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

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low energy ions: \( \frac{dE}{dx} \sim 1/\beta^2 \) 
→ favorable depth-dose:
- none behind tumor
- low in entrance

Context: Particle Therapy

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1. imaging: X-ray Computed Tomography
2. treatment planning:
   photon absorption \( \leftrightarrow \) \( \frac{dE}{dx} \)
3. fractionated treatment

ion range uncertainties: 3\% + artifacts
- photon X-ray to stopping power conversion
- patient anatomy changes
- patient positioning
\( \rightarrow \) mitigate: proton CT just before treatment
pre-clinical oncology research: closely mimic clinical routine with proper tumor models & realistic treatment regimes

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

- online beam position visualization
- precision beam monitor
- pre-treatment: pCT

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

exper. beamline @ clinical accelerator

BEAMLINE degrading collimation focussing

monitor chamber

support

PET

IA & US

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

2017-2021
K. Parodi
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
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

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prototype with flex-PCB readout structure (1.1% $X_0$)
  • spatial resolution (0.5mm pitch): < 100μm
  • single particles: $\leq 7$MHz/cm²

- HV
  Ne:CF₄

- GND

- +HV
  22MΩ

- ionization
- mesh
- anode

- y-readout strips (perpendicular)
- x-readout strips (parallel)

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


February 11, 2020
Jona Bortfeldt - Aluminum Floating Strip Micromegas for pCT
FLUKA Simulation: Detector Parameter Optimization

path accuracy for different anode structures

path accuracy vs tracker plane distance

S. Meyer

Root-mean square path deviation [mm]

Depth in water [mm]

Cu strips (3 layers)
Cu strips (2 layers)
Al strips (2 layers)

Average root-mean square path deviation [mm]

Upstream detector separation [cm]

1 cm
3 cm
6 cm
8 cm
10 cm

Jona Bortfeldt - Aluminum Floating Strip Micromegas for pCT
Aluminum Floating Strip Micromegas Readout Structure

12µm Al anode & y-strips on 32µm Kapton & glue
→ x-readout strips outside active area
→ 0.15 X₀ 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
Thank you very much, Rui, for the invaluable advice!

**current process**
- cleaning
- manual masking
- pickling
- zincate
- alkaline Cu electroplating
- acidic Cu electroplating
- mask removal
- etch resist spray + curing
- UV exposure
- development
- etching
- stripping

**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
$\Delta I/I \sim 1\% @ 1\text{MHz}$

reference FSMs
4 x APV25 + SRS

aluminum FSM
single layer
2x APV25 + SRS
Ne:CF, 80:20

trigger scintillator
NIM electronics
APV25 $\rightarrow$ jitter correction
Pulse Height Behavior vs Voltages
September 19

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

- x strips
- y strips

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

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

- x strips
- y strips

→ it works!
→ operation in large parameter space possible

signal modeling y-strips: weighting fields & Garfield++
- pulse height ratio $y/x \sim 0.5 \rightarrow$ 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
Visual Inspection for Damage due to Discharges

irradiated region

not irradiated region
Visual Inspection for Damage due to Discharges

irradiated region

not irradiated region
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
Summary

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

proton computed tomography system
- animal anatomy & positioning
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Thank you!
backup
includes all components and real beam parameters*

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**beamline nozzle**

**upstream tracker**  **downstream tracker**

**range telescope**

**ionization chamber**  **rotating phantom**

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**proton trajectories using tracker information**

limited by tracker geometry, material budget & spatial resolution

→ **spatial resolution**

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**range information from range telescope**

limited by range telescope granularity & homogeneity

→ **RSP accuracy**

↔ **resolution of water equivalent path length (WEPL)**

→ **optimize detector parameters**

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**simulation**: S. Meyer (LMU), PhD thesis in progress


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*On the clinical potential of ion computed tomography with different detector systems and ion species*
backup: Floating Strip Micromegas with Ultra-Low Material Budget

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

anode strips
x-strips
y-strips*

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backup: FLUKA Simulation: Detector Parameter Optimization

determine: absorber thickness $\rightarrow$ WEPL resolution
↔ total number of absorbers

WEPL (object thickness) vs range in TPC

$\rightarrow$ 0.5mm thick foils: WEPL resolution close to physical limit & good compromise between complexity & avoidance of artifacts
$\rightarrow$ 66 absorbers to fully stop beam
backup: Range Time Projection
Chamber: First Prototype

- 88mm drift region
- 64x64mm² 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
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

→ 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

photolithographic structuring: thin foils recently mastered in-house

etch-resist lamination

mask positioning

UV illumination

UV

resist development

wet developer

acid

alu etching

warm ethanol

resist stripping

700μm strips
300μm gap

1mm strips
1mm gap
backup: Reconstruction: Particle Path in the Object

ions don’t follow straight lines

→ mathematical description to account for MCS: cubic spline path*

backup: Reconstruction: Combining Path & Range

the mathematical problem

\[ \int_L RSP(r) \, dr = WEPL \]

\[ Ax = b \]

A \text{ system matrix (calc.)} \\
\text{system matrix (calc.)} \\
n_{\text{events}} \times n_{\text{voxels}}

\text{RSP image (tbd)} \\
x \text{ RSP image (tbd)} \\
n_{\text{voxels}} \times 1

b \text{ WEPL values (meas.)} \\
WEPL values (meas.) \\
n_{\text{events}} \times 1

\rightarrow \text{compute } A \text{ and solve for } x! \\
\text{Ordered } \textbf{Subset Simultaneous Algebraic Reconstruction Technique (OS-SART)}