PImMS
Pixel Imaging Mass Spectrometry sensor

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Outline

- Context and requirements for PlmMS sensors
- PlmMS1 and PlmMS2 sensors
  - Specifications, design and operation
  - PlmMS1 application results
  - PlmMS2 application results
- Summary and future work
Context – Imaging Mass Spectrometry

Combines time-of-flight mass spectrometry with 2D ion imaging – measuring time and x-y position

Basics of time-of-flight MS:

1) Molecules are dissociated and ionised – often with lasers

2) The ions are accelerated in an electric field created with charged plates = “ion optics”

3) Their time of arrival is proportional to their mass-to-charge ratio (m/z)

4) Ions arrive at a micro-channel plate (MCP), generating electron showers. Often these are converted to photons with a phosphor screen.

A time-of-flight mass spectrometer
Context – Imaging Mass Spectrometry

Depending on how the ion optics are biased, we can image:

**The velocities of the ions**
- “velocity map imaging”
- Learn about reaction dynamics

**The positions of the ions**
- “spatial imaging”
- Can study tissue samples
Context – timing structure of data

Mass spectrometry and the International Linear Collider have a similar time structure of data:

- **MS**: $O(50 - 200 \ \mu s)$ duration @ 20 Hz
- **ILC**: 868 $\mu$s duration @ 5 Hz

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**Mass spectrometry timing**

- 50ms
- $O(50 - 200 \ \mu s)$

**ILC timing**

- 200ms
- 308 ns
- 868 $\mu$s
- 2820x
## Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>Self-triggering</td>
<td>Avoid needing prior knowledge of time of arrival of ions</td>
</tr>
<tr>
<td>Time-stamping and thresholding</td>
<td>Record the time of arrival of significant pulses of light (or electrons) as a digital timestamp</td>
</tr>
<tr>
<td>Storage of multiple timestamps</td>
<td>Avoid the ‘loss’ of a pixel after being hit once</td>
</tr>
<tr>
<td></td>
<td>Optimised science versus pixel size constraints to arrive at 4 timestamps per pixel</td>
</tr>
<tr>
<td>Time resolution</td>
<td>Initial spec: 50ns time bins to gain sufficient mass resolution</td>
</tr>
<tr>
<td></td>
<td>Updated spec after improvements to mass spectrometers: 12.5ns time bins</td>
</tr>
<tr>
<td>Length of experimental cycle</td>
<td>The period when ion data should be recorded is generally 50 - 200µs long</td>
</tr>
<tr>
<td>Readout frame rate</td>
<td>10 Hz minimum, higher desirable</td>
</tr>
<tr>
<td></td>
<td>Based on repetition rate of commonly-used lasers</td>
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</tbody>
</table>

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# PlmMS sensors: specifications

<table>
<thead>
<tr>
<th>Spec</th>
<th>PlmMS1</th>
<th>PlmMS2</th>
</tr>
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<tbody>
<tr>
<td>Array size</td>
<td>72 x 72 pixels</td>
<td>324 x 324 pixels</td>
</tr>
<tr>
<td>Active area</td>
<td>5mm x 5mm</td>
<td>22.7mm x 22.7mm</td>
</tr>
<tr>
<td>Sensor size</td>
<td>7mm x 7mm</td>
<td>25.4mm x 26.1mm</td>
</tr>
<tr>
<td>Pixel size</td>
<td>70µm x 70µm</td>
<td>70µm x 70µm</td>
</tr>
<tr>
<td>Pixel threshold trim</td>
<td>4 trim bits + 1 masking bit per pixel</td>
<td>Four 12-bit registers per pixel</td>
</tr>
<tr>
<td>Timestamp storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test pixel</td>
<td>1 test pixel with access to inner analogue nodes</td>
<td></td>
</tr>
<tr>
<td>Time resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(timecode period)</td>
<td>Initial spec: 50ns</td>
<td>Simulation target: 25ns</td>
</tr>
<tr>
<td>Current performance</td>
<td></td>
<td>12.5ns timecode period</td>
</tr>
<tr>
<td>Substrate</td>
<td>5µm epi</td>
<td>5µm epi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18µm high-resistivity epi</td>
</tr>
</tbody>
</table>
PlmMS pixel

![Diagram of PlmMS pixel](image)

- **Collection Diodes**
- **Pre-Amplifier**
- **Shaper**
- **Comparator Trim Block**
- **Comparator**
- **Digital Control Logic**
- **Pixel Memories 12 bits each**
  - Memory 1
  - Memory 2
  - Memory 3
  - Memory 4

**Analogue Readout**
- vD
- vPA
- vS1
- vS2
- vS
- vC1
- vC2
- DAC
- vTh1
- vTh2
- vTr1
- vTr2

**Digital Readout 12 bits**

**Digital Timecode 12 bits**

**Pixel Memories 12 bits each**

![Graphs of vD, vPA, vS, vC, and vO over time](image)
Pixel operation

diode

preamplifier

shaper

comparator inputs

hit indicator

timecode

memory 1

memory 2
Pixel layout

- 615 transistors per pixel
- Process: 0.18µm CMOS INMAPS
  (Isolated N-Well Monolithic Active Pixel Sensor)
PlmMS sensors: overview

**PlmMS1**

- Timecode Distribution
- Test Pixel @ (3, 2)
- 72 x 72 Pixel Array
- Sense Amplifiers
- Readout Circuit
- Analogue Output Path

**PlmMS2**

- Timecode Generation (Counter)
- Test Pixel @ (3, 2)
- 324 x 324 Pixel Array
- Trim and row control
- Trim readback + row control
- Sense Amplifiers
- Readout Circuit
- Analogue Output Path
- Bias DACs
Readout: camera

- USB control and readout
- F-mount SLR lens
- C-mount SLR lens also possible – delivers more light to sensor

- Cooling system based on copper finger and Peltier device
- Connection for nitrogen/dry air flushing
Application results
Coincidence imaging

- Here bromine gas ($\text{Br}_2$) is dissociated. By switching the polarity of the ion optics, first the electrons are imaged, then the ions.
- (a) shows the mass spectrum including $^{79}\text{Br}^+$ and $^{81}\text{Br}^+$
- (b) shows the mass intersections for the electrons and Br ions
- (c) zooms in on the two isotopes, $^{79}\text{Br}^+$ and $^{81}\text{Br}^+$

Spatial imaging

- This is imaging the mass spectrum over a 2D surface.
- Materials used: lines of Auramine O (yellow) and Rhodamine 590 (red)
- The samples produced 10 mass peaks in all. 5 are highlighted here.
- Data taken at 25ns time resolution
- Demonstrates multi-mass imaging

Coulomb Explosion Imaging

- Using PlmMS to record images on Henrik Stapelfeldt’s coulomb explosion rig
- Acknowledgements: Aarhus: Henrik Stapelfeldt, Lauge Christensen, Jens Nielsen
- Oxford: Craig Slater, Alexandra Lauer, Sophie Blake

- A biphenyl molecule is aligned using a 1064 nm, 10 ns pulse, linearly polarised (from a Nd:YAG laser, 20 Hz)
- It is then ionised using an 800 nm, ~30 fs probe pulse (amplified Ti:Sapphire laser)
- Stripped of valence electrons, the molecule breaks up due to electrostatic repulsion, termed a coulomb explosion

Coulomb Explosion Imaging 2

Parallel 1D alignment and Coulomb explosion imaging
Coulomb Explosion Imaging 3

Perpendicular 1D alignment and Coulomb explosion imaging
Neutron detection

- Daniel Pooley of ISIS’ Neutron Detectors Group is developing a neutron detector based on PlmMS, working with Jason Lee (Oxford Chemistry)
- Gadolinium is thinly sputtered onto the surface of PlmMS (4µm) which creates showers of electrons immediately above the pixel array
- Here are early results using a cadmium mask to demonstrate neutron sensitivity:

![Diagram of neutron detection setup](image)

*Not to scale*
Imaging two materials with PlmMS2 (GP2)

Cu

Fe

DE Pooley, JWL Lee
Neutron tomography – assorted metal
Summary and future work

- PImMS is a self-triggered time-stamping sensor.
- Initially designed for imaging mass spectrometry, it has also been successfully applied to neutron imaging.
- PImMS1 is producing science in a variety of chemistry applications.
- PImMS2 is under development as a neutron imaging sensor.
- PImMS2 is currently being commissioned for chemistry work – calibration is under development.
- Once PImMS2 calibration is established, much interesting sensor characterisation becomes possible.
Thank you for your attention. Questions?

The PImMS Collaboration

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Backup material
Requirements: self-triggering

- Proof of concept experiments with a fast-framing camera: multiphoton fragmentation of dimethyldisulfide (images recorded in 2008 using a Dalsa Zenith CCD camera).

- Required prior knowledge of timing of mass peaks, programming the framing for the known time of arrival of each peak.

Requirements: multiple timestamps

- Want a fast sensor, flexible to analyse any mass spectrum
- Sparse events $\rightarrow$ consider time-stamping approach
- To record both early and late ions, need multiple memories. How many? Simulate:
Requirements: timing resolution

- Initial spec for time resolution: 50ns
- Updated spec, based on our significant progress in mass spectrometer timing, is to distinguish ions with a mass difference of 1 Dalton over a wide range of masses.
- This gives an updated target spec of 12.5ns

\[
\frac{m}{\Delta m} \approx \frac{t}{2\Delta t}
\]

\[
\Delta t = \frac{t}{2m}
\]

\[
\begin{align*}
\Delta t & \approx 25\text{ns} \\
\Delta t & = 12.5\text{ns} \\
\Delta t & = 6.25\text{ns}
\end{align*}
\]