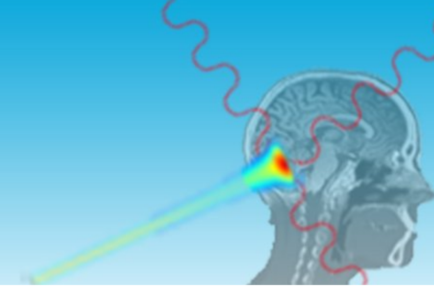


# Production and Test of an Aluminum Floating Strip Micromegas for Small Animal Proton Imaging

**Jona Bortfeldt**[a,b], Sebastian Schinzel[a], Sebastian Meyer[a], Othmar Belker[a], Franz Englbrecht[a], Katrin Schnürle[a], Matthias Würl[a], Katia Parodi[a]

a: Ludwig-Maximilians-Universität Munich, Department for Medical Physics

b: CERN, Geneva

RD51 Mini-Week February 10 - 13 2020, CERN

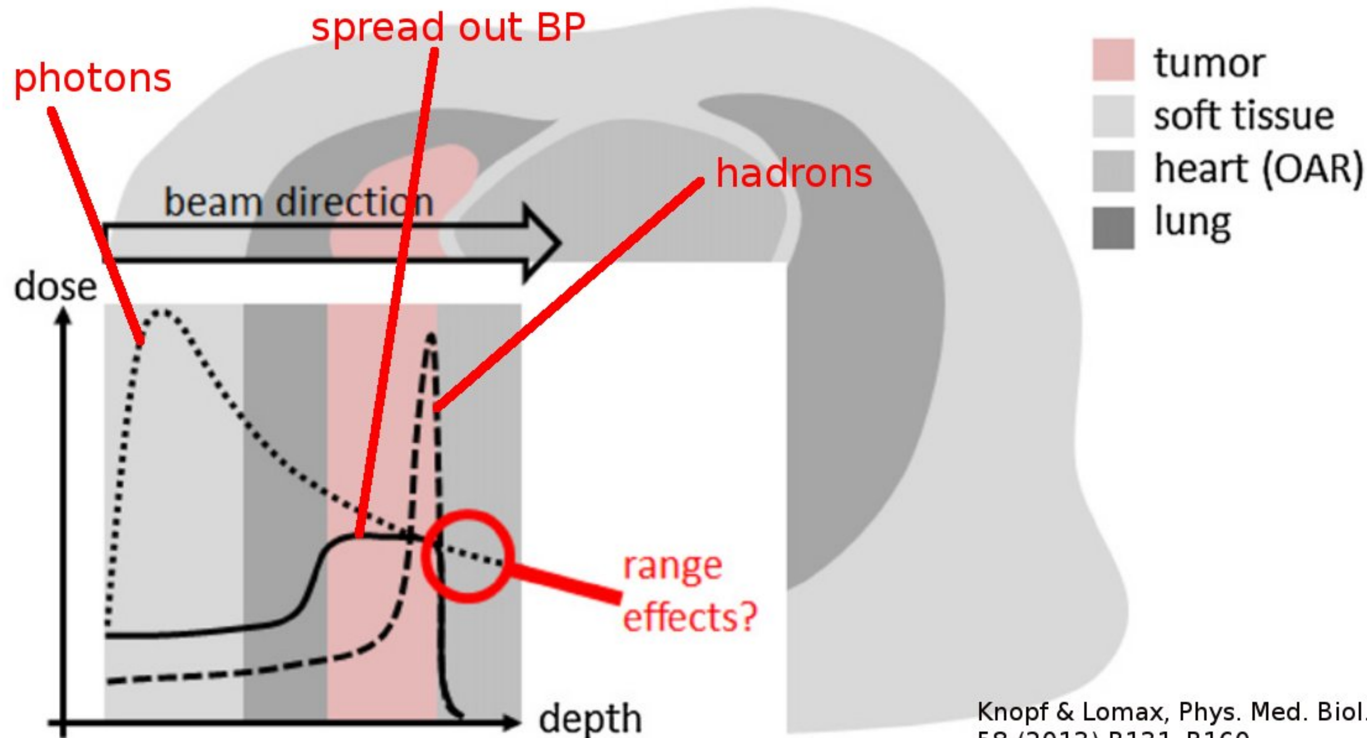
February 11th 2020

# Context: Particle Therapy

low energy ions: $dE/dx \sim 1/\beta^2$

→ favorable depth-dose:

- none behind tumor
- low in entrance

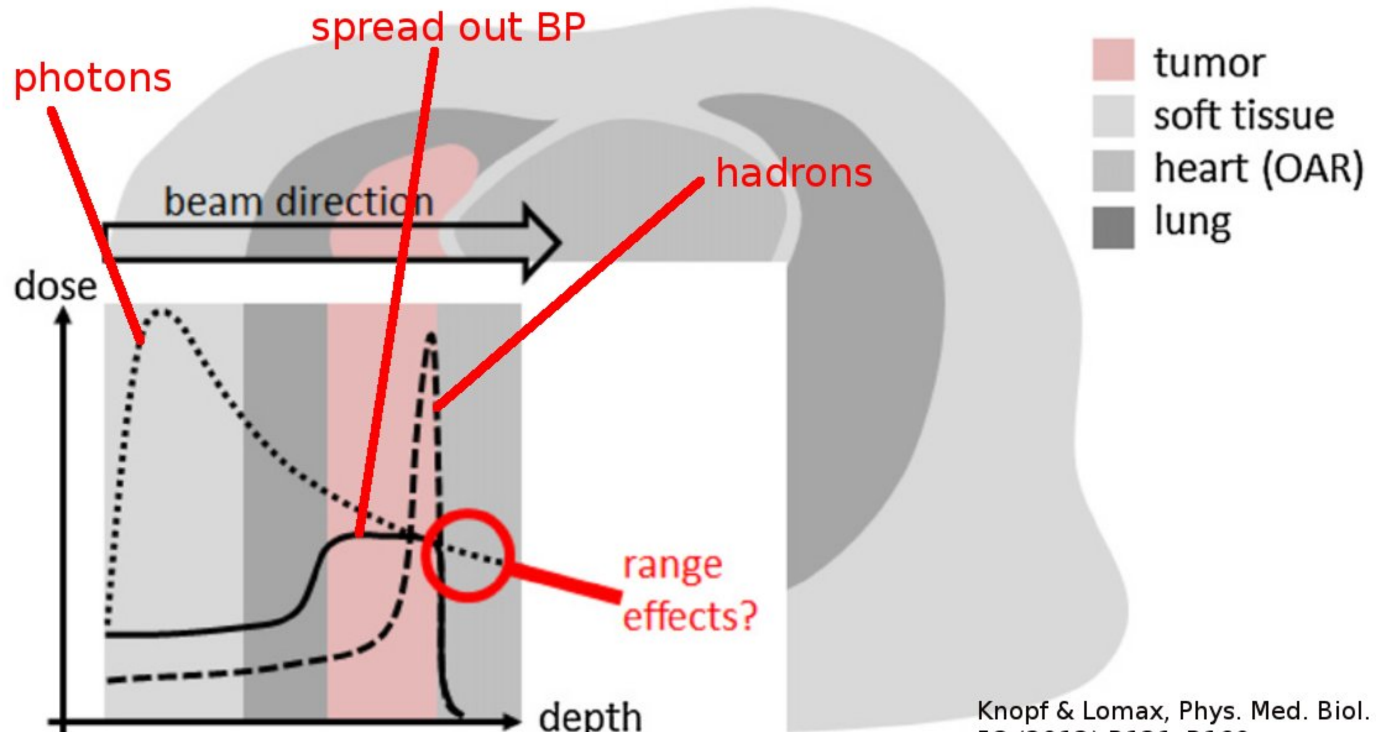



Knopf & Lomax, Phys. Med. Biol. 58 (2013) R131–R160

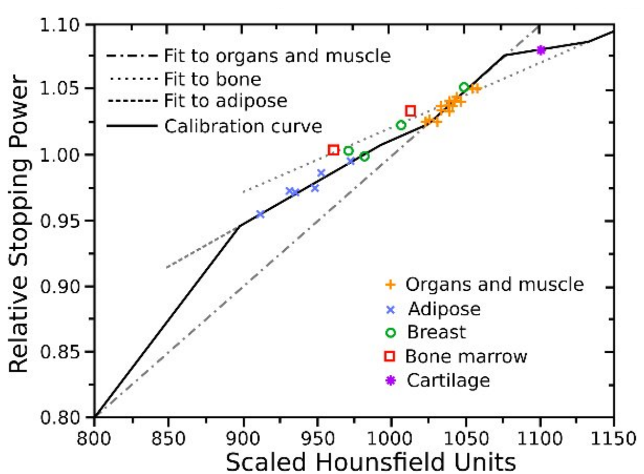
# Context: Particle Therapy

low energy ions: $dE/dx \sim 1/\beta^2$
→ favorable depth-dose:
- none behind tumor
- low in entrance

1. imaging: X-ray Computed Tomography
2. treatment planning: photon absorption ↔ dE/dx
3. fractionated treatment




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




Schaffner and Pedroni, PMB 43, 1579 (1998)

ion range uncertainties: 3% + artifacts
- photon X-ray to stopping power conversion
- patient anatomy changes
- patient positioning

→ mitigate: proton CT just before treatment

# Preclinical Research: Small Animal Proton Irradiator

pre-clinical oncology research: closely mimic clinical routine with proper tumor models & realistic treatment regimes

build portable demonstrator: precise, image-guided irradiation of mice

SIRM

2017-2021
K. Parodi

erc
European Research Council
Established by the European Commission

details: Parodi, … , Bortfeldt et al., Acta Oncol. (2019) 58, 1470-1475

# Preclinical Research: Small Animal Proton Irradiator

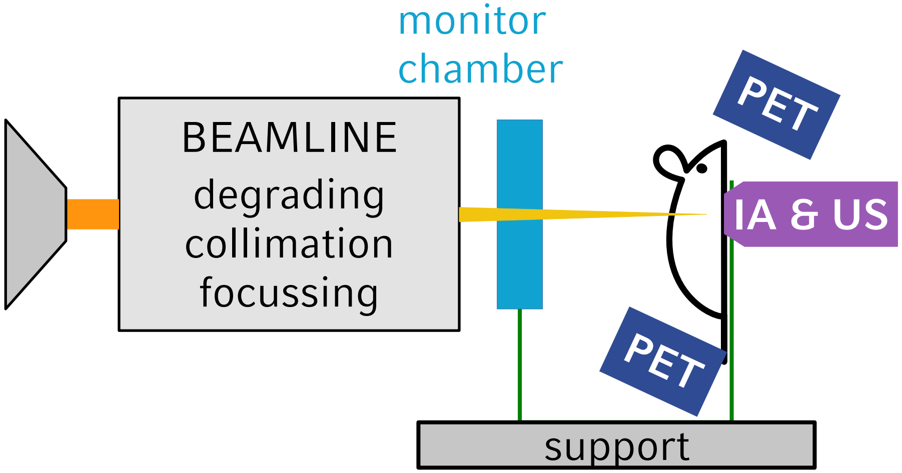
pre-clinical oncology research: closely mimic clinical routine with proper tumor models & realistic treatment regimes

build portable demonstrator: precise, image-guided irradiation of mice

precise, image-guided:
- online beam position visualization
- precision beam monitor
- pre-treatment: pCT

mice:
- energies < 70MeV
- beam spot O(1mm²)
- anesthesia
- gnotobiotic or spf → sterile environment

exper. beamline @ clinical accelerator

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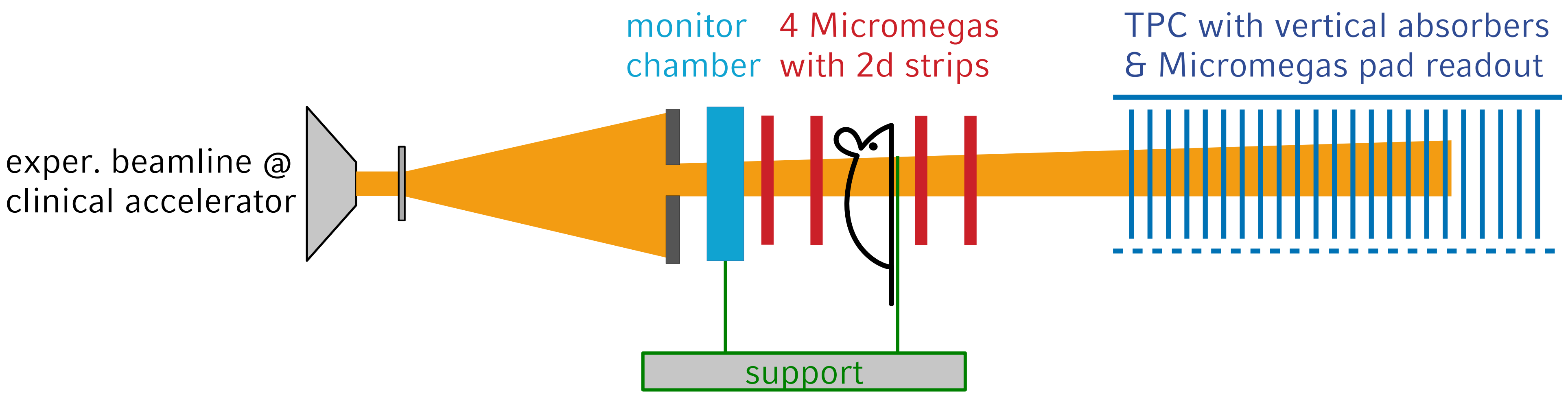
# Proton Computed Tomography for Small Animals



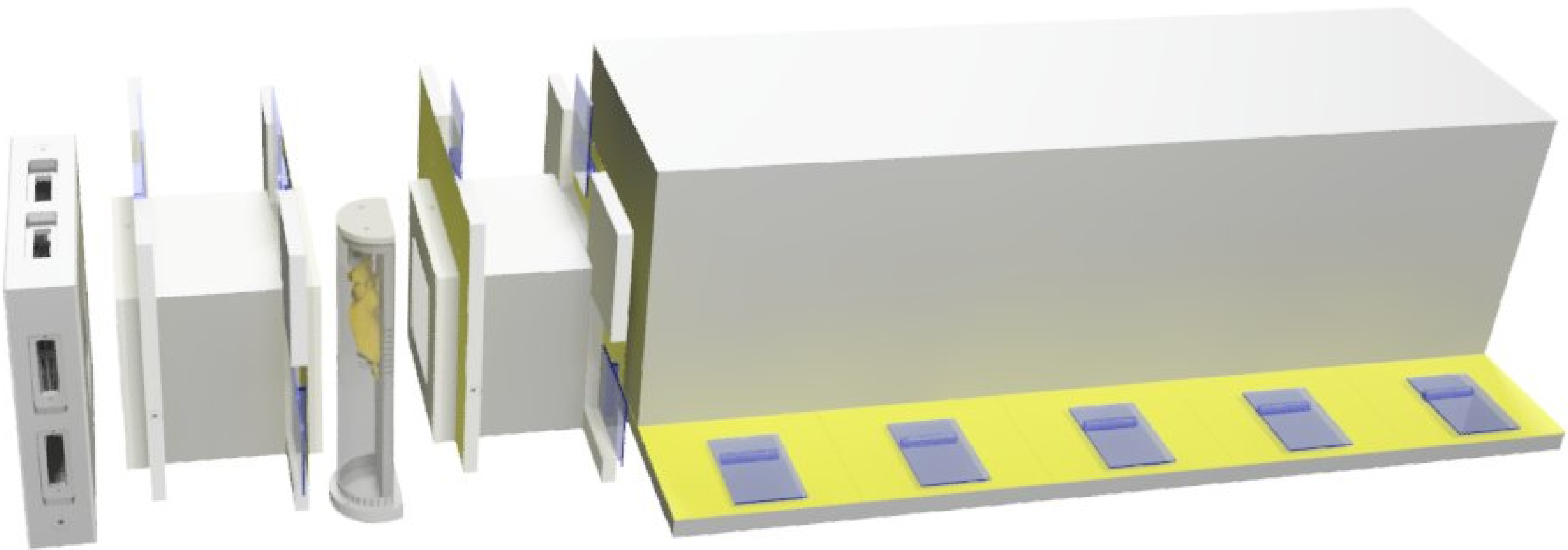

imaging concept: spatial information from 2d floating strip Micromegas trackers
residual range (→ energy loss) from TPC with vertical absorbers
reference to treatment beam from 2d strip ionization chamber

boundary conditions: 75MeV beam energy (compromise spatial resolution ↔ range straggling)
minimum scattering in tracking detectors
range resolution < 1.5%
field of view 64mm x 64mm

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

# Proton CT System Overview

**4 aluminum FSM trackers**
dual strips (x & y)



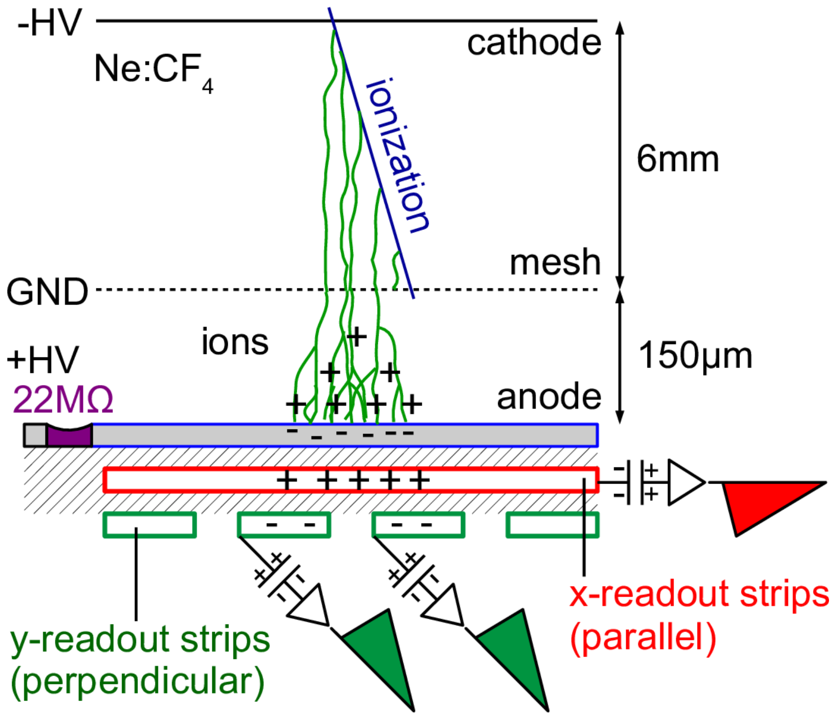
**IC: monitor**
dual strip (x & y)
dual unsegmented

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

**Time Projection Chamber range detector**
65 absorber foils (500µm Mylar)
7mm gaps in between

# Floating Strip Micromegas* with Low Material Budget

copper anode strips: individually connected to HV via 22MΩ
x-readout strips: signals capacitively decoupled via O(10pF)
y- readout strips: signals directly inductively decoupled
→ anode strips can "float" in discharge
→ fast discharge interruption
→ negligible impact on efficiency




Bortfeldt et al., NIM A 2017, 845, 210 - 214

*: inspired by the COMPASS MM, considerably improved in: Bortfeldt, The Floating Strip Micromegas Detector, Springer, 2014

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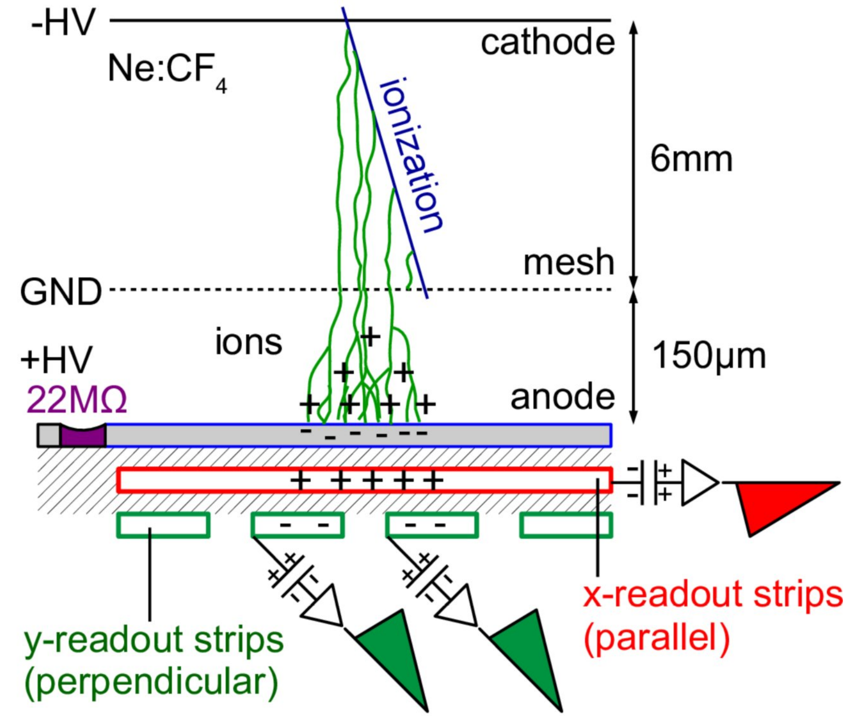
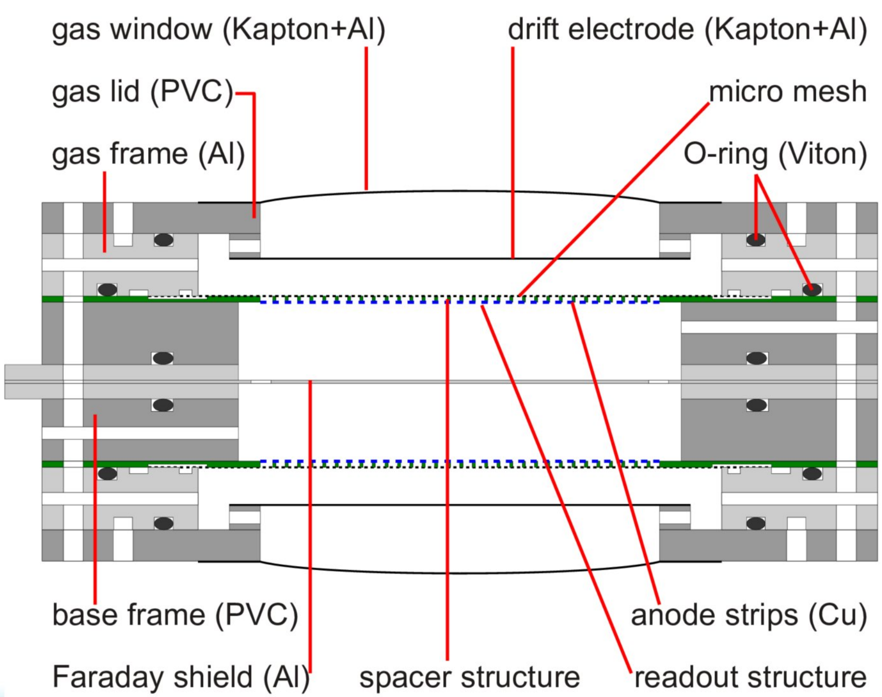



Bortfeldt et al., NIM A 2017, 845, 210 - 214

## prototype with flex-PCB readout structure (1.1% $X_0$)

- spatial resolution (0.5mm pitch): < 100μm
- single particles: ≤ 7MHz/cm2

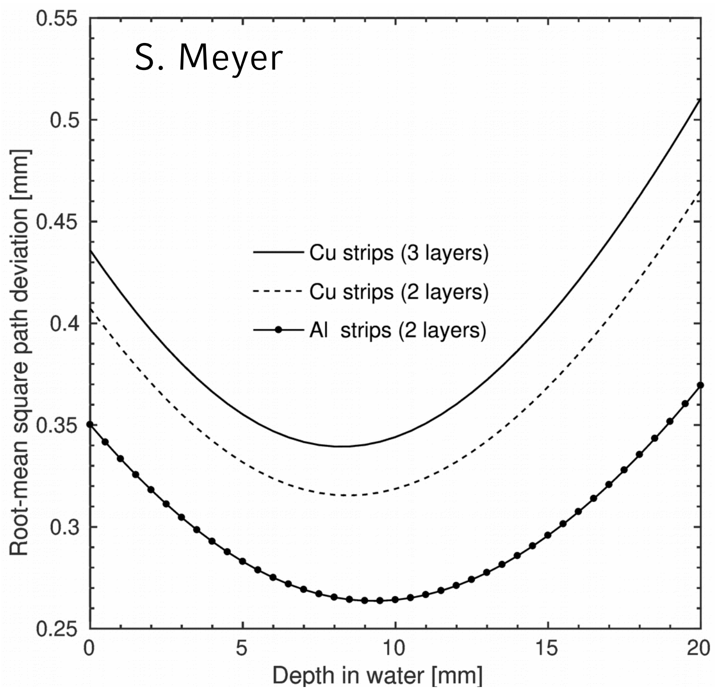



- two detectors back-to-back
  → 80mm distance
- flexible readout structures: overpressure stabilized

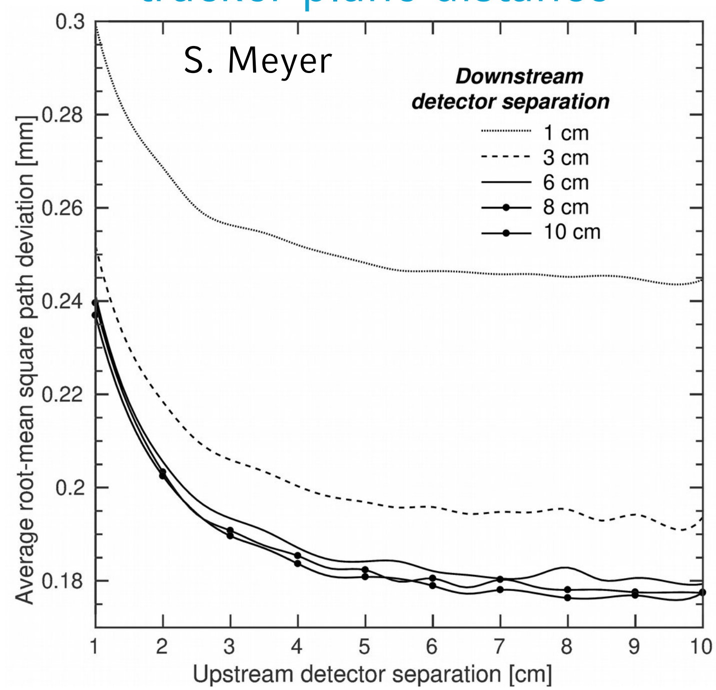
*: inspired by the COMPASS MM, considerably improved in: Bortfeldt, The Floating Strip Micromegas Detector, Springer, 2014

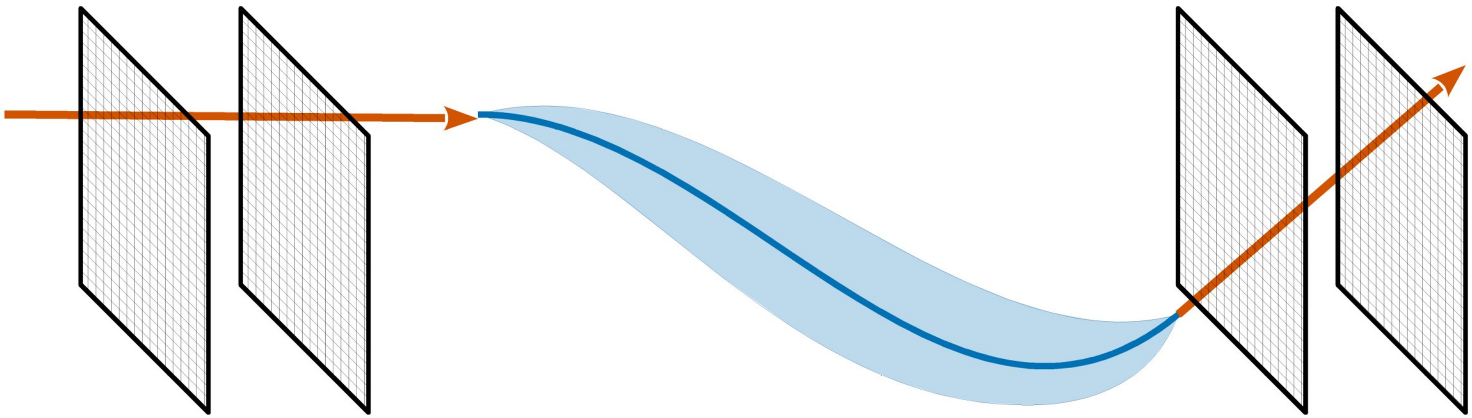
# FLUKA Simulation: Detector Parameter Optimization

path accuracy for different anode structures



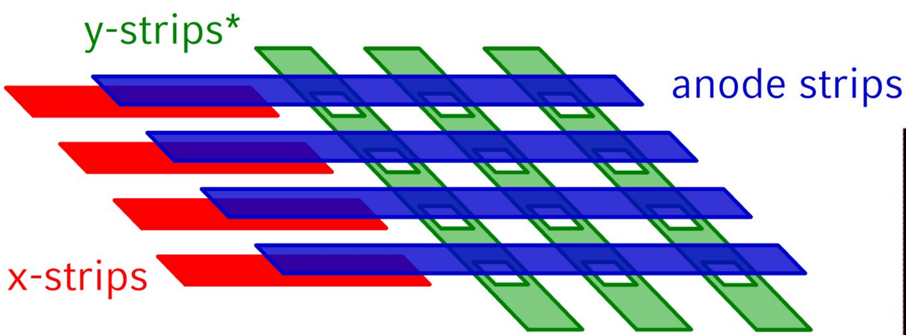

path accuracy vs tracker plane distance



# Aluminum Floating Strip Micromegas Readout Structure

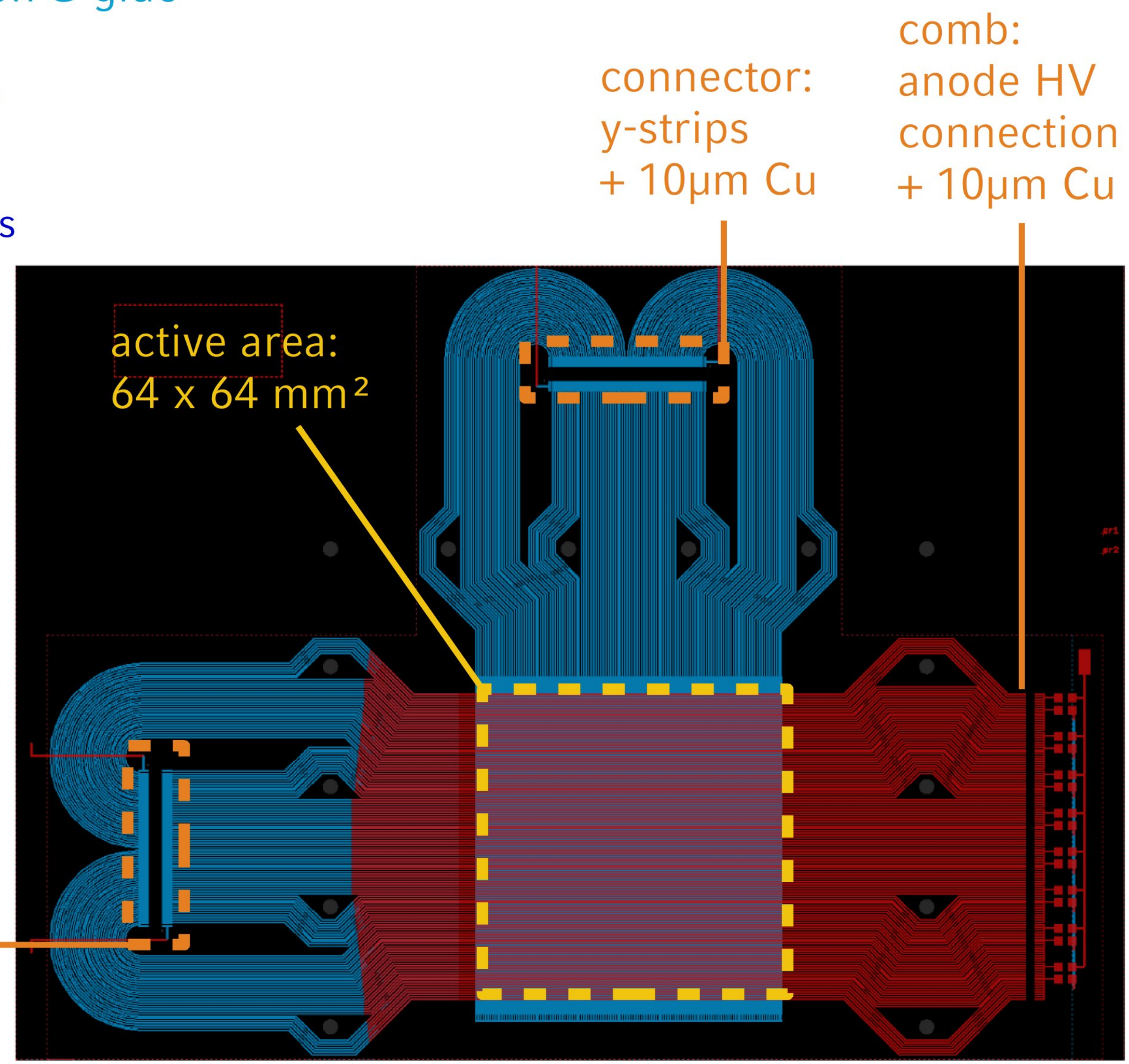
12µm Al anode & y-strips on 32µm Kapton & glue
→ x-readout strips outside active area
→ 0.15 $X_0$ per detector (70% from mesh)




*: pattern inspired by F. Klitzner, LMU Munich

**locally producible**

- LMU PCB workshop: laminator, UV exposure unit, developing
- detector lab: solder resist spray, chemical & electroplating, etching, stripping, curing, mesh stretching, screen printing



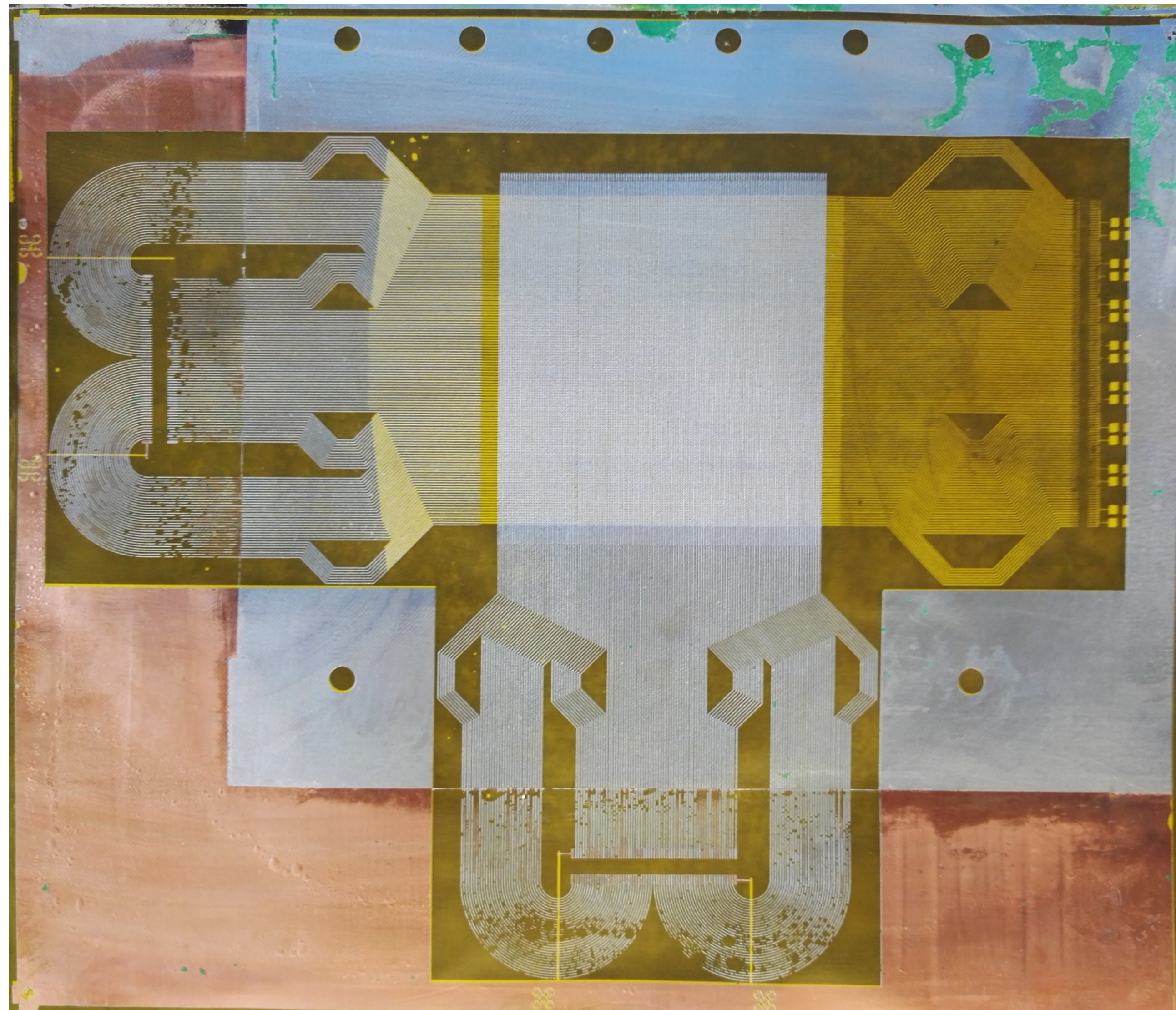
# Aluminum Electroplating & Photolithography

### current process

- cleaning
- manual masking
- pickling
- zincate
- alkaline Cu electroplating
- acidic Cu electroplating
- mask removal

- etch resist spray + curing
- UV exposure
- development
- etching
- stripping

Thanks a lot Rui, for the invaluable advice!



### results

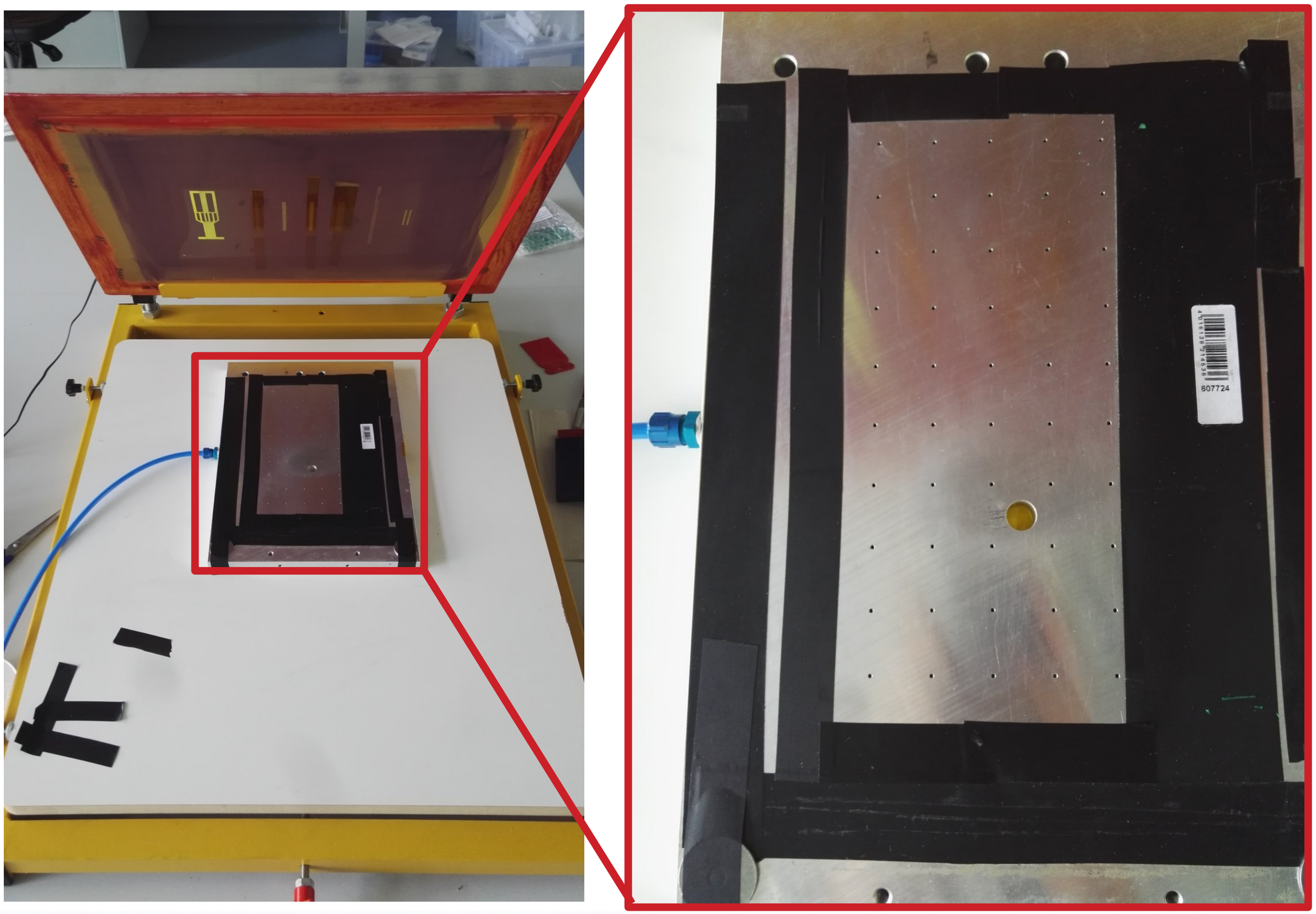
- etch quality in unplated region good, few small resist defects
- etch way more aggressive to Cu → partial resist detachment in plated region
- Cu attachment fair

→ connectors on Cu PCB, connected to strips by silver paste

# Anode Strip ↔ High Voltage: Screen Printing of Resistors

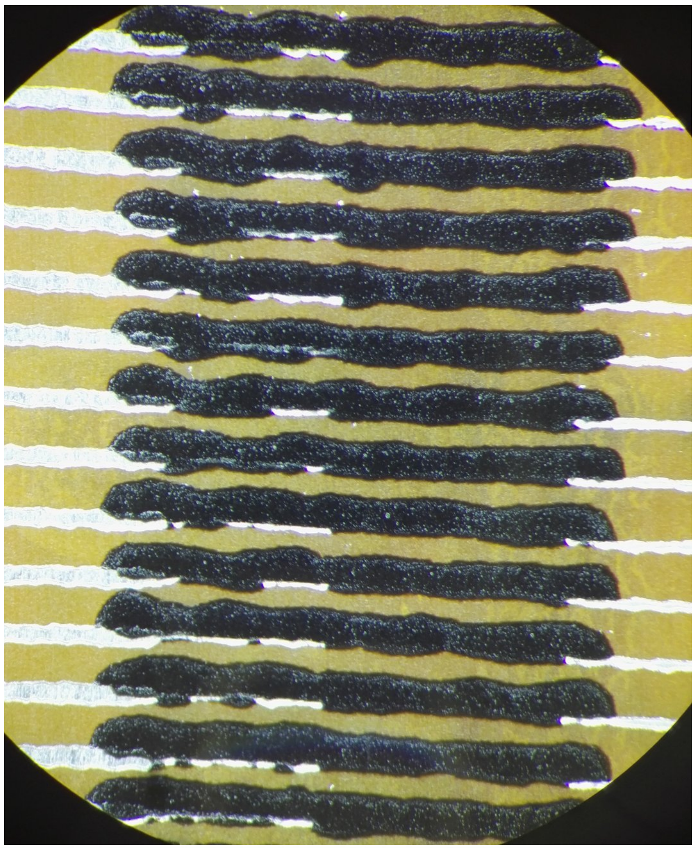
- avoid soldering of 128 resistors, also space issue
- screen from local company

**manual printing machine** with vacuum suction plate



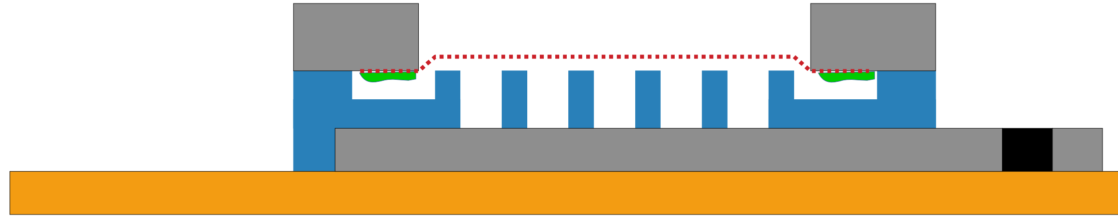
**after curing**

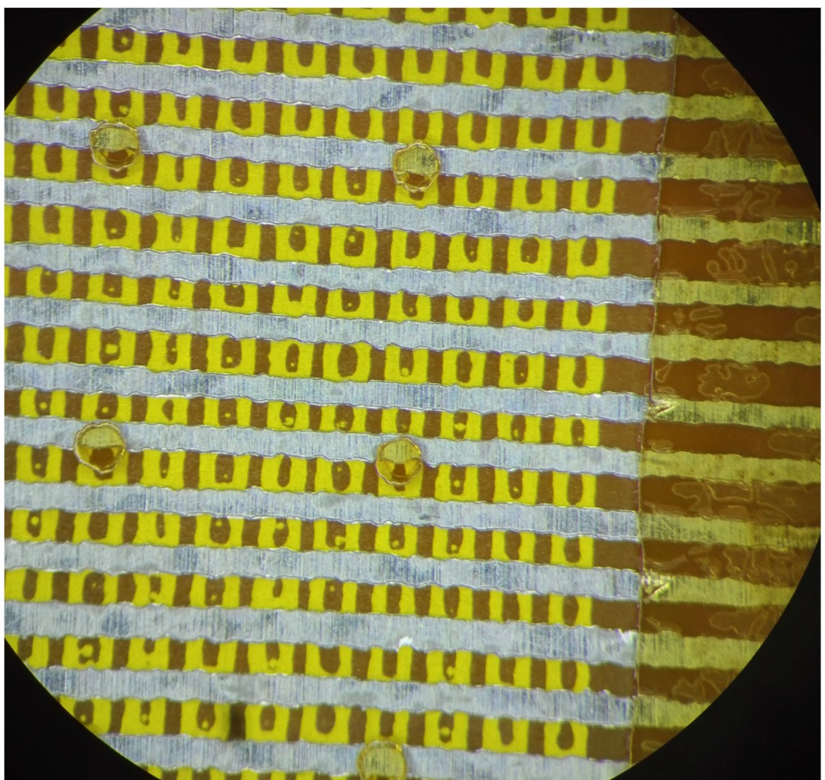
- very good results
- masks from different sources
  → slightly different scaling
- O(5) reworked manually

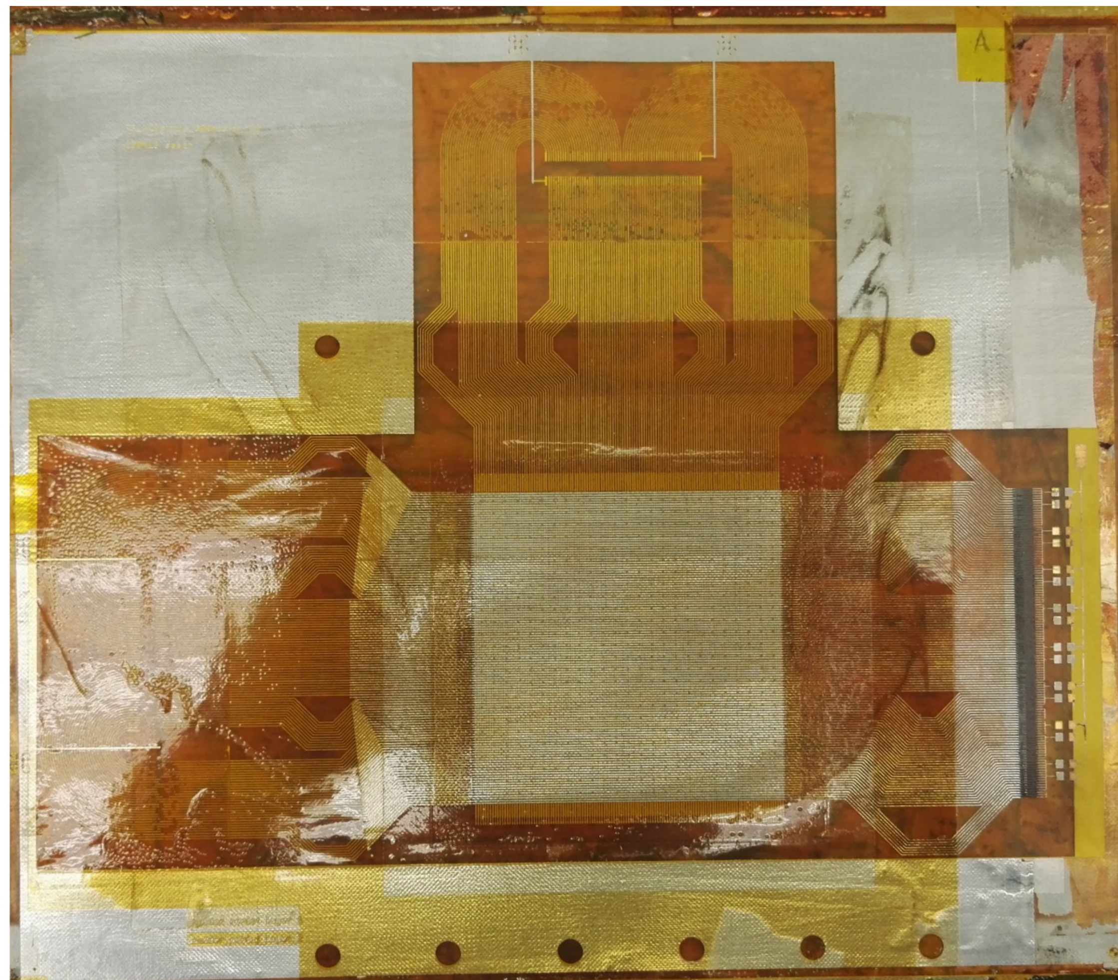


# Pillars: Coverlay

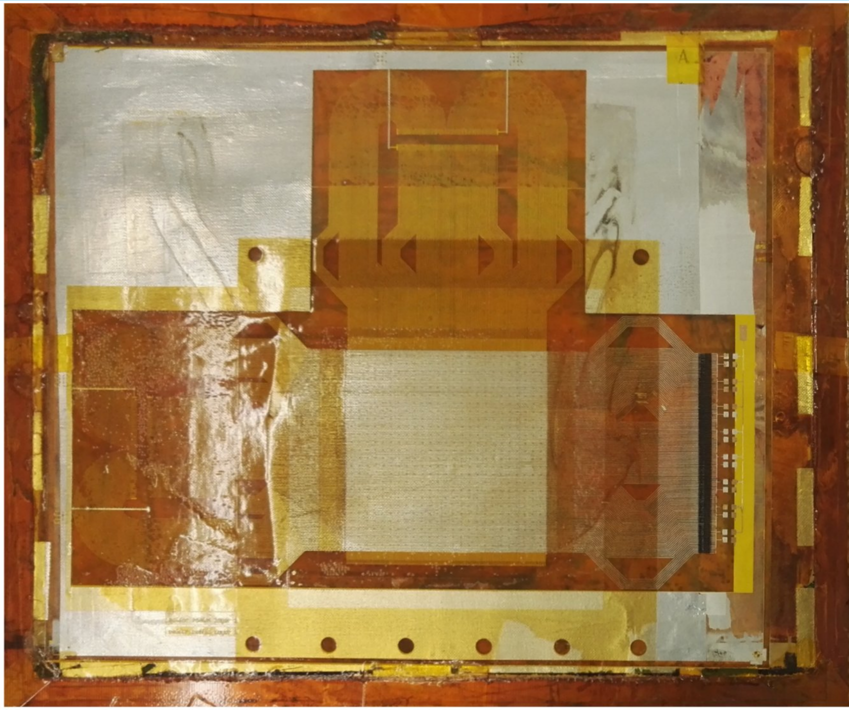
- two step lamination & exposure process
  → create space for glue on mesh edge
- quality OK, exposure not optimized
- pillar shape OK
- adhesion good: 675 / 676 pillars there

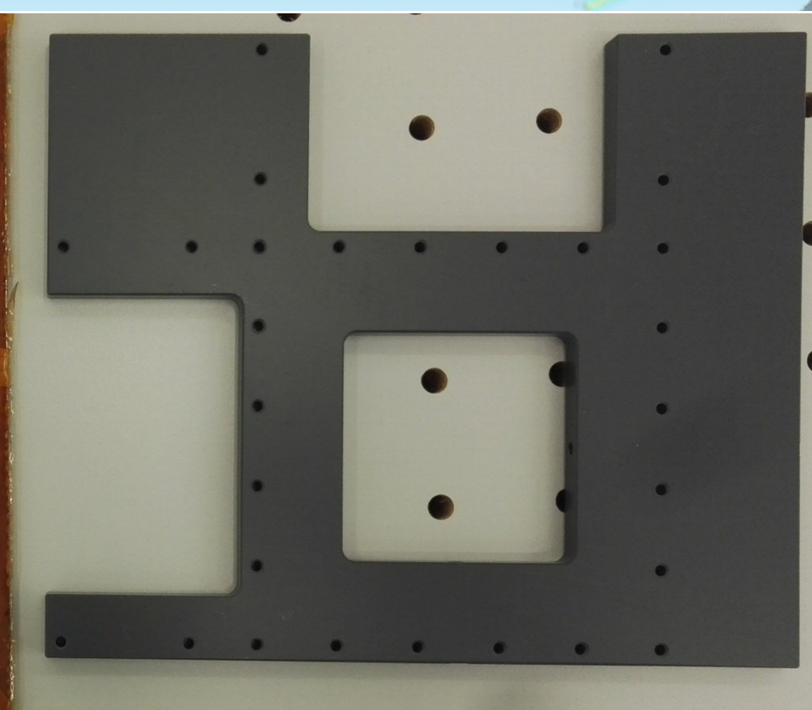


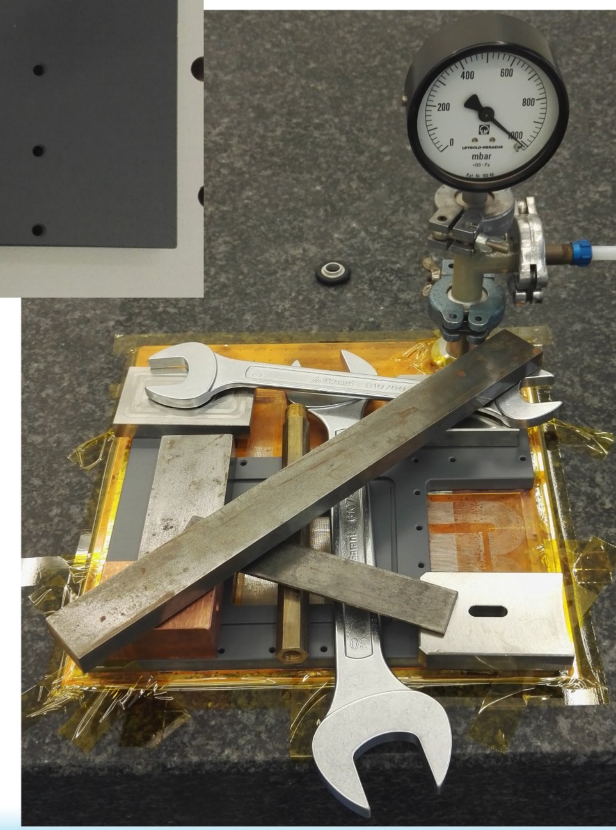




# Gluing on Supportive PCB Frame & Assembly

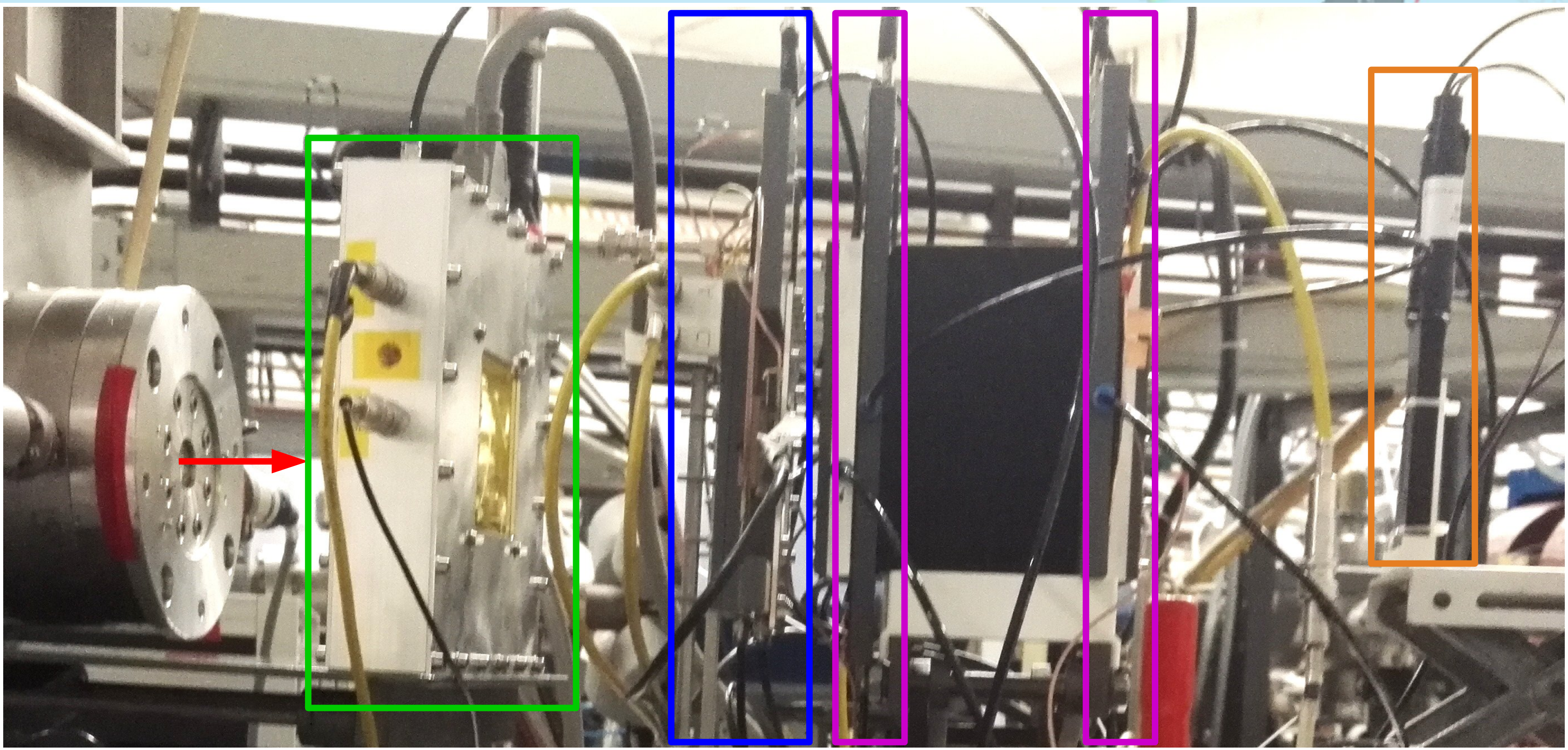






- suck PCB face down onto granite table
- glue PVC frame onto it → cure 24 h
- trim edges, punch & drill holes
- wet cleaning in ISO 5 clean room
- assemble with gas frame (carrying mesh) & lid (carrying cathode) in ISO 3 clean room

# Tests in 22&21 MeV Proton Beams @ MLL Tandem Sept. 19 & Nov. 19



**beam**
kHz to 5MHz
4x5mm² FWHM
(pCT<0.5MHz/cm²)

**dual strip IC**
multi-channel
electrometer ro
ΔI/I ~ 1% @
1MHz

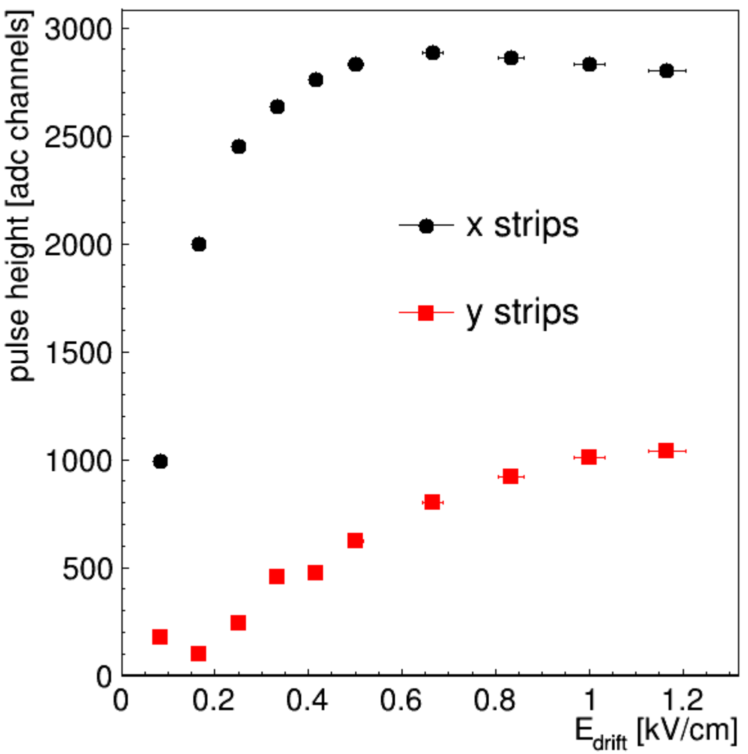
**aluminum FSM**
**single layer**
2x APV25 + SRS
Ne:$CF_4$ 80:20

**reference FSMs**
4 x APV25 + SRS

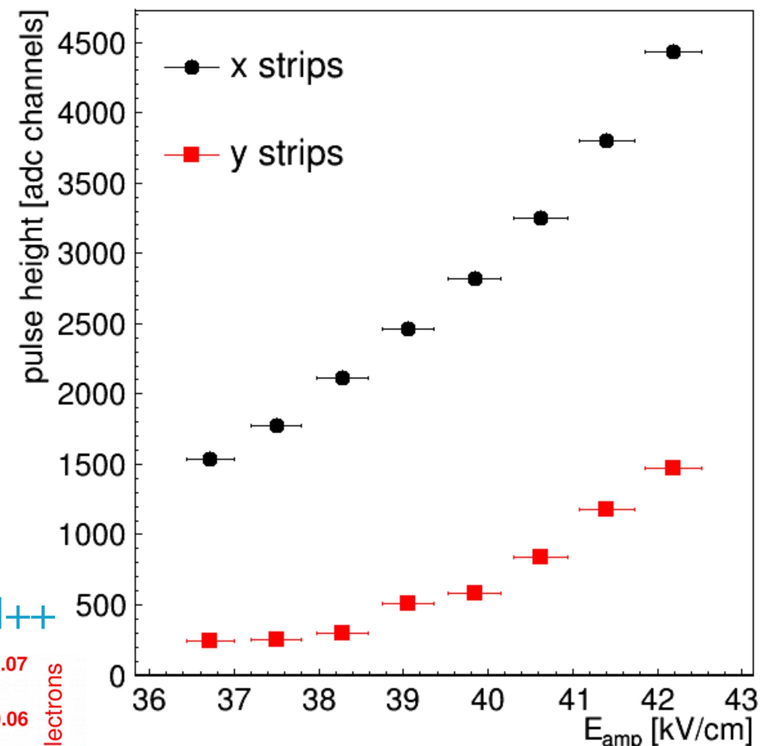
**trigger scintillator**
NIM electronics
APV25 → jitter correction

# Pulse Height Behavior vs Voltages September 19

pulse height vs $E_{drift}$ @ 39.9kV/cm

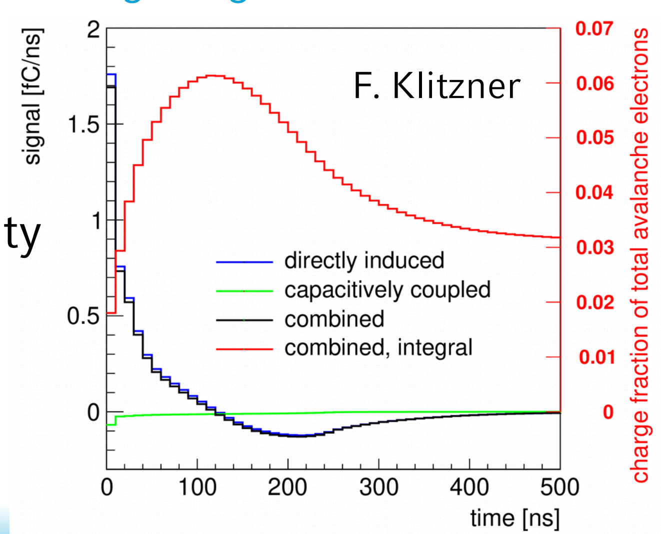



pulse height vs $E_{amp}$ @ 0.5kV/cm




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

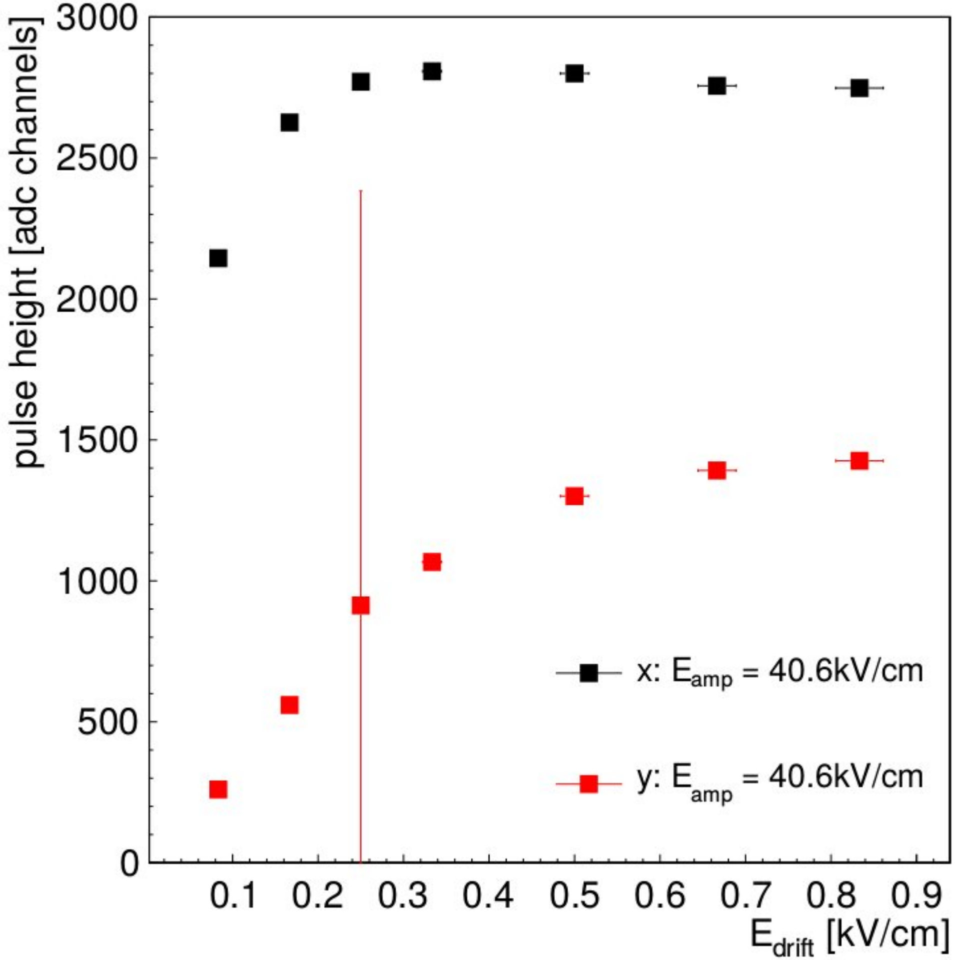
signal modeling y-strips: weighting fields & Garfield++



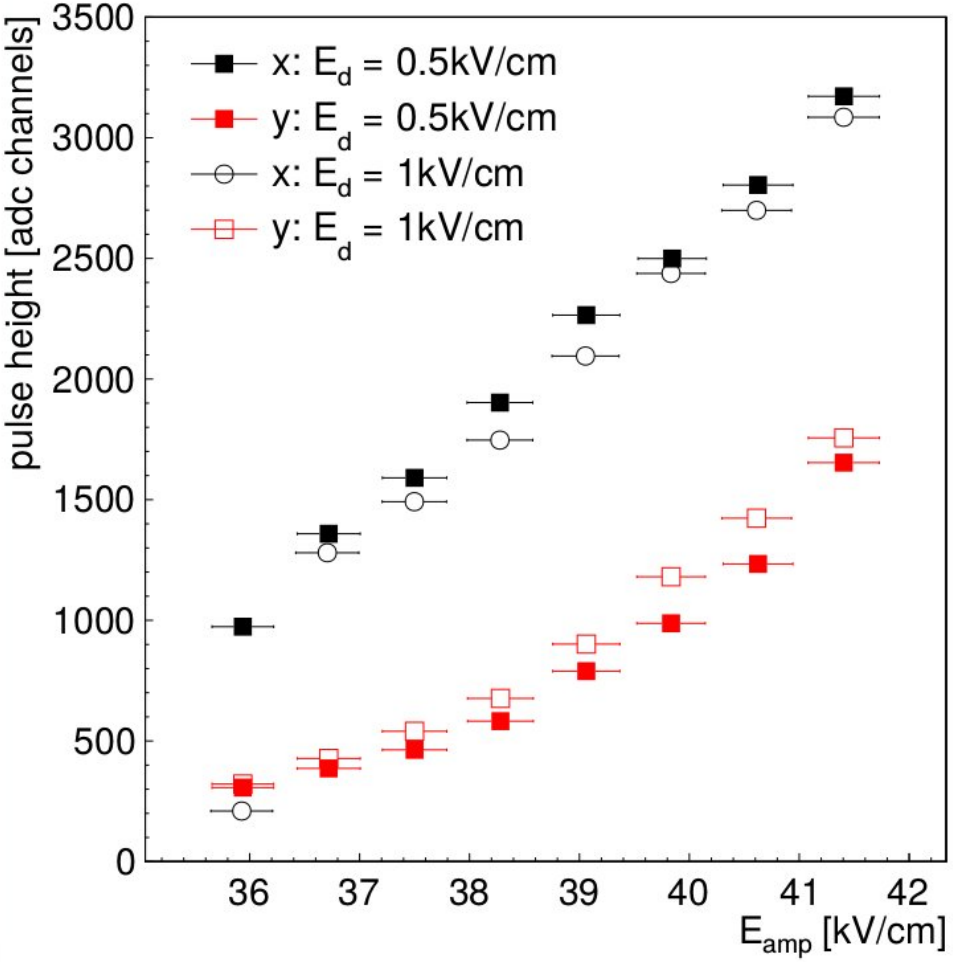

→ it works!
→ operation in large parameter space possible

# Pulse Height Behavior vs Voltages November 19

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



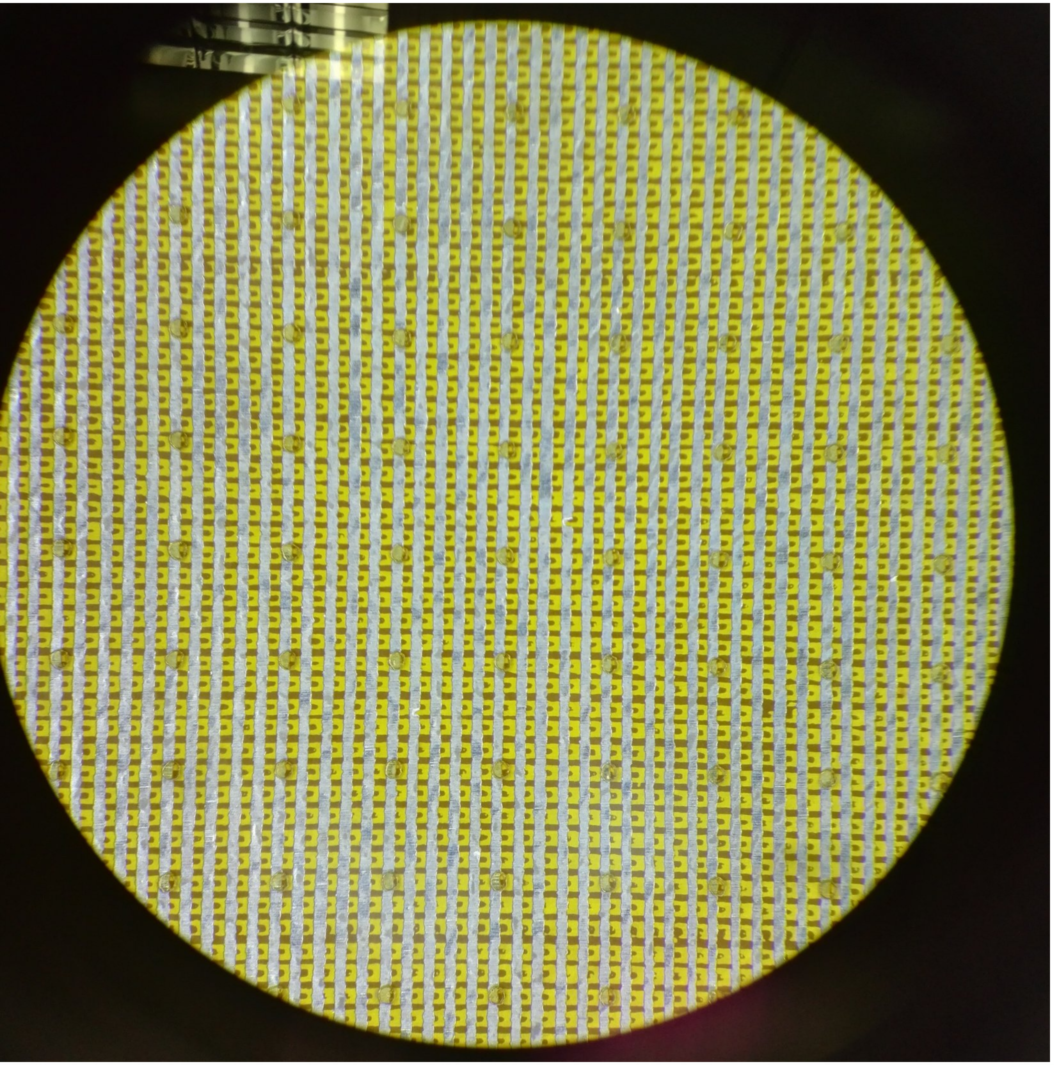

pulse height vs $E_{amp}$ @ 1kV/cm



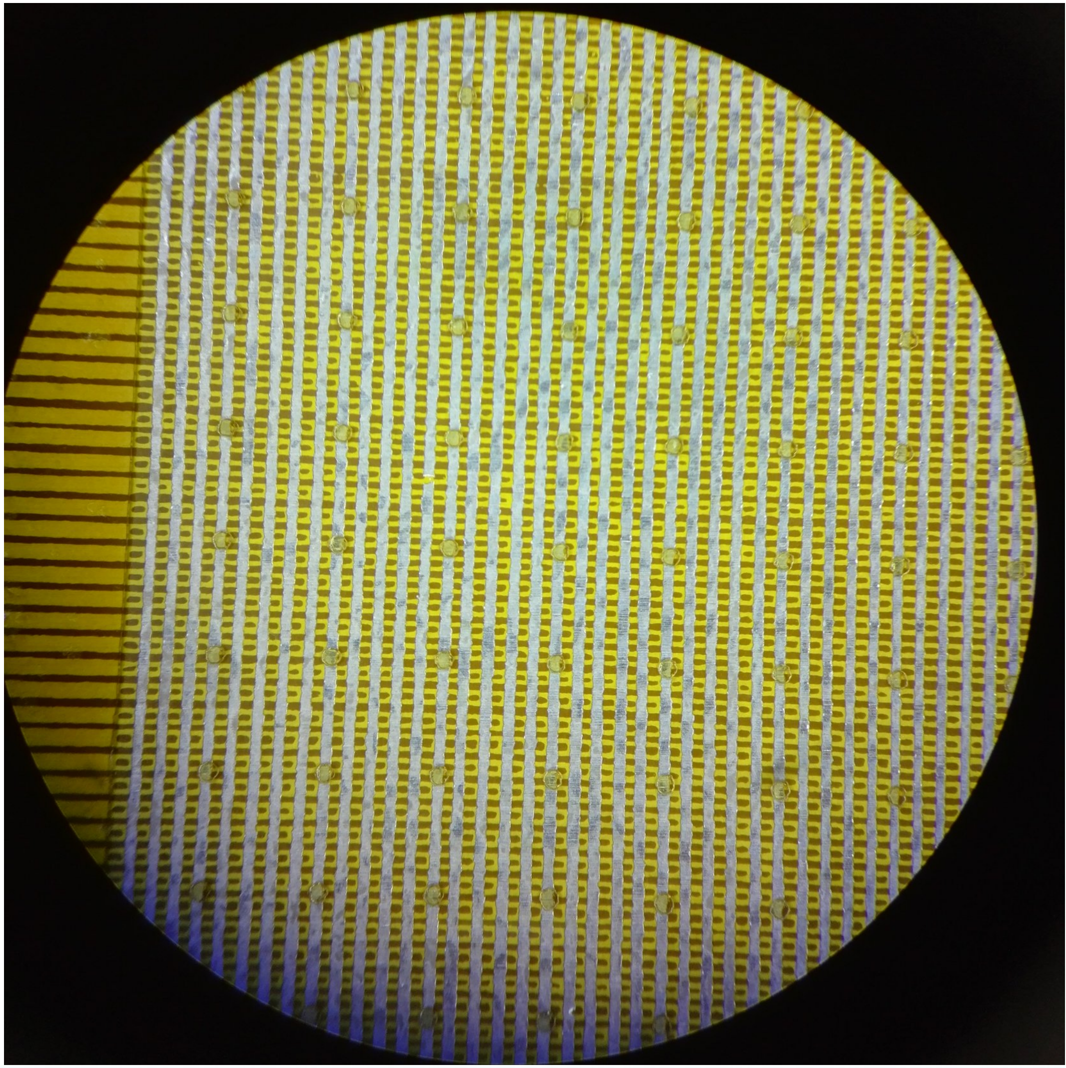

- pulse height ratio y/x ~ 0.5 → well usable
- tracking works well: analysis ongoing, limited by scattering in reference detectors

# Visual Inspection for Damage due to Discharges

irradiated region



not irradiated region



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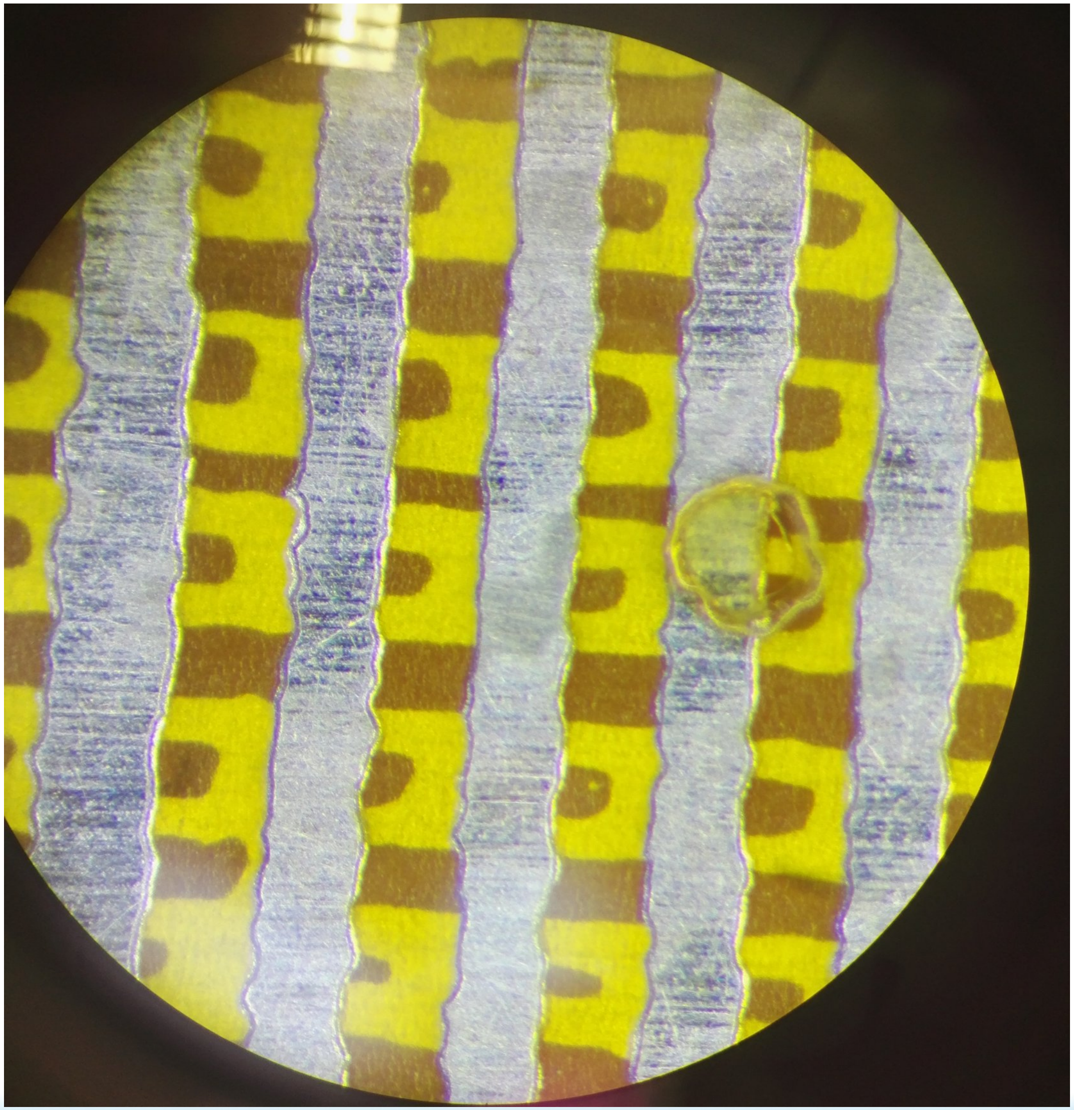

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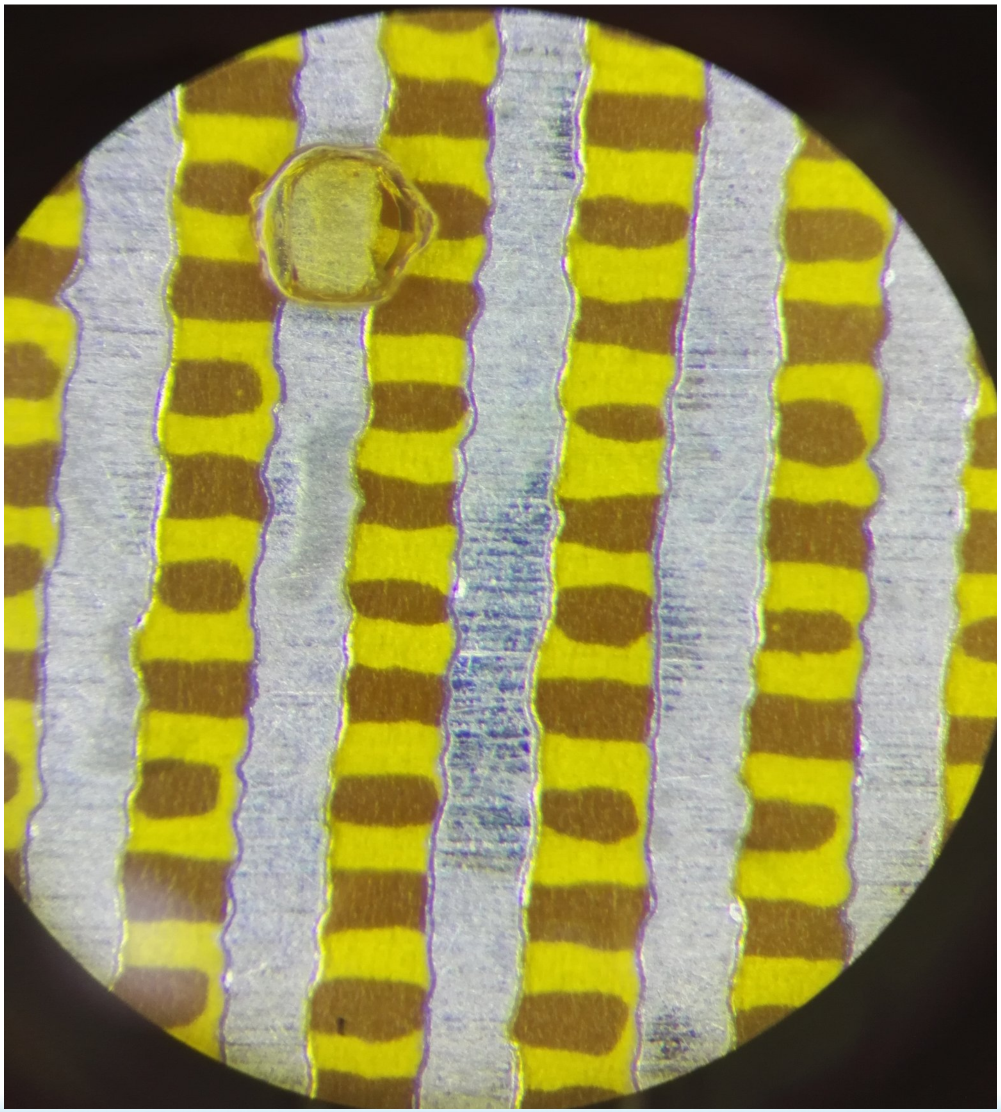

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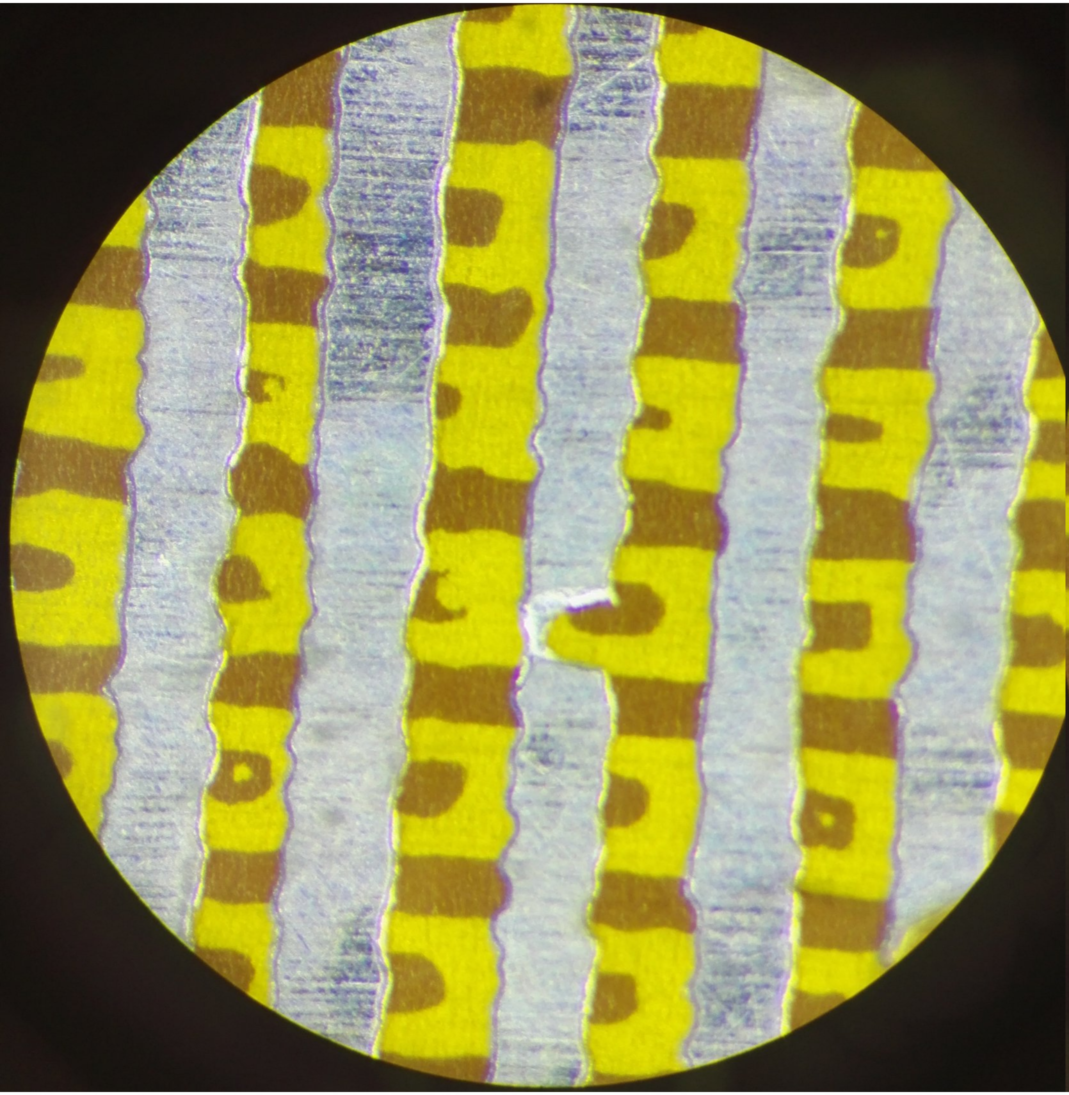
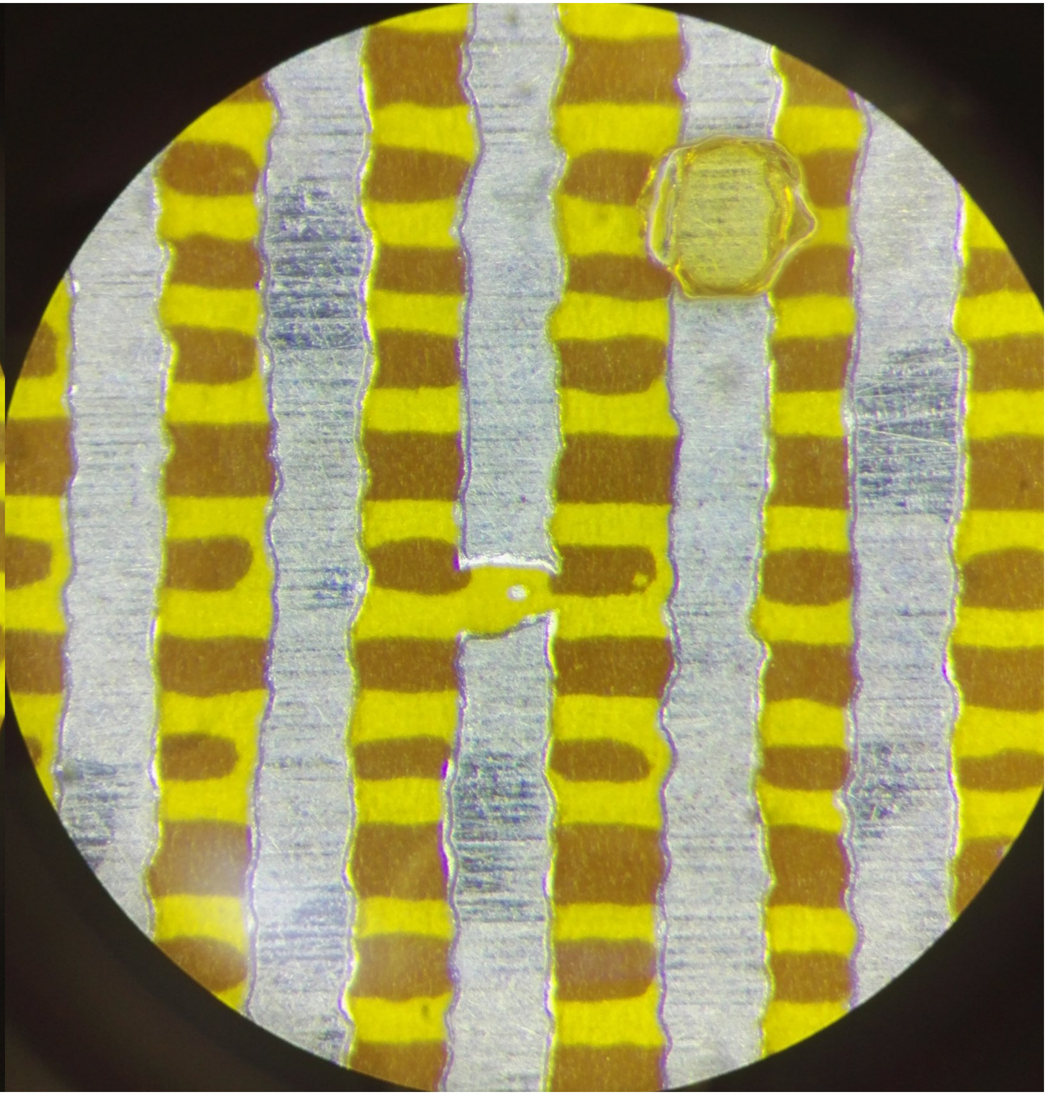


not irradiated region



# Summary

development of portable platform: small animal proton irradiation for oncology research

**proton computed tomography system**

- animal anatomy & positioning
- 4 floating strip Micromegas tracking detectors → spatial information
- Time Projection Chamber with vertical absorbers → residual range → contrast information
- detailed FLUKA simulation including image reconstruction
  → reduce scattering in tracking detectors

**low material budget Micromegas with aluminum readout structure**

- developed and optimized photolithography and readout production processes in-house
- full-size prototype assembled and working
- tested in 22 & 21 MeV proton beams
  - stable operation in large gain parameter space possible
  - operation at particle flux x40 possible
  - no sign of aging (visually or performance)
  - analysis ongoing

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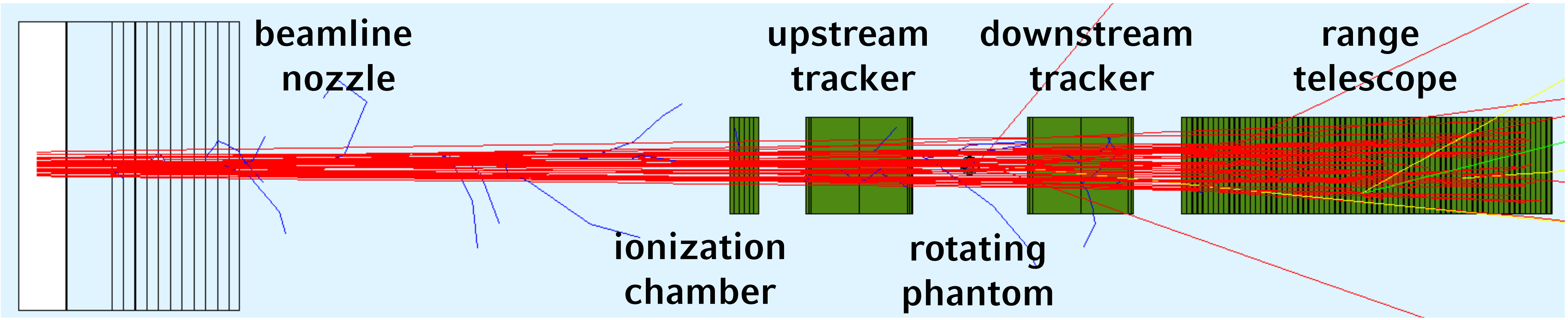
Thank you!

# backup

# backup: FLUKA Simulation Model

includes all components and real beam parameters*




**proton trajectories using tracker information**
limited by tracker geometry, material budget & spatial resolution
**→ spatial resolution**

**range information from range telescope**
limited by range telescope granularity & homogeneity
**→ RSP accuracy**
**↔ resolution of water equivalent path length (WEPL)**

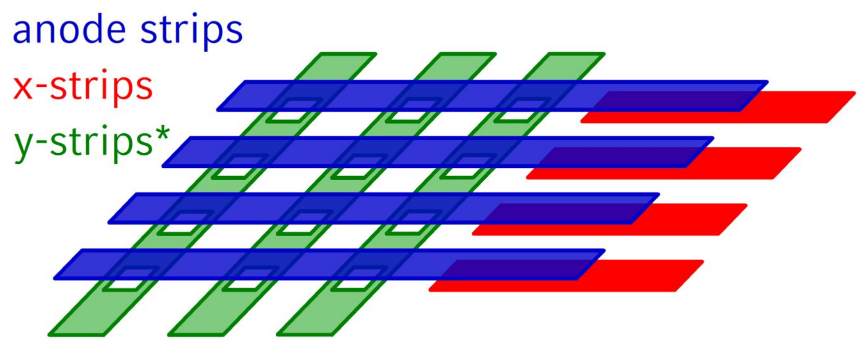
**→ optimize detector parameters**

simulation: S. Meyer (LMU), PhD thesis in progress
*On the clinical potential of ion computed tomography with different detector systems and ion species*

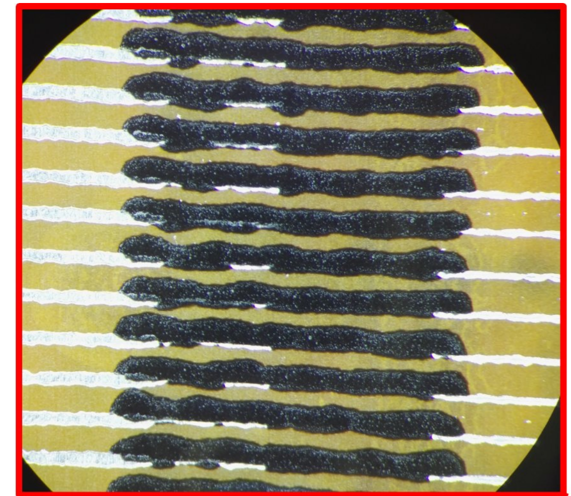
*Würl et al., Phys. Med. Biol. 61, 958–973 (2016)

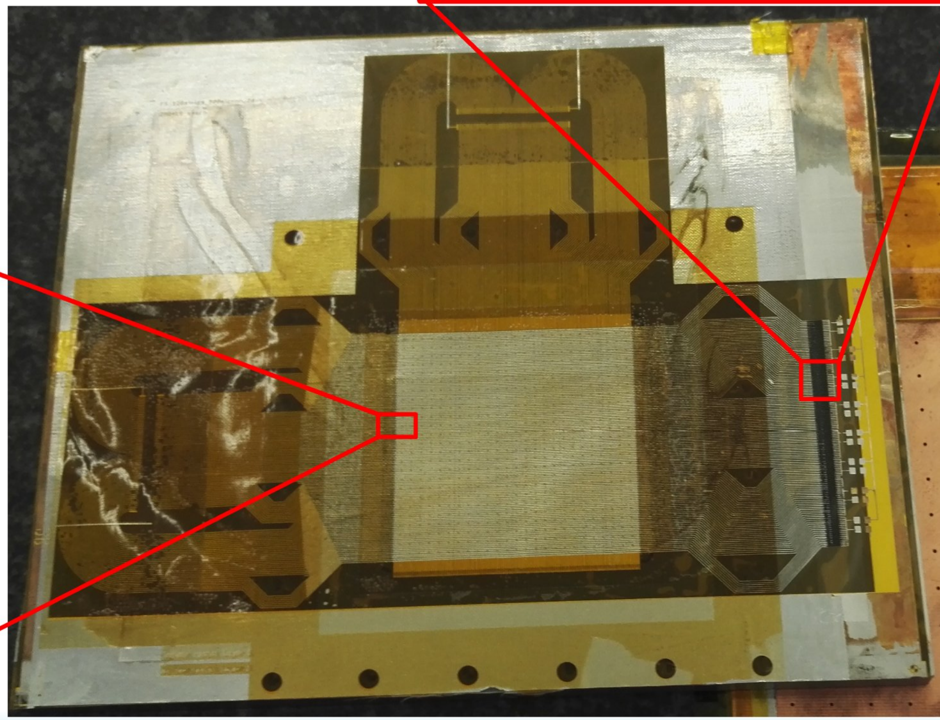
# backup: Floating Strip Micromegas with Ultra-Low Material Budget

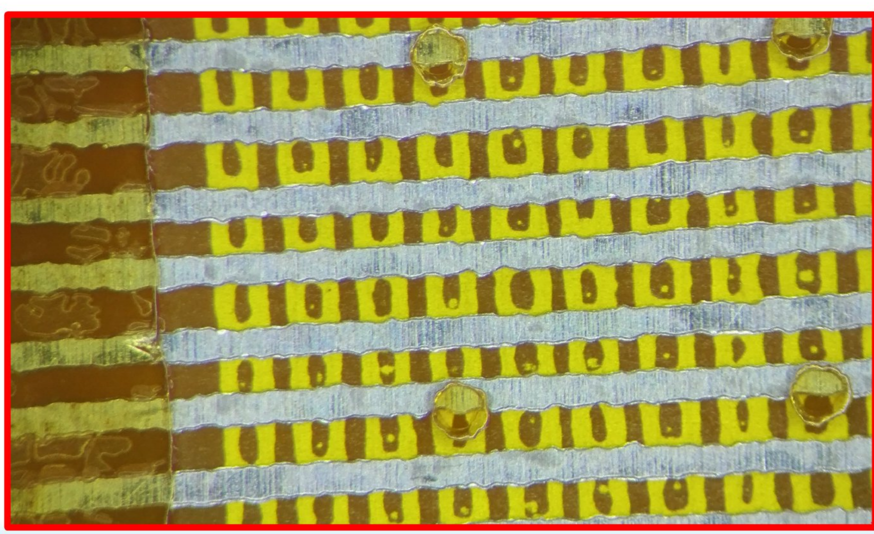
12μm Al anode & y-strips on 32μm Kapton & glue
→ x-readout strips outside active area




*: pattern inspired by F. Klitzner, LMU Munich



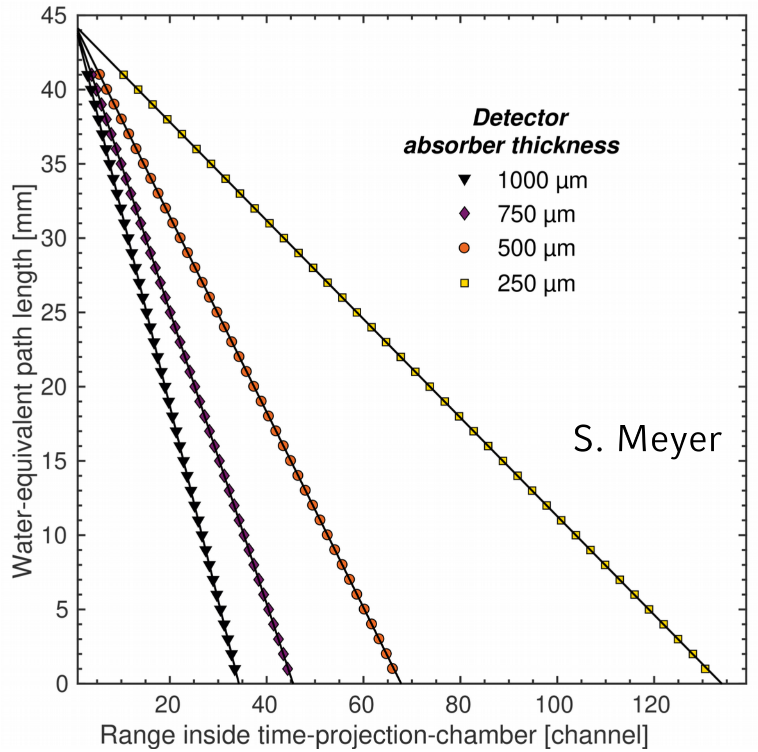




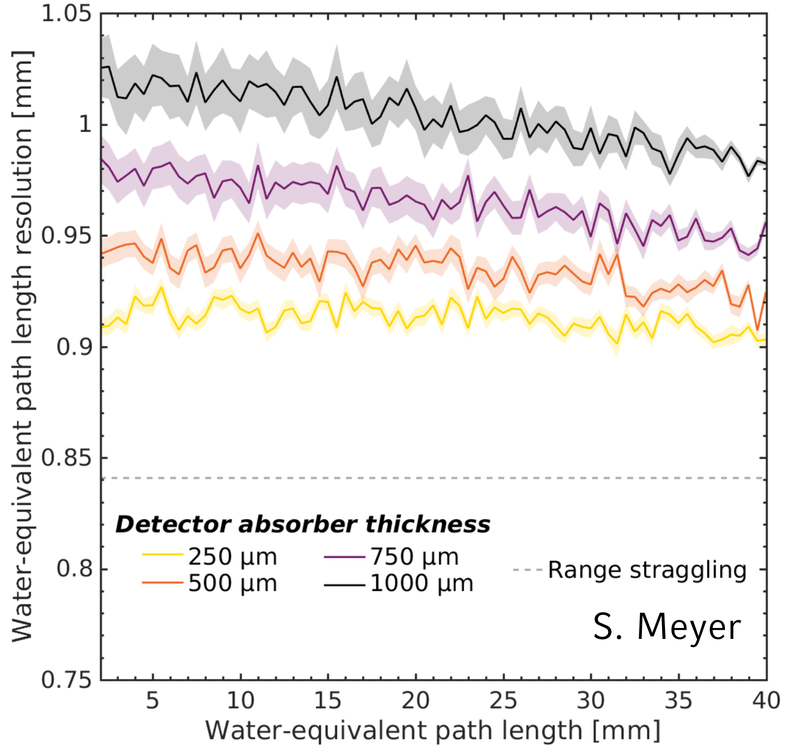
# backup: FLUKA Simulation: Detector Parameter Optimization

determine: absorber thickness → WEPL resolution
↔ total number of absorbers

WEPL (object thickness) vs range in TPC



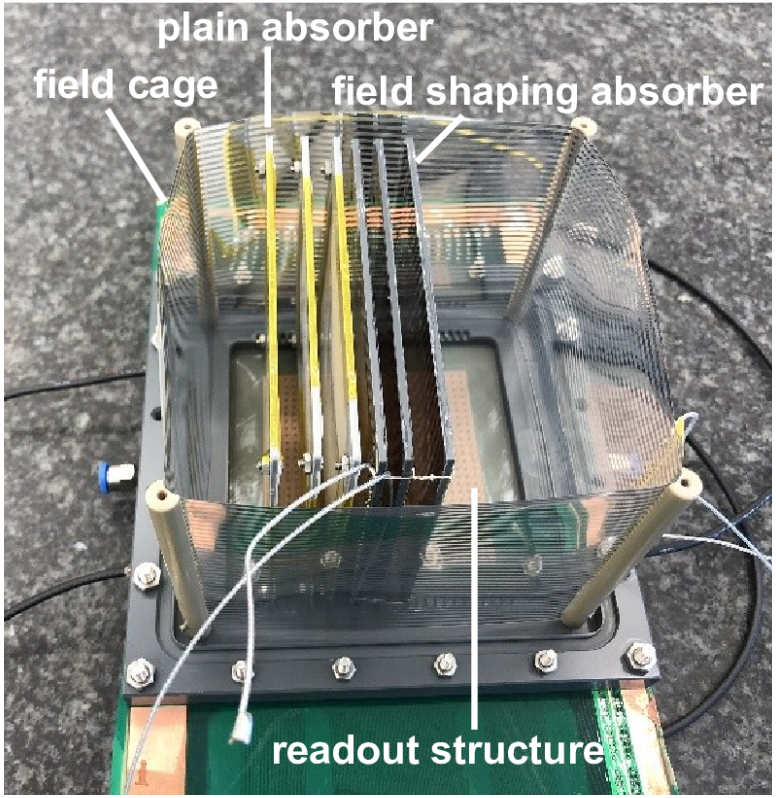

WEPL resolution for different absorbers

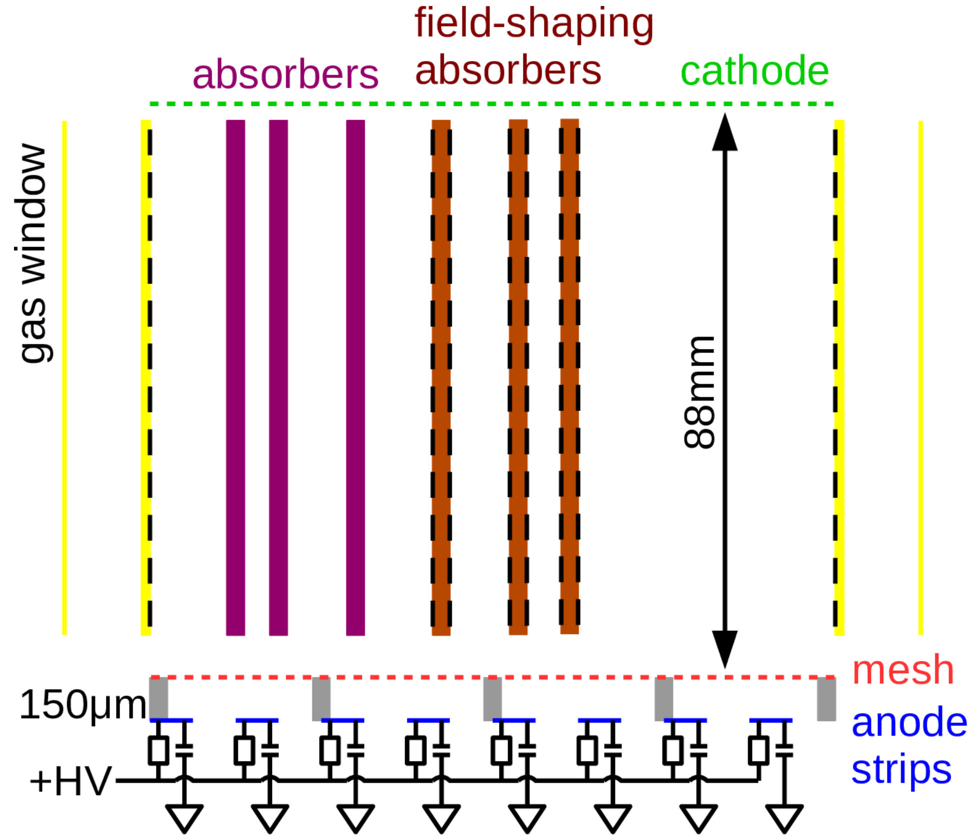



**→ 0.5mm thick foils: WEPL resolution close to physical limit & good compromise between complexity & avoidance of artifacts**

**→ 66 absorbers to fully stop beam**

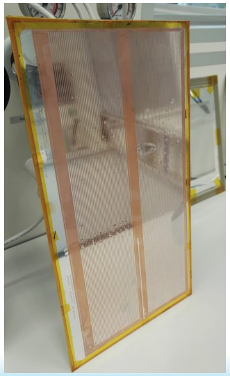
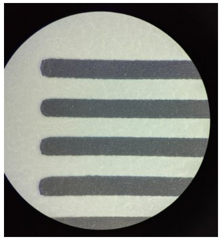
# backup: Range Time Projection Chamber: First Prototype



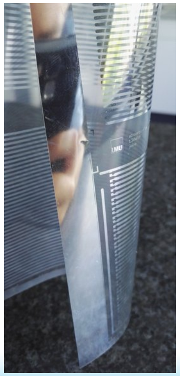




- 88mm drift region
- 64x64mm$^2$ strip Micromegas readout structure
- 50µm Mylar field cage
- absorbers: 3 field-shaping, 4 plain (PTFE or Mylar)

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

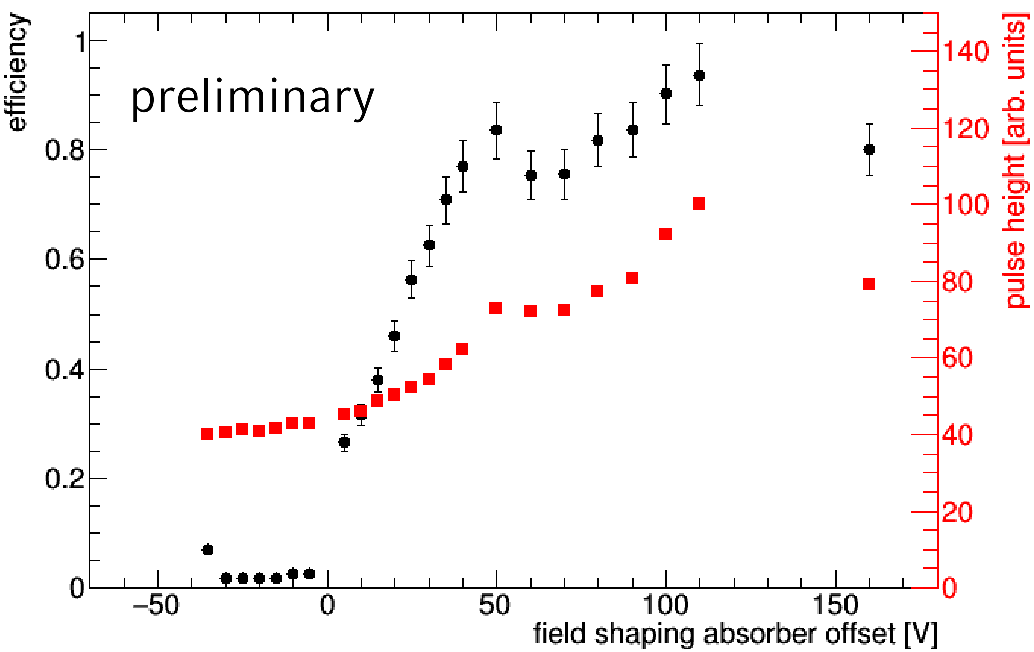



1mm strips
1mm gap

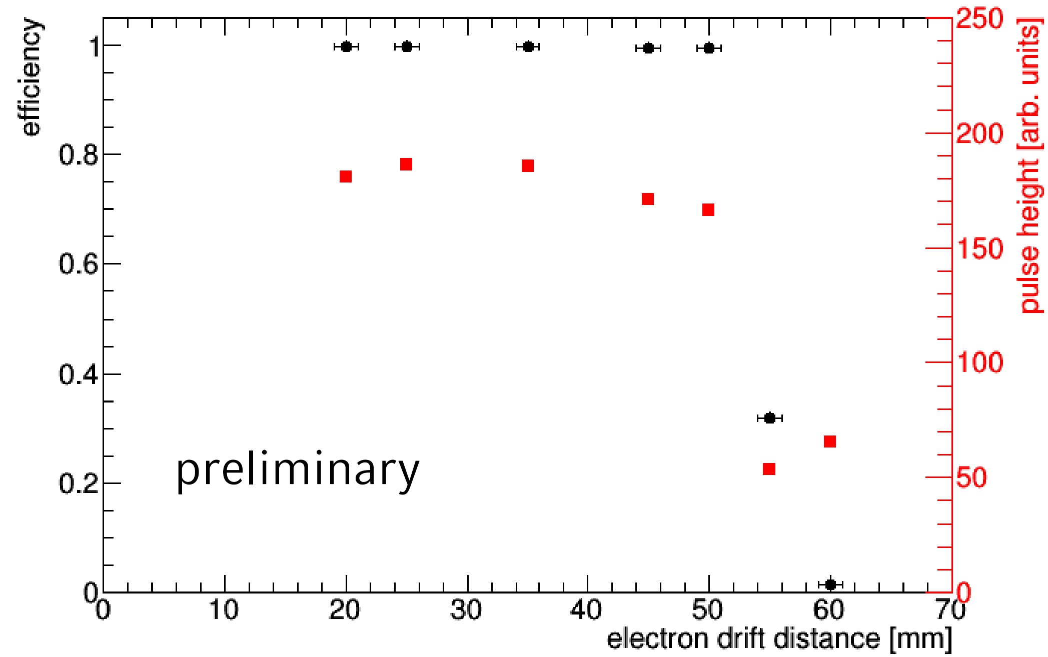


# backup: 22MeV p, Ne:CF4 : Efficiency vs Absorber Fields

variation of absorber offset voltage
@ 54mm electron drift distance



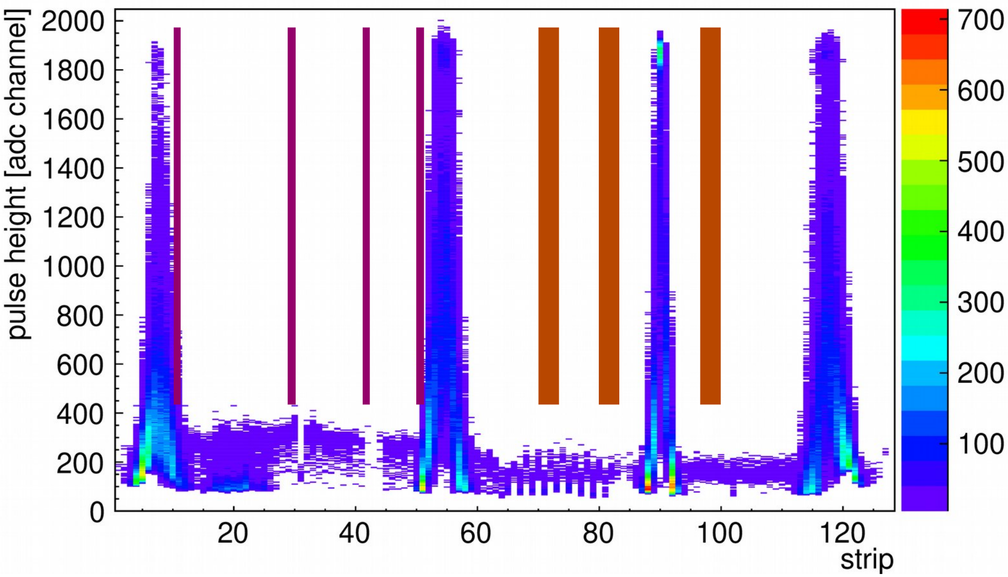

variation of mean electron drift distance
@ absorber offset = 110V + 20V/80mm gradient



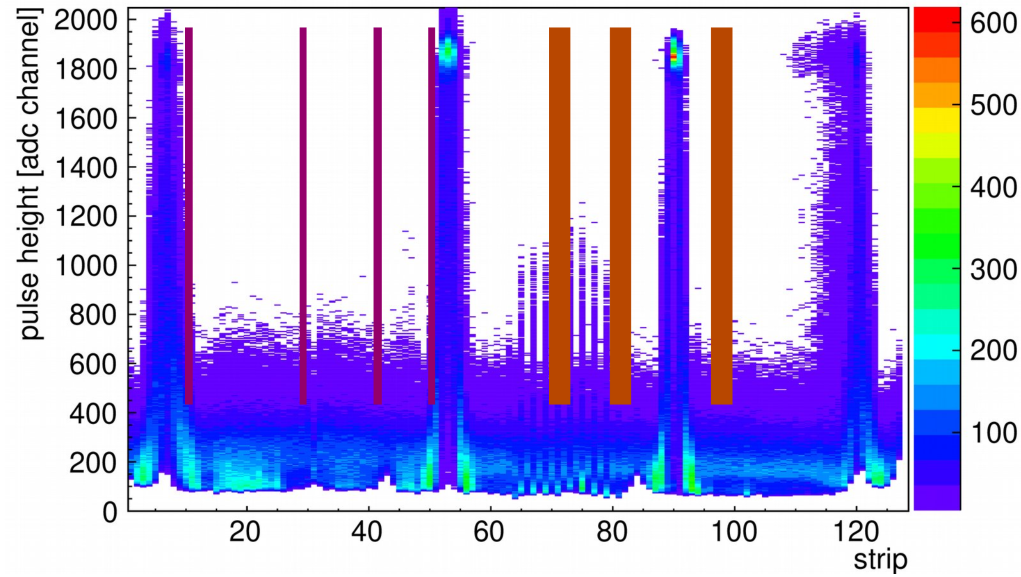

→ **reliable electron extraction over 50mm drift distance for 6mm absorber spacing**

# backup: 22MeV p, Ne:CF4 : High-Rate Behavior

pulse height vs strip @ 50kHz




pulse height vs strip @ 470kHz




**→ electron extraction well possible even at high rates**

detailed analysis ongoing. ANSYS + Garfield++ simulation under development.

field shaping absorbers show reproducible results. plane absorbers don't.

next: test field shaping absorbers with non-homogeneous field (non equidistant strips)

# backup: Technology Development: Thin & Structured Electrodes

etch-resist lamination

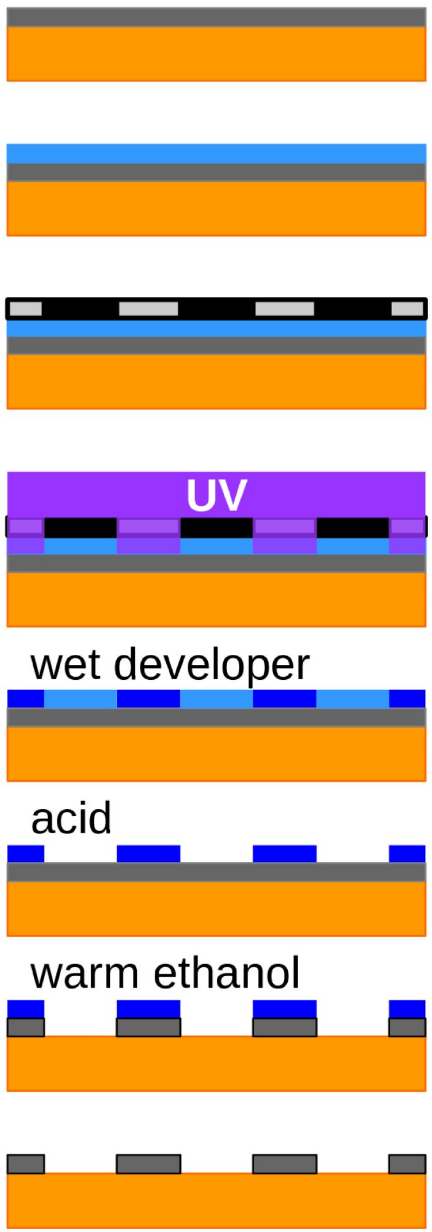
mask positioning

UV illumination

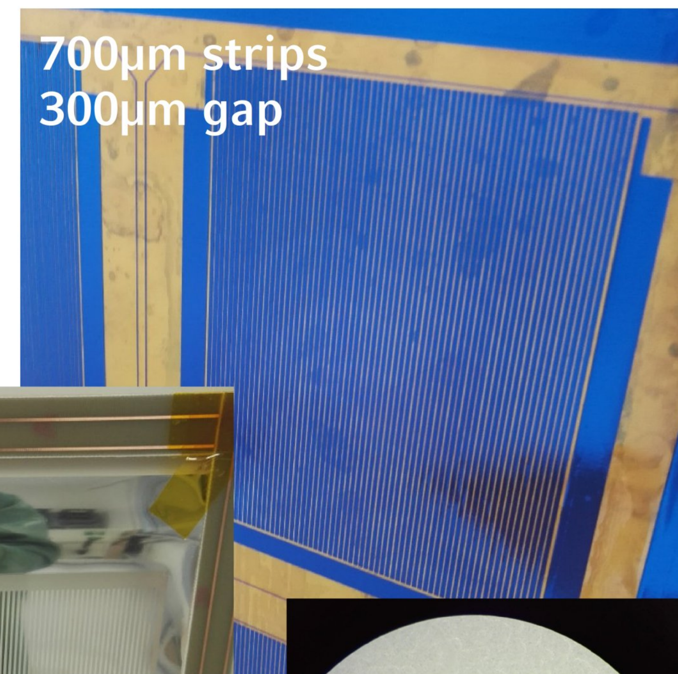
resist development

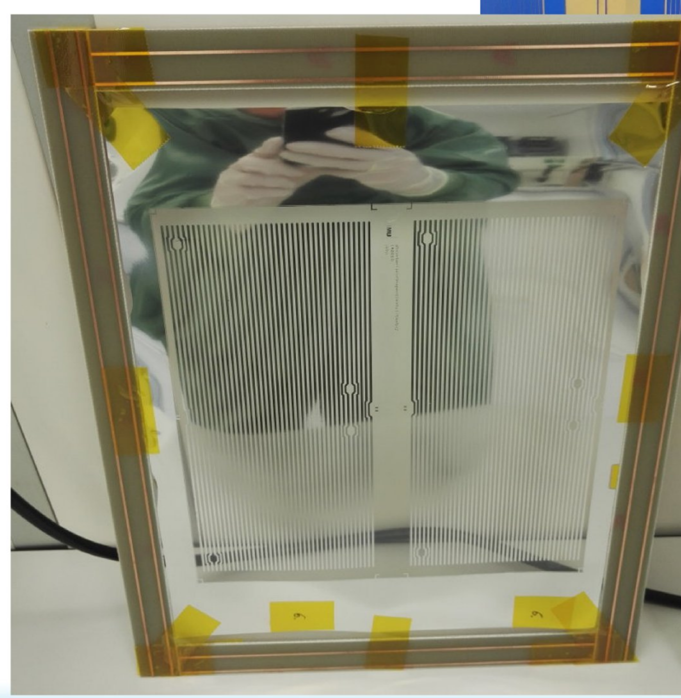
alu etching

resist stripping



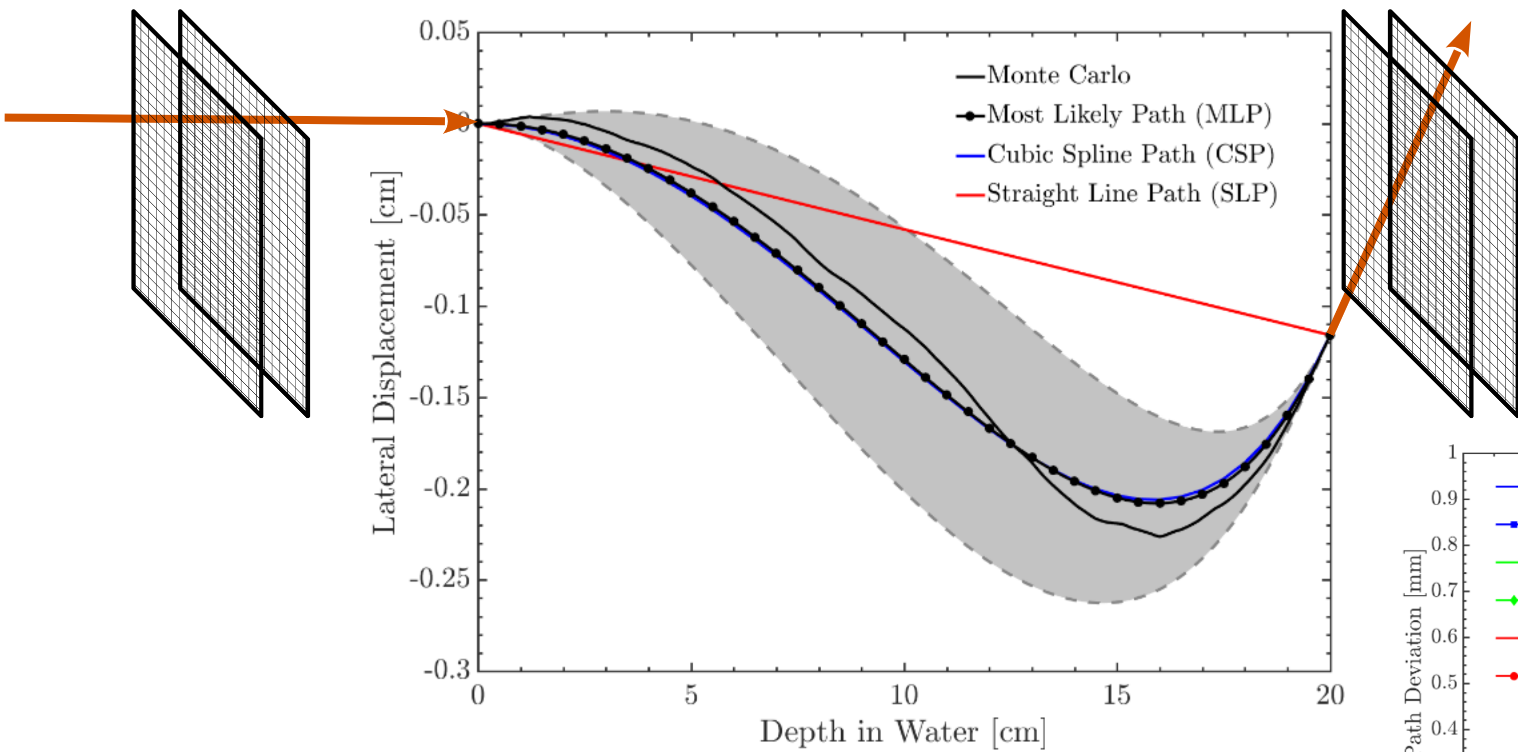

**photolithographic structuring:** thin foils recently mastered in-house



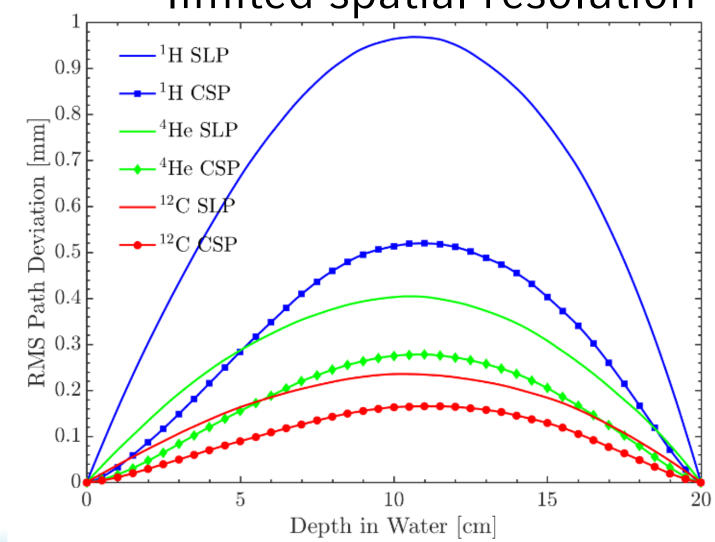



# backup: Reconstruction: Particle Path in the Object

ions don’t follow straight lines
→ mathematical description to account for MCS: cubic spline path*




limited spatial resolution




*Collins Fekete et al., Phys. Med. Biol. 60, 5071–5082 (2015)

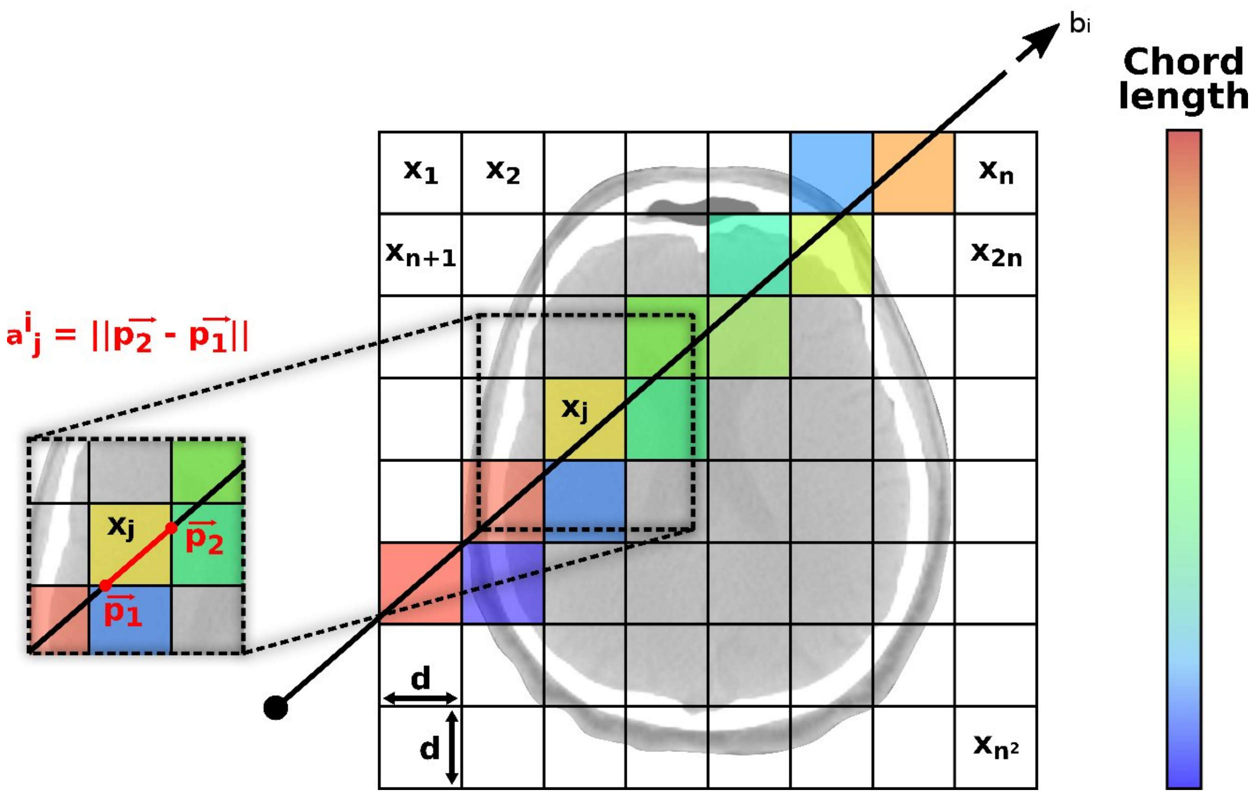
# backup: Reconstruction: Combining Path & Range

the mathematical problem

$$\int_L RSP(\mathbf{r})d\mathbf{r} = WEPL$$

↓

$$Ax = b$$




$A$ system matrix (calc.)
$n_{events}$ x $n_{voxels}$

$x$ RSP image (tbd)
$n_{voxels}$ x 1

$b$ WEPL values (meas.)
$n_{events}$ x 1

**→ compute A and solve for x!**
Ordered Subset Simultaneous Algebraic Reconstruction Technique (OS-SART)