3.3. Microtomography of a biological object: a horsefly

The neutron radiography and tomography of a horsefly shown in Figs. 6 and 7 demonstrate the achievable contrast in neutron tomographical reconstruction of a biological sample. The efficient neutron counting capability of MCP/Timepix detector enables accurate quantitative measurements of absorption coefficient of different tissues existing within the sample. For example, some structure like a nerve formation behind the eyes can be easily seen separately from the rest of the eye and denser outer tissues of the fly.

4. Conclusions

The results of our high-resolution neutron radiography and microtomography experiments demonstrate the powerful capabilities of a neutron counting detector employing MCPs and a Timepix electronic readout. The high spatial resolution of this detector combined with high neutron detection efficiency offered by the latest generation of neutron-sensitive MCPs from Nova Scientific, Inc., and the absence of readout noise make these detectors quite attractive for a variety of neutron imaging applications where the performance of other more conventional detectors (e.g., scintillator screens and CCDs) is inadequate, simply due to limited neutron detection efficiency at high spatial resolutions, coupled with the presence of background noise. Although the spatial resolution of neutron imaging is certainly quite inferior to the sub-micrometer resolution of X-ray imaging, some unique features of neutron interactions with matter may provide complementary and occasionally unique information, concerning the inner structure of many interesting samples.
I. Applications of Position–Sensitive MCP Detectors

II. Existing Technologies to Make an MCP Position–Sensitive

III. Determining Position with Induced Signals

IV. Characterizing the Induced Signal with a Resistive Anode

V. Future Plans
Whether one is detecting photons, ions, or electrons inevitably one is concerned with the detection of electrons.

- We aim to develop a high resolution position-sensitive MCP–PMT (microchannel plate–photomultiplier tube) detector.
  - First step: develop a position-sensitive MCP detector
To develop a detector with:

- single-electron sensitivity
- sub-millimeter position resolution
- sub-nanosecond time resolution
- capability of resolving two spatially separated, simultaneous electrons
I. **Medicine**

Better time and position resolution would improve medical imaging techniques such as Time-of-Flight Positron Emission Tomography (PET).

http://www.oaimaging.com/procedures/alz_pet.html

www.cmis.riken.jp/english/howto/howto_pet01_en.html
II. Homeland Security/Border Control of Nuclear Materials

- MEGa-ray beam absorption techniques could detect a piece of U–235 smaller than 5 millimeters in less than 1 second.
- Improvements to time and position resolution are necessary for higher quality imaging and throughput.

III. Fundamental Science

- A common challenge faced in Time-of-Flight Mass Spectrometry occurs when two or more particles arrive simultaneously on a detector.

- Certain position-sensitive MCP detectors not only allow you to distinguish such events but allow the two particles to be resolved.

Applications of PS–MCP Detectors

Other applications include:

- Time–Resolved Fluorescence Lifetime Imaging Microscopy
- Three–Dimensional Atom Probe Techniques (cover story 3 weeks ago in C&EN)
- Time Correlated Single Photon Counting
- Cherenkov Ring Imaging in High Energy Physics
- And more!
MCP—Operating Principles


- The concept of the continuous channel electron multiplier was originally proposed in 1950.

- A microchannel plate is composed of millions of leaded glass tubes (2–10 μm in diameter) that can detect electrons, ions, and photons.
- Each channel acts as an independent secondary electron emitter.
- An applied voltage across the plate causes the initial electron to be cascaded with an amplification of $\sim 10^3–10^4$.
- Individual plates can be stacked to achieve a gain of $10^6–10^8$.
  - 2 MCPs $\rightarrow$ chevron
  - 3 MCPs $\rightarrow$ Z-stack

The simplest of the multi-anode systems consists of 4 anodes.

Each metal anode collects charge quickly, resulting in a fast signal.

Challenges to overcome include:
- charge buildup between anodes
- expense of separate readout electronics for each anode
- cross-talk between anodes
- image distortion

State-of-the-art systems consist of up to ~100 anodes.

Fraser, G. W. *Nuclear Instruments and Methods in Physics Research* 1984, 221, 115–130.
Cross-Strip Anode Approach

- Two orthogonal planes of parallel strips serve to detect position.
- The charge from the electron cloud is collected on several strips (approximately 5) for each axis and this allows for the accurate determination of the centroid of the event.
- Good spatial resolution ($<$10 $\mu$m FWHM) can be achieved with a lower MCP gain ($10^6$ electrons). Thus a Chevron MCP can be used, which will lead to less charge spreading between MCP plates and an extended lifetime of the detector.
- The main disadvantage is the expense of having separate readout electronics for each strip.

Resistive Layer Anode Approach

- Charge is readout at the 4 corners of the resistive anode.
- The centroid of the electron cloud can be determined by the relative charge of the signals collected at the 4 corners.
- The main advantage is the simplicity of the readout electronics.
- The approach is limited to low count rates (\(<100\) kHz). At higher count rates, multi-hit events corrupt the position information.

\[
X = \frac{Q_0 + Q_3}{Q_{total}} \quad \quad Y = \frac{Q_0 + Q_1}{Q_{total}}
\]

where \( Q_{total} = Q_0 + Q_1 + Q_2 + Q_3 \)
Helical Delay Line Approach

- Position is determined by taking the temporal difference at each end of the delay line with respect to a signal on the back of the MCP.
- The main disadvantage is signal dispersion—a consequence of the delay line.

Advantages include:

a) low electronic cost that makes tiling large areas feasible
b) insensitivity to quality and uniform gain across the MCP
c) ability to distinguish multi-hit events at high count rates (10 MHz)

- All of existing techniques utilize charge centroiding to achieve optimal resolution.
- This limits the ability of the detector to measure particles at small relative distances.
- This fundamental limitation can be overcome by use of the induced signal approach.
Concept of Induced Signal

- **Microchannel Plate**
- **Z-Stack**
- **10^7 – 10^8 Electrons**
- **X – Y Wire Plane**
- **Anode**
- **Single Electron or Photon**

Voltage vs. Time
① An $\alpha$-particle from a radioactive source strikes the electron emission foil.

② A silicon detector provides part of a coincidence measurement to reject background events.

③ The ejected electron is accelerated towards a MCP Z-stack, where it is amplified to $10^7$–$10^8$ electrons.

④ The electron cloud induces a signal as it passes by the sense wire plane.

⑤ The electron cloud is collected on an anode.
- Digitize signals with 2 GS/s waveform digitizer.
- The induced signals have the expected, bipolar shape, where the zero-crossing point corresponds to the passage of the charge cloud past the sense wire planes.
- Induced signals are 30x smaller than the anode signal, so each induced signal is amplified by a LNA-530 low noise amplifier.
- Cross-talk from the anode is of the order of 2–3%.

① Inserted a mask at the front of the MCP to determine the position resolution.

② Arrival at the two ends of the delay line relative to the anode has a characteristic anti-correlated behavior.

③ Projection of the two-dimensional spectrum allows for extraction of the position resolution.

Raw Position Resolution = 526 μm (FWHM)

To improve the position resolution, the following signal processing was performed:

1. Reject frequencies above 150 MHz by use of fast Fourier transform (FFT) filtering
2. Double pulse rejection (DPR)
3. Reject transition times < 3 ns
   (where transition time = time between minima and maxima peak)

<table>
<thead>
<tr>
<th>Step</th>
<th>FWHM (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>526</td>
</tr>
<tr>
<td>FFT</td>
<td>482</td>
</tr>
<tr>
<td>FFT + DPR</td>
<td>475</td>
</tr>
<tr>
<td>FFT + DPR + Transition Time Selection</td>
<td>466</td>
</tr>
</tbody>
</table>

Path Forward:

☑ A proof of concept for the induced signal has been demonstrated.

☑ A position resolution of 466 μm has been achieved.

Path Forward:

☐ Develop an efficient means for testing detector designs.

☐ Determine the optimal resolution possible using the induced signal approach (both with centroiding and non-centroiding).

☐ Characterize limitations of the induced signal approach.
Wire Winder

Constructed and commissioned an efficient, compact wire winder dedicated to the project with the following properties:

- Active area: 25 cm x 28 cm
- Minimum wire spacing: 200 μm
- Au–W wire diameter used: 25 μm

50 wires were wound onto this sense wire plane with a pitch of 1 mm.
Vacuum Test Station

Constructed and commissioned a vacuum test station with the following properties:

- Oil free
- Base vacuum = $8.9 \times 10^{-8}$ torr
- Time from pumpdown to testing = 4 hrs
- Efficient insertion of detector by an individual
One puzzle in characterizing detector v1.0 was the variation in transition times (3–12 ns).

A sense wire plane was fabricated with the individual readout of sense wires.

Single Wire Transition Time = 3–4 ns

Variation in the transition time of the induced signal was due to the delay line.
In transitioning from detector v1.0 to detector v2.0,

- The method to generate electrons is the same.
- The silicon detector was exchanged for a scintillator photomultiplier tube assembly to have larger coverage.
- The stainless steel anode was exchanged for a resistive anode to allow for the characterization of induced signals using resistive-anode position.
A biased conduit minimizes the number of electrons ejected from the conduit initiated by the $\alpha$-particles.

### Detector Configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Count rate (cps/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Current of MCP (Bkgd)</td>
<td>5</td>
</tr>
<tr>
<td>Bkgd + Conduit (0V)</td>
<td>14</td>
</tr>
<tr>
<td>Bkgd + Conduit (0V) + Alpha Source</td>
<td>1700</td>
</tr>
<tr>
<td>Bkgd + Conduit (+1000V) + Alpha Source</td>
<td>49</td>
</tr>
</tbody>
</table>

### Detector Region

<table>
<thead>
<tr>
<th>Region</th>
<th>Bias (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Emission Foil</td>
<td>-300</td>
</tr>
<tr>
<td>Photomultiplier Tube</td>
<td>-1700</td>
</tr>
<tr>
<td>Conduit</td>
<td>+1000</td>
</tr>
<tr>
<td>Front of the MCP Stack</td>
<td>0</td>
</tr>
<tr>
<td>Back of the MCP Stack</td>
<td>+2880</td>
</tr>
<tr>
<td>Resistive Anode</td>
<td>+3184</td>
</tr>
</tbody>
</table>
1. Inserted a mask at the entrance of the MCP in order to determine the position resolution.

2. Calculated the position using:

\[
X = \frac{Q_0 + Q_3}{Q_{\text{total}}} \quad Y = \frac{Q_0 + Q_1}{Q_{\text{total}}}
\]

where \( Q_{\text{total}} = Q_0 + Q_1 + Q_2 + Q_3 \)
Background events are eliminated by gating on the 2-dimensional spectrum of charges at opposite corners.

Events of similar MCP charge are selected by applying a tight gate to the MCP pulse height distribution.
Detector v2.0 Position Resolution

Raw Position Spectrum

Gated Position Spectrum
① Performed Gaussian fit to determine slit characteristics (centroid, width). $\chi^2$/DOF typically ranges from 0.5 to 1.1.

② Performed a linear calibration to establish a conversion between a.u. and mm.
Detector v2.0 Position Resolution

$R_s = 277 \mu m \pm 5 \mu m$
## Detector v2.0 Position Resolution

How does the resistive-anode resolution compare with other approaches?

<table>
<thead>
<tr>
<th>Illuminating source</th>
<th>FWHM Resolution (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Light</td>
<td>100 – 200†</td>
</tr>
<tr>
<td>b) $^{63}$Ni negatron ($\beta^-$) emitter</td>
<td>250</td>
</tr>
<tr>
<td>c) Electron ejected from foil by $\alpha$-particles or $^{86}$Kr beam</td>
<td>588</td>
</tr>
</tbody>
</table>

† A resolution of 50 μm is achieved with a 5 stack MCP (Chevron + Z-Stack)

- When generating electron avalanches with light, one has a significantly larger S/B and the illuminating particles have a well defined trajectory.
- Detection of a single electron represents the ultimate in sensitivity.

---

Future Plans

☑ Develop an efficient means for testing detector designs.

☐ Determine the optimal resolution possible using the induced signal approach (both with centroiding and non-centroiding).

☐ Characterize limitations of the induced signal approach.

To realize these goals:

① A resistive anode will be used to characterize the position dependence of induced signals.

② A new differential readout method for the induced signal approach will be tested.
A. Improve the resistive–anode resolution

- Currently, signal amplitude is the only information utilized to calculate position.

- But the entire signal contains information.

- Will a joint use of pulse shape and pulse amplitude information improve the resistive–anode resolution?

- To make use of the entire signal, we intend to digitize the signal.
New Shaping Amplifier

B. Develop a high quality shaping amplifier

A new shaper has been designed, and is undergoing construction by Electronic Instrument Services (EIS).

Features include:

a) 8 independent channels
b) Baseline restore circuit
c) Computer controlled (USB):
   ▪ Shaping time (1–8 μs)
   ▪ Gain
      - coarse (8 bit)
      - fine (12 bit)
   ▪ Pole-zero (12 bit)
   ▪ Polarity
C. Characterizing the induced signal with the resistive anode

- Different trajectories lead to different induced signals on the sense wires planes.
- These signals will be digitized.
- Induced signals will be characterized by correlation with the position of the resistive anode.
Implementing a Differential Readout System

D. Differential/readout analysis of the induced signals

- We have a new design of sense wire harps and delay boards that allows for an independent readout of even and odd wires.

- Readout of the even and odd wires allows for differential measurement of the induced signal.
D. Differential/readout analysis of the induced signals

- The differential readout should be sensitive to small differences in induced signals produced on adjacent wires, and consequently should provide a significant improvement to the resolution.

  a) Simulations suggest a factor of 5 improvement to position resolution.

  b) Noise common to both the even and odd wires will be rejected by use of the differential readout.

A \hspace{1cm} B
\hspace{1cm} 1 \text{ mm pitch}

Implementing a Differential Readout System

\[
\begin{align*}
\text{Induced charge on wire (mC)}
\end{align*}
\]

\[
\begin{align*}
\text{Distance cloud - wire A (μm)}
\end{align*}
\]

Cloud Wires
100 μm • A ○ B
200 μm • A ○ B
400 μm △ A △ B
D. Differential/readout analysis of the induced signals

- Much of the variation in transition times of the induced signal was due to the delay line, so a new delay line was implemented that eliminates meander geometry (by utilizing 10 layer printed circuit board).

- Other features of the design include:
  a) Sense wire harp and delay boards are decoupled, which allows for testing of multiple delay board designs.
  b) A more compact design, which goes toward the goal of an MCP–PMT detector.

Characterization of new delay boards will commence soon!
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