Sensing the Position of a Single Electron Using Induced Signals

Blake Wiggins
Motivation

- Good spatial information is essential for quality imaging.
  - Good time information is also essential in certain applications (e.g. positron emission tomography).

- Whether detecting photons, ions, or neutrons inevitably one is concerned with the detection of electrons.

- We aim to develop a detector with:
  1) single-electron sensitivity
  2) sub-millimeter spatial resolution
  3) sub-nanosecond time resolution
  4) the capability of resolving two spatially separated, simultaneous electrons

- We are going to focus on microchannel plate (MCP) detectors, which are a type of electron amplifier.

I. Overview of existing position-sensitive MCP technologies

II. Development phase- What spatial resolution can be achieved with:
   i. Resistive anode technology
   ii. Induced signal approach

III. Application phase
   i. Neutron radiography
   ii. Beam imaging
Types of PS-MCP Detectors

- Multi-Anode
- Cross-Strip Anode
- Medipix2 CMOS
- Resistive Anode
- Helical Delay Line
- Induced Signal
- Charge Sensing Technology
- High Speed Digitization
1) High gain
2) Fast temporal response
3) Sensitive to charged particles, uv radiation, X-rays, and neutrons
4) Compact size
5) Stable operation even in high magnetic fields
6) Low power consumption

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Detection Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td></td>
</tr>
<tr>
<td>0.2 - 2 keV</td>
<td>50-85</td>
</tr>
<tr>
<td>2 - 50 keV</td>
<td>10-60</td>
</tr>
<tr>
<td>Positive ions</td>
<td></td>
</tr>
<tr>
<td>0.5 - 2 keV</td>
<td>5-85</td>
</tr>
<tr>
<td>(H(^+), He(^+), A(^+))</td>
<td>2 - 50 keV</td>
</tr>
<tr>
<td>50 - 200 keV</td>
<td>4-60</td>
</tr>
<tr>
<td>Thermal Neutrons</td>
<td></td>
</tr>
<tr>
<td>0 - 25 meV</td>
<td>14-78</td>
</tr>
<tr>
<td>uv Radiation</td>
<td></td>
</tr>
<tr>
<td>300 - 1100 Å</td>
<td>5-15</td>
</tr>
<tr>
<td>1100 - 1500 Å</td>
<td>1-5</td>
</tr>
<tr>
<td>Soft X-rays</td>
<td></td>
</tr>
<tr>
<td>2 - 0.50 Å</td>
<td>5-15</td>
</tr>
<tr>
<td>Diagnostic X-rays</td>
<td></td>
</tr>
<tr>
<td>0.12 - 0.20 Å</td>
<td>1</td>
</tr>
</tbody>
</table>

P. Schagen, Advances in image pick-up and display 1, 69 (1974).  
W. J. Williams, M.S. Thesis, Oregon State University, Corvallis, OR (2013).
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 $10^3 - 10^4$.

Individual plates can be stacked to achieve a gain of $10^6 - 10^8$.

- 2 MCPs = chevron
- 3 MCPs = Z-stack
14 mm x 14 mm area (3 sides abuttable)
64k pixels each measuring 55 μm x 55 μm
At 100 MHz/cm², 55 μm resolution reported
At 2–3 MHz, ~15 μm resolution reported
Simultaneous events can be detected (up to ~25k).
Low noise (<100e⁻)
Very uniform readout (lithographic processing) – no image distortions.

Price and small active area prohibits tiling a large area.

https://www.gla.ac.uk/schools/physics/research/researchimpact/headline_300603_en.html
### Summary of Existing PS-MCP Detectors

<table>
<thead>
<tr>
<th>PS-MCP Detector</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Anode</td>
<td>Can distinguish multi-hit events</td>
<td>Cost of readout electronics</td>
</tr>
<tr>
<td></td>
<td>Spatial resolution 25-50 µm</td>
<td>Cross-talk between anodes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistive Anode</td>
<td>Simplicity of readout</td>
<td>Limited to count rates &lt;100kHz (large RC)</td>
</tr>
<tr>
<td></td>
<td>Low power consumption</td>
<td>Cannot distinguish multi-hit events</td>
</tr>
<tr>
<td></td>
<td>Spatial resolution 50 – 100 µm</td>
<td></td>
</tr>
<tr>
<td>Cross-Strip Anode</td>
<td>Spatial resolution 10 – 30 µm</td>
<td>Cost of readout electronics</td>
</tr>
<tr>
<td></td>
<td>Can distinguish multi-hit events</td>
<td>High power consumption</td>
</tr>
<tr>
<td></td>
<td>Spatial resolution 10 – 30 µm</td>
<td></td>
</tr>
<tr>
<td>Helical Delay Line</td>
<td>Spatial resolution 85 – 100 µm</td>
<td>Fragility of single wound wire</td>
</tr>
<tr>
<td></td>
<td>Can tile large areas</td>
<td>Attenuation and dispersion of signal in delay line</td>
</tr>
<tr>
<td></td>
<td>Simplicity of readout</td>
<td></td>
</tr>
<tr>
<td>Medipix2/Timepix</td>
<td>Spatial resolution 15 – 55 µm</td>
<td>High cost</td>
</tr>
<tr>
<td></td>
<td>Uniform spatial response</td>
<td>Small active area</td>
</tr>
<tr>
<td></td>
<td>Low power consumption (1 W/chip)</td>
<td>Cost prohibits tiling large area</td>
</tr>
</tbody>
</table>
Resolution vs. Cost for PS-MCP Detectors

Detector Area = 1256 mm²

- RA (3 MCPs)
- HDL
- I RA (5 MCPs)
- XS
- MED2

Cost (k USD)
There is no ideal detector for every application. Compromises will always be found.

The resistive anode is limited by count rates exceeding 100 kHz and the Medipix2 is expensive and cannot tile large areas easily.

The induced signal approach is a cost effective and scalable alternative.

Detector Area = 1256 mm$^2$
I. Overview of existing position-sensitive MCP technologies

II. Development phase - What spatial resolution can be achieved with:
   i. Resistive anode technology
   ii. Induced signal approach

III. Application phase
   i. Neutron radiography
   ii. Beam imaging
A spatial resolution of 100 – 200 μm FWHM is typically achieved for a Z-Stack MCP.
Start by using conventional electronics (charge sensing amplifiers, shaping amplifiers, peak sensing ADCs).

\[ Y = \frac{Q_0 + Q_1}{Q_0 + Q_1 + Q_2 + Q_3} \]

\[ X = \frac{Q_0 + Q_3}{Q_0 + Q_1 + Q_2 + Q_3} \]

- The active area of the MCP is evident.
- All slits in the mask are visible (100 μm wide with a 4.2 – 4.5 mm pitch).
- There is a non-linear distortion at the edges of the RA.

Using only charge division, resolution = 157 μm FWHM

A clear correlation is evident between the signal risetime and $Y_{\text{position}}$.

A clear correlation is evident between the signal risetime and $Y_{\text{position}}$.

- Peaks correspond to slits in the mask.
- Use of the signal risetime in addition to the charge-division method results in a significantly improved resolution.

Using pulse shape analysis, resolution = 64 μm (FWHM)

I. Overview of existing position-sensitive MCP technologies

II. Development phase- What spatial resolution can be achieved with:
   i. Resistive anode technology
   ii. Induced signal approach

III. Application phase
   i. Neutron radiography
   ii. Beam imaging
A single electron is amplified to a cloud of $10^7$-$10^8$ electrons, which is sensed by a wire plane (2 orthogonal planes can provide 2D).

Wires in the sense wire plane have a 1 mm pitch and are connected to taps on a delay line.

Position is related to the time difference between the signals arriving at the ends of the delay line.

Digitize signals with 2 GS/s waveform digitizer.
The induced signals have the expected, bipolar shape.
Induced signals are amplified by x30 low noise amplifier (LNA-530).
Signals can be improved with use of an FFT filter.

Although the induced signals are 10x smaller than direct collection, does the unique induced signal allow for extraction of good spatial resolution?

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

 Non-linear response at the edges correspond to a signal propagating the full length of the delay line.

 Peaks correspond to slits in the mask.

Photograph of the mask inserted at the front of the MCP to determine the position resolution.

Projection of the two-dimensional spectrum (time correlation) allows for extraction of the position resolution.

Raw Position Resolution = 526 μm FWHM
Cleaned Position Resolution = 466 μm FWHM
Constructed and commissioned a vacuum test station:

- Oil free
- Base vacuum = $4 \times 10^{-8}$ torr
- Time from pumpdown to testing = 4 hrs
- Efficient insertion of detector by an individual

Constructed and commissioned an efficient, compact wire winder:

- Active area : 25 cm x 28 cm
- Minimum wire spacing : 200 μm
- Au-W wire diameter used : 25 μm
Transitioning from MCP-SW v1.0 to v2.0

- Larger PMT for higher coincident rates
- Compact design
- Decoupled sense wires from delay board


MCP-SW v2.0 Spatial Resolution

- MCP-SW distance: 12.7 mm → 2.9 mm
- Mask: 50 μm wide slits, horiz. oriented, 4.2 - 4.5 mm pitch

Raw 1D Spectrum
- Data acquired using 10 GS/s digitization
- FFT applied to signals
- All slits in mask are evident
- Average resolution = 276 μm

Improvement to the Induced Signal Approach

With digital signal processing, resolution = 98 µm FWHM
## Improvement to the Induced Signal Approach

### Conditions and Results

<table>
<thead>
<tr>
<th>Condition</th>
<th>FWHM (μm)</th>
<th>% Rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>276</td>
<td>0</td>
</tr>
<tr>
<td>FFT</td>
<td>228</td>
<td>0</td>
</tr>
<tr>
<td>FFT + ΣDelay</td>
<td>202</td>
<td>20</td>
</tr>
<tr>
<td>FFT + ΣDelay + Qwide</td>
<td>168</td>
<td>62</td>
</tr>
<tr>
<td>FFT + ΣDelay + Qtight</td>
<td>136</td>
<td>80</td>
</tr>
<tr>
<td>FFT + ΣDelay + An &lt; -190mV</td>
<td>119</td>
<td>71</td>
</tr>
<tr>
<td>Intrinsic (FFT + ΣDelay + An &lt; -190mV)</td>
<td>98</td>
<td>71</td>
</tr>
</tbody>
</table>

Experiment parameters:

\[ V_{\text{Foil}} = -1000V \]
\[ \Delta V_{\text{MCP-Z}} = +2528V \]
\[ V_{\text{SW}} = +2755V \]
\[ V_{\text{An}} = +2805V \]
\[ G_{\text{Amp}} = 30 \]

Improvement to the Induced Signal Approach

98 μm FWHM was achieved with 10 GS/s.

But what can be achieved with:
a) 5 GS/s? 159 μm FWHM
b) 2 GS/s? 169 μm FWHM

<table>
<thead>
<tr>
<th>Condition</th>
<th>FWHM (μm)</th>
<th>% Rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>276</td>
<td>0</td>
</tr>
<tr>
<td>FFT</td>
<td>228</td>
<td>0</td>
</tr>
<tr>
<td>FFT + ΣDelay</td>
<td>202</td>
<td>20</td>
</tr>
<tr>
<td>FFT + ΣDelay + Qwide</td>
<td>168</td>
<td>62</td>
</tr>
<tr>
<td>FFT + ΣDelay + Qtight</td>
<td>136</td>
<td>80</td>
</tr>
<tr>
<td>FFT + ΣDelay + An &lt; -190mV</td>
<td>119</td>
<td>71</td>
</tr>
<tr>
<td>Intrinsic (FFT + ΣDelay + An &lt; -190mV)</td>
<td>98</td>
<td>71</td>
</tr>
</tbody>
</table>

Simulations for the Induced Signal Approach

Steps:

1) Simulate bipolar signal by differentiating a Gaussian
   a) bipolar signal has Amp = 30 mV p-p and transition time = 4 ns

2) Generate $Y_{position}$ randomly

3) Account for attenuation of delay line

4) Add Amplifier noise to signals
   a) noise added does not include capacitive coupling with anode or MCP

5) Analyze signals in the same way as data
Simulations for the Induced Signal Approach

- Simulations predict a raw resolution 280 μm → consistent with measurement of 276 μm.
- Simulations suggest using half the delay length → raw resolution = 150 μm.
- Simulations suggest best resolution converges at ~76 μm and can be achieved by:
  - decreasing amplifier noise by 4.
  - decreasing attenuation in delay line.
Implementing 0.5 ns/tap Delay Boards

Can the induced signal approach be improved by going from 1 ns/tap to 0.5 ns/tap delay boards (halving the total delay length)?

- There is a clear improvement to S/N for typical digitized waveforms.
- The average resolution does not improve.
- The linearity is improved from ± 2% to ± 0.5%.
I. Overview of existing position-sensitive MCP technologies

II. Development phase - What spatial resolution can be achieved with:
   i. Resistive anode technology
   ii. Induced signal approach

III. Application phase
   i. Neutron radiography
   ii. Beam imaging
Characteristics of LENS:

- 13 MeV proton linac driver
- $^9$Be(p,n) reaction to produce neutrons
- Thermalization (polyethylene, solid CH$_4$ at 6.5K)
- $1 \times 10^5$ n s$^{-1}$ cm$^{-2}$ neutron flux
- $2.7 - 5 \times 10^4$ n s$^{-1}$ cm$^{-2}$ neutron flux on SANS beamline

First Neutron Radiographs


$^{10}\text{B} + \text{n} \rightarrow ^{11}\text{B}^*$

$^{7}\text{Li}^*$

94%

478 keV $\gamma$

$^{7}\text{Li}$

6%

$^{7}\text{Li}$

Outline of MCP-Z (40 mm) and MCP-B (25 mm) is evident

3 slits in our mask are clearly evident

Peak/Background is only ~2

Non-uniform intensity fluctuations are present

This DAQ was limited to 300 cps (near MCP background ~100 cps)
An Improved DAQ for Neutron Imaging

Developed new DAQ that can acquire data at rates up to 200k cps (limited to 300 cps before) and incorporates a TDC (background reduction).

With 2 GS/s digitization, a spatial resolution of 169 μm can be achieved with electrons.

An Improved DAQ for Neutron Imaging

GUI developed by Dave Bancroft at EIS.
40 mm MCP-Z outline and 25 mm MCP-B outline clearly visible
355 μm wide slits, 1 mm start holes, and 0.5 mm key hole clearly visible
Measured Resolution = 329 μm FWHM
Intrinsic Resolution = 216 μm FWHM (169 μm FWHM with electrons at 2GS/s)

### Improved Neutron Imaging

#### FWHM (μm) and % Rejected

<table>
<thead>
<tr>
<th>Step</th>
<th>FWHM (μm)</th>
<th>% Rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>676</td>
<td>0</td>
</tr>
<tr>
<td>FFT</td>
<td>627</td>
<td>0</td>
</tr>
<tr>
<td>FFT+ Rotation (Rot)</td>
<td>607</td>
<td>0</td>
</tr>
<tr>
<td>FFT+ Rot + ΣDelay (ΣD)</td>
<td>595</td>
<td>8</td>
</tr>
<tr>
<td>FFT + Rot + ΣD+ NTOF</td>
<td>535</td>
<td>93</td>
</tr>
<tr>
<td>FFT + ΣD + NTOF + Thr&gt;6mV</td>
<td>329</td>
<td>99</td>
</tr>
<tr>
<td>Intrinsic (ΣD + NTOF + Thr&gt;6mV)</td>
<td>216</td>
<td>99</td>
</tr>
</tbody>
</table>


---

![Graph showing counts and amplitude over time](image-url)
I. Overview of existing position-sensitive MCP technologies

II. Development phase - What spatial resolution can be achieved with:
   i. Resistive anode technology
   ii. Induced signal approach

III. Application phase
   i. Neutron radiography
   ii. Beam imaging
An ExB MCP detector is an excellent beam imaging detector because it introduces the minimum amount of material into beam path and is compact.

- Anode strips are 250 μm wide with a 75 μm inter-strip isolation.
- Anode area is approximately 3 cm x 3 cm.
- Couple delay lines from MCP-SW v2.0 to extract position.

Resolution = 94 μm FWHM
Position is calibrated using rotated time correlation and known 2mm spacing.

The resolution worsens as move to the location on MCP furthest from the foil.

Association between resolution and position can be understand using SIMION.

# Resolution Summary for MCP-ExB Detector

![Diagram showing the MCP-ExB detector setup.](image)

* 355 μm wide slits, 2 mm pitch

<table>
<thead>
<tr>
<th>Step</th>
<th>FWHM (μm)</th>
<th>% Rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>520</td>
<td>0</td>
</tr>
<tr>
<td>FFT</td>
<td>488</td>
<td>0</td>
</tr>
<tr>
<td>FFT + ΣDelay</td>
<td>482</td>
<td>8</td>
</tr>
<tr>
<td>FFT + ΣDelay + &gt;50mV</td>
<td>413</td>
<td>66</td>
</tr>
<tr>
<td>Intrinsic ( FFT + ΣDelay + &gt;50mV )</td>
<td>334</td>
<td>66</td>
</tr>
</tbody>
</table>

Collaborators at ND will use an ExB detector in their study of $(\alpha, \gamma)$ reactions of astrophysical importance after the St. George Recoil Separator.

Figures courtesy of Luis Morales and Zach Meisel

Collaborators at MSU will use an ExB detector to track the beam before it reaches their AT-TPC.

Figures courtesy of Kyle Brown and Bill Lynch
### Summary: Position-Sensitive MCP Detectors

<table>
<thead>
<tr>
<th>Induced Signal Approach</th>
<th>Spatial Resolution FWHM (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Gen Induced Signal</td>
<td>466</td>
</tr>
<tr>
<td>2nd Gen Induced Signal with DSP (Single Electron)</td>
<td>98</td>
</tr>
<tr>
<td>2nd Gen Induced Signal for Slow Neutron Radiography</td>
<td>216</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Auxiliary Developments</th>
<th>Spatial Resolution FWHM (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive Anode</td>
<td>157</td>
</tr>
<tr>
<td>Resistive Anode- Risetime Analysis</td>
<td>64</td>
</tr>
<tr>
<td>Multi-Strip Anode (Delay Line Readout)</td>
<td>94</td>
</tr>
<tr>
<td>ExB with Multi-Anode for Beam Imaging</td>
<td>334</td>
</tr>
</tbody>
</table>
Resolution vs. Cost for PS-MCP Detectors

Detector Area = 1256 mm²

- RA (3 MCPs)
- SW
- HDL
- IU RA (3 MCPs)
- I RA (5 MCPs)
- XS
- MED2

Cost (k USD)

FWHM (μm)
My Advisor:
Prof. Romualdo de Souza

Nuclear Chemistry Group:
Sylvie Hudan
Jacob Huston
James Johnstone
Amrit Parihar
Justin Vadas
Tyler Werke
Aubrey Whiteman

Collaborators:
Prof. David Baxter (IUB)
Keith Solberg (IUB)
Luis Morales (ND)
Prof. Manoel Couder (ND)

My Committee:
Prof. Reilly, Prof. Hieftje, Prof. Jacobson

Past Nuclear Chemistry Group:
Zarya de Souza
Eric Richardson
John Schmidt
Varinderjit Singh
Davinder Siwal
Tracy Steinbach

Acknowledgements

Mechanical Instrument Services
Electronics Instrument Services
(esp. Andy Alexander and Dave Bancroft)

LENS Staff:
Tom Rinckel
Jak Doskow

Imaged with neutrons

National Nuclear Security Administration
Award No. DE-NA0002012

Blake Wiggins
Indiana University
Acknowledgements

And a special thanks to...

my lovely wife...

and my friends.