A Large Area GEMPix detector for treatment plan verification in hadron therapy

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Outline

• Motivation: Hadron Therapy & QA
• The GEMPix Detector
• A larger area GEMPix (LaGEMPix) detector
• Characterization: spatial resolution
• Conclusions & Outlook
Motivation

Hadron Therapy & Quality Assurance

- Hadron therapy: Well-defined region of energy deposition
- 2D images with better spatial resolution than ion chambers
- Quality Assurance (QA): check range, spread of Bragg peak, treatment plan verification
- QA: typical dose uncertainty $O(1\%)$

a) Photon beam  
b) Proton beam
The GEMPix Detector
Measurements at CNAO

3D energy deposition by $^{12}$C ion beam

Why a Large Area GEMPix? 

- **Underestimation** of the dose of a pencil beam in the GEMPix:
  - The beam is spread out with increasing depth in water
  - It is especially evident in the tail!

- Larger detector area of 20 cm x 20 cm needed to:
  - **cover typical maximum** radiation field size for scanned beams
  - avoid **losses** due to beam spread out

- On-going work focused on **larger sensitive area readout**:
  - Large area GEMs already exist
  - Check new readout possibilities

GEMPix active area: 2.8 cm x 2.8 cm!

Aim: 20 cm x 20 cm!

The LaGEMPix detector
Triple-GEM

The IBA 18-MeV cyclotron at Bern
• Test the behaviour at high proton flux of the Triple-GEM detector:
  • 10 x 10 cm²
  • Perform **beam current scans:**
    • Typical range used in hadrontherapy:
      • $[10^9 ; 10^{10}]$ protons/s
    • Range used at Bern:
      • $[10^7 ; 10^{10}]$ protons/s
      • $[10^{-2} ; 10^0]$ nA

Successful measurements with currents up to 1.5 nA
Triple-GEM

Readout options

Different readouts

- **Charge** readout
  - relies on collecting electrons from the avalanche in the GEMs.
    - electron diffusion in the gas volume

- **Optical** readout
  - relies on detecting optical photons emitted during the electron avalanche multiplication processes, which can be achieved when specific gas like ArCF$_4$ mixtures are used.
    - electron diffusion in the gas volume
    - isotropic emission of the scintillation light
Readout Options

Gas Electron Multipliers (GEM’s) + Pixelated Read-out

Charge readout or Optical readout?

01 Timepix or Timepix3
- Well-known system
- Good performance
- Cost
- Difficult to increase area

02 TFT (Thin Film Transistor)
- Printed on any size
- Easy to couple to Triple-GEM
- Radiation hardness (to be studied)

03 TFT + OPD (Organic Photodiode)
- Printed on any size
- Easy to couple to Triple-GEM
- Radiation hardness (to be studied)

04 CCD/CMOS Camera
- High resolution
- Complexity of set-up

05 Light sensitive Timepix 3

CERN Medical Applications Funding

ATTRACT funding project

TIPP 2021 – 26/05/2021
**Matrix TFT+OPD**

Organic photodiodes coated on an organic TFT backplane

This project has received funding from CERN Medical Applications Project and the ATTRACT project funded by the EC under Grant Agreement 777222.
1. Development of the first prototype:
   - Triple-GEM @ CERN
     - 10x10 cm²
     - Gas mixture - ArCF₄
   - Image sensor @ TNO
     - 60 x 80 mm²
     - pixels of 126 x 126 μm²
   
   **Increase of 6x active area!**

2. The first LaGEMPix detector has been **successfully** assembled.

3. First tests of the LaGEMPix prototype were performed in the CERN Calibration Laboratory of Radiation Protection Group.
The LaGEMPix Detector
First test of the merged detector

Calibration Laboratory of the RP group

No radioactive source

3 TBq
137-Cs source
γ-rays: 662 keV

First functional test
The LaGEMPix Detector
Characterization optical signal

→ Calibration Laboratory of the RP group

Gain scan

Exponential behavior!
Same behavior measured with electrons.

Dose scan

Linearity with dose!

3 TBq 137-Cs source
γ–rays:
662 keV

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The LaGEMPix Detector

Spatial resolution

→ Edge response - ESF
  • Block of lead in front of the detector
    • thickness 2.5 cm

![Image of the LaGEMPix Detector]

Logistic function fit to the experimental data
FWHM = 9.70 ± 0.09 mm

X-Ray generator 40 kV

TIPP 2021 – 26/05/2021
The LaGEMPix Detector

Spatial resolution

➔ “Hole” response - LSF
  • Copper plate in front
    • 5 mm Ø holes
    • thickness 3 mm

Two holes in a distance of 3 mm (edge to edge) can be resolved (FWHM limit)!
The LaGEMPix Detector

Spatial resolution

→ Mask: X-ray lead test pattern
  - thickness 0.05 mm
  - resolution range: from 0.5 up to 10 LP/mm

The current version of the LaGEMPix is not able to distinguish the 0.5 LP/mm, which corresponds to two slits separated by 2 mm!
The LaGEMPix Detector

Spatial resolution

→ Calibration Laboratory of the RP group

Summary of the spatial resolution obtained for different experimental configurations and different detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Edge Response</th>
<th>5 mm hole Cu</th>
<th>Distinguished 2 holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaGEMPix</td>
<td>9.70 ± 0.09</td>
<td>6.73 ± 0.08</td>
<td>3 mm (edge to edge)</td>
</tr>
<tr>
<td>GEMPix</td>
<td>5.20 ± 0.10</td>
<td>5.23 ± 0.05</td>
<td>1 mm¹ (edge to edge)</td>
</tr>
<tr>
<td>GAFCHROMIC®</td>
<td>0.86 ± 0.07</td>
<td>5.09 ± 0.03</td>
<td>1 mm¹ (edge to edge)</td>
</tr>
<tr>
<td>FLUKA simulation</td>
<td>4.53 ± 0.01</td>
<td>--</td>
<td>1 mm¹ (edge to edge)</td>
</tr>
</tbody>
</table>

¹ minimum distance Cu plate

FLUKA simulation  GAFCHROMIC® XR-SP2 films  LaGEMPix
**The LaGEMPix Detector**

**Next steps**

### TFT + OPD

**Option 3.1**

- Distance between GEM3 and readout is **3 mm**.
  - 1.9 mm induction gap + 1.1 mm thick anode
- Sub-millimetre spatial resolution was not achievable!

### TFT + OPD

**Option 3.2**

- New version of the detector:
  - The effect of the isotropic emission of the photons depends on the distance between the places of production and detection of the photons
  - **Reduced gap of 1.5 mm**: 1 mm induction gap + 0.5 mm thick anode
- Sub-millimetre spatial resolution was not achievable!

### TFT-only

**Option 2**

- **Charge** readout - Better spatial resolution:
  - Exclusion of the contribution of the isotropic emission of the scintillation light to the spatial resolution

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**CNAO Measurements (2021)**

- Perform depth scans with the LaGEMPix inside the **water phantom**
- **Ionization chamber** for normalization to beam intensity
- FLUKA simulation of full setup
Conclusions & Outlook

- **GEMPix** (active area of 2.8 x 2.8 cm\(^2\)) in water phantom is able to provide 2D images, Bragg curves and 3D energy deposition of carbon ion beam

- **Larger sensitive area** of 20 x 20 cm\(^2\) needed to cover typical maximum radiation field size and to avoid losses due to beam spread out

- On-going work focused on **larger sensitive area readout**
  - Large area GEMs already exist
  - Check new readout possibilities

<table>
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<th>Feasibility of optical readout</th>
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<tr>
<td>LaGEMPix in collaboration with TNO (6.0 x 8.0 cm(^2))</td>
</tr>
<tr>
<td>Sub-millimetre spatial resolution was not achievable!</td>
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</tbody>
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<table>
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<th>Charge readout</th>
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<tr>
<td>Matrix 4x4 or 5x5 Timepix chips</td>
</tr>
<tr>
<td>Very detailed pencil beam!</td>
</tr>
<tr>
<td>Matrix TFT-only (6.0 x 8.0 cm(^2))</td>
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<tr>
<td>Sub-millimetre spatial resolution achievable!</td>
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Muito obrigada! Thank you!

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