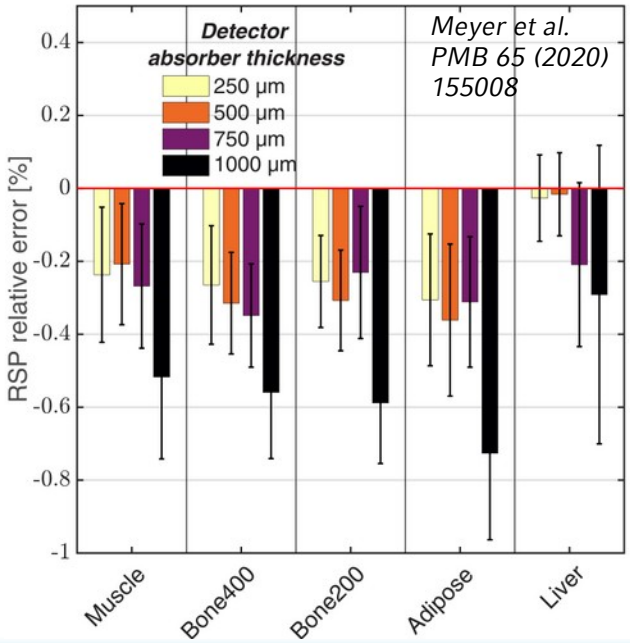
FLUKA Simulation: Geometry & Parameters

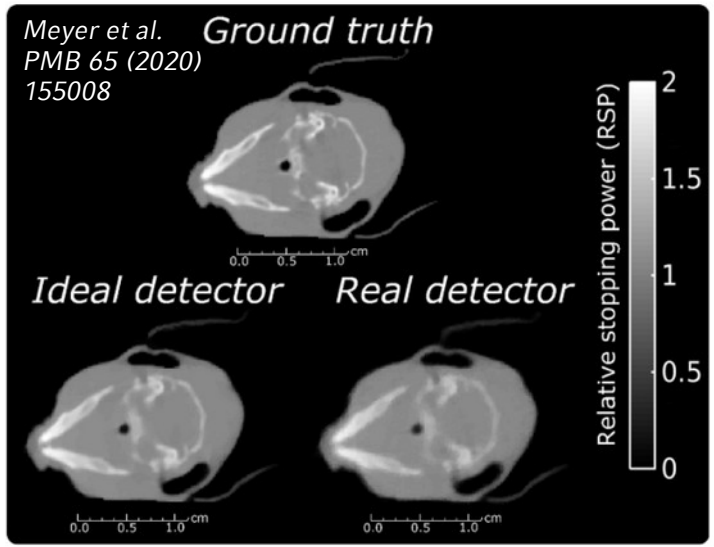
detailed simulation of trackers, object & TPC range detector

→ trackers with aluminum electrodes considerably better & spacing > 7cm: **mean path resolution 0.18mm**

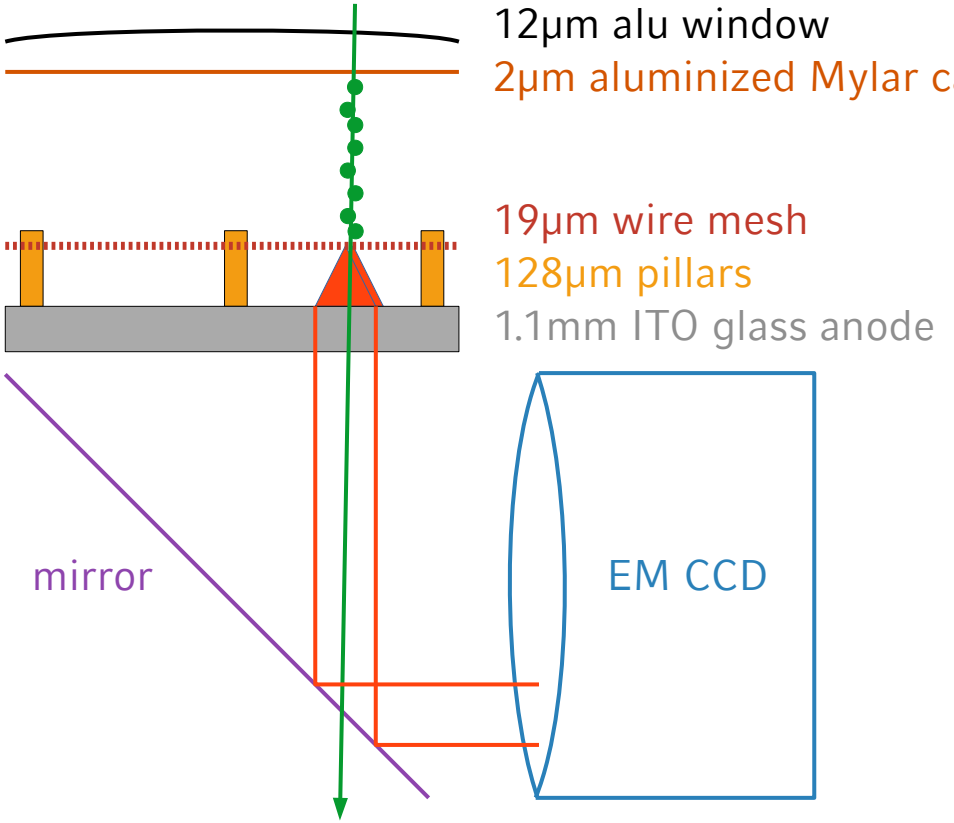
→ TPC absorber thickness 500 – 750µm: compromise between complexity & **RSP accuracy < 0.3%**







Concept: Optically Read Out Micromegas



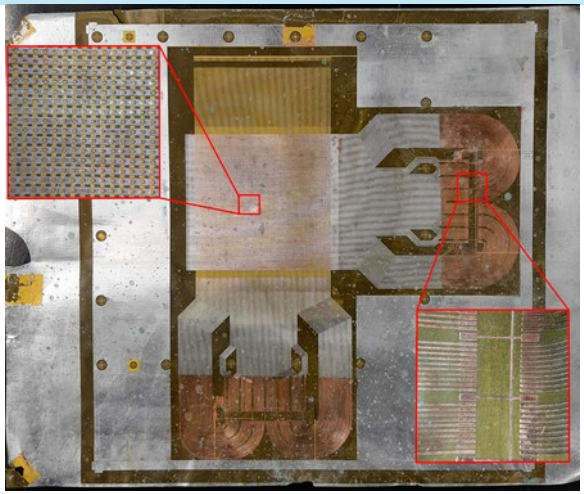
ionization by particle beam, 0.5kV/cm

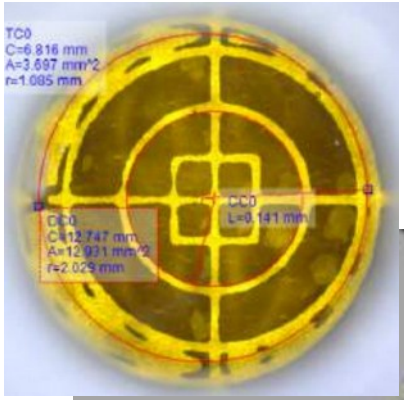
gas amplification avalanche in Ne:CF_4
→ local & proportional production of charge
+ photons (620 & 300nm)

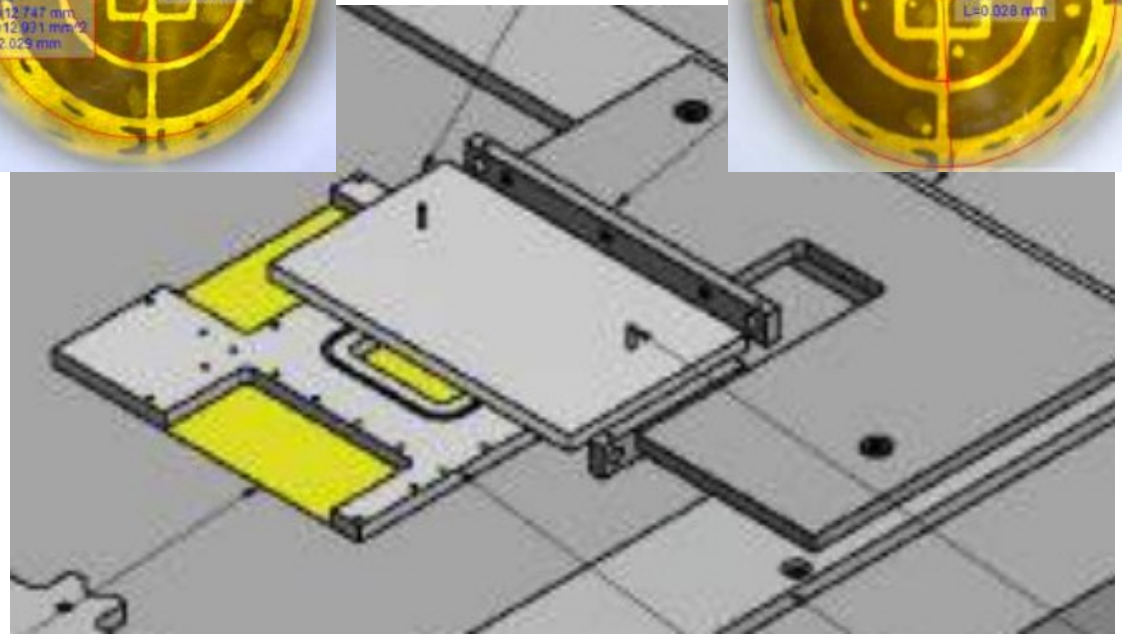
optically transparent anode 25x25mm² with support pillar structure

detect optical photons with EM CCD
→ beam position & intensity
→ gas gain adjustable for integrating or single particle detection
→ exposure time and binning adjustable

SIRMIO Aluminum Micromegas Production







readout structures (12µm alu on 32µm Kapton)

- confirm HV stability, bubble repair
- glue with O(30µm) accuracy on support

stretch and glue micro-mesh

stretch and glue cathode + gas window

clean & assemble

Bac theses Marchfelder, Meurer