Neutron Imaging Detector Based on the µPIC Micro-Pixel Chamber

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Contents

★ Basic operating characteristics.
★ Spatial resolution study.
★ Future detector improvements.
★ Recent demonstration measurements.
Time-resolved neutron imaging detector

- Ar:C$_2$H$_6$:$^3$He gas mixture at 2 atm.
- Gas gain < 1000 for neutron imaging.
- Efficiency of 18% at 25.3 meV and up to 65% at 0.35 meV (2.5-cm gas depth).
- ~105 µm spatial resolution; 0.6 µs time resolution; <10$^{-12}$ gamma sensitivity.
- 2 years operation or more on single gas filling.

FPGA encoder with time-over-threshold (TOT)

TPC measures 3D track (2D strip + time)

Improved position accuracy and background rejection via detailed tracking.
**Data encoding**

- Two words per pulse.
- ‘Edge bit’ saved with each data word.

DAQ shows good linearity up to a data rate of 10~12MHz (neutron rate of ~200kcps).

Deviation due to internal FIFO overflows in FPGAs.
Fast neutron and gamma rejection

**TOT distribution for scattered proton**
Fast neutrons from $^{252}$Cf source

- Track length and total energy can be similar to neutron events.
- Distinguished by shape of TOT distribution.

**Event-by-event TOT sum (1-MBq $^{137}$Cs)**
Gas gain ~600, track-length cut applied

- Gamma efficiency $<10^{-3}$ at gain of 600.
- Cosmic-ray muons

- Fraction of detected $\gamma$’s surviving neutron cuts $<10^{-6}$ (effective gamma sensitivity of $<10^{-9}$ at gain of ~600).

**TOT sum with no cuts and n and $\gamma$ event rates ($^{137}$Cs + $^{252}$Cf)**

- Sensitivity of order $10^{-12}$ or less can be achieved at reduced gain without loss of neutron efficiency.
Spatial resolution

- Proton-triton separation essential for spatial resolution.
- Proton direction, neutron position determined by ‘template’ fit.

**Image taken at NOBORU, J-PARC in Feb. 2011.**
Gas gain ~470, Exposure time 29 mins.

 Templates generated with GEANT4 simulation of detector.

\[
TOT(x, m) = A \ Template_m[\hat{x}f_w(x - x_N)]
\]

Resolution with PID: 104 to 124\(\mu m(\sigma)\)
(Final resolution depends on tracking cuts.)

Preliminary
Spatial resolution: Characterization

Resolution from knife-edge test
Cadmium test chart, gas gain ~470

<table>
<thead>
<tr>
<th>Res(µm)</th>
<th>Eff(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>131 ± 3</td>
</tr>
<tr>
<td>B</td>
<td>125 ± 3</td>
</tr>
<tr>
<td>C</td>
<td>111 ± 4</td>
</tr>
</tbody>
</table>

A. Gamma-rejection cuts on track-length/energy deposition.
B. + Z-consistency of proton direction between anode and cathode.
C. + Two peaks (proton and triton) in TOT distribution.

Image taken at NOBORU, J-PARC in March 2012.
Spatial resolution: Uniformity

**Uniformity of resolution**

Image taken at gas gain of ~470. Uniformity evaluated over 3cm × 3cm area.

**Spatial resolution (µm)**

- Mean: 108µm RMS: 6.4%
- Mean: 104µm RMS: 5.3%

After correcting for beam divergence:

- Mean: 104µm RMS: 5.3%

**Resolution vs gas gain**

- A. Gamma-rejection cuts.
- B. + Z-consistency.
- C. + Two peaks in TOT.

- Resolution improves by ~3µm per 100 decrease in gain.
- Optimum gain 250~300 (neutron efficiency decreases below gain of ~200).

Data taken at NOBORU, J-PARC in March 2012.
Improvement of spatial resolution

Gas properties

- Shorten proton-triton track lengths.
- Reduce electron diffusion.

Improvements to µPIC

- Improve gain variation (better manufacturing controls).
- Reduce pixel pitch.

Simulation results for different gas mixtures

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>Pressure (atm)</th>
<th>Transverse diffusion (µm/cm$^{1/2}$)</th>
<th>p-t track length (mm)</th>
<th>Expected improvement in resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar:C$_2$H$_6$:$^3$He (63:7:30)</td>
<td>2</td>
<td>273</td>
<td>7.9</td>
<td>(105µm~)</td>
</tr>
<tr>
<td>Ar:C$_2$H$_6$:$^3$He (63:7:30)</td>
<td>3</td>
<td>231</td>
<td>5.3</td>
<td>~15%</td>
</tr>
<tr>
<td>Xe:C$_2$H$_6$:$^3$He (50:20:30)</td>
<td>2</td>
<td>183</td>
<td>5.0</td>
<td>~15%</td>
</tr>
<tr>
<td>Ar:CO$_2$:$^3$He (50:20:30)</td>
<td>2</td>
<td>107</td>
<td>7.4</td>
<td>~15%</td>
</tr>
</tbody>
</table>

Gas parameters determined by MAGBOLTZ. Resolutions estimated with GEANT4.

- Reducing gain variation improves spatial resolution by 5~10% and uniformity by 15~30%.
- In low gain operation, pixel pitch can be reduced to ~200µm.
- GEANT4 studies are ongoing.

Resolution after diffusion and gain variation improvements: 80~90µm.

Plus smaller pixel pitch: < 70µm. Preliminary!
DAQ upgrade

- New ASICs and encoder for higher rate DAQ.
**DAQ upgrade**

### Current DAQ

- Amplifier-shaper-discriminators
- ASD to Encoder
- Encoder to VME
- FPGA encoder

**VME-PC transfer**

- Implement faster VME readout (block transfer, double-buffer).
- Block transfer gives 1.5X increase; double-buffer not yet tested.
- For future, switch to SiTCP.

**Many cables transfer signals to FPGA encoder**

- Output through single FPGA limits DAQ rate to 10~12MHz (~200kcps)
- VME-PC transfer limits live-time

### New encoder module

- 128 channels per board.
- ASICs and FPGA on single board.

**118mm × 220mm**

- Analog signals 128ch
- CMOS ASICs
- ADC
- FPGA

**Expect rate increase by factor of 4 or more.**
DAQ upgrade

**Neutron event**
(proton-triton track)

- **Flash ADC**
- **Time-over-threshold**
- **Anode**
- **Cathode**
- **Strip No.**

Double-peak from stopping proton and triton in ADC and TOT.

**ADC spectrum**

- Peak for neutron events at 764 keV

- Preliminary check OK.
- Determine threshold for optimum TOT behavior.
- Write FPGA code specific for neutron imaging.
Recent measurements

- Resonance absorption.
- CT test measurement.
Neutron resonance absorption

- Measurement of neutron TOF allows selective imaging of nuclides via resonance absorption.
- Good time resolution is essential.

Data taken at NOBORU in March 2012.
CT test measurement

- Goniometer with $\theta$-rotation from $-155^\circ$ to $155^\circ$.
- 9 angles (6 independent), 54 minutes/angle.
- TOF: 0 – 3 ms
- Neutron rate ~10 kcps, Live time 60%.
- CT reconstruction using simple back-projection method.

Data taken at NOBORU in March 2012.
Summary

- µPIC-based time-resolved neutron imaging detector.
  - For radiography, neutron resonance absorption imaging/spectroscopy, Bragg-edge transmission, CT imaging, SANS.

- Detector performance.
  - Spatial resolution of 104 µm (100% reconstruction eff.) to 124 µm (32% reconstruction eff.).
  - Time resolution ~0.6 µs; very small effective gamma sensitivity < $10^{-12}$.
  - Can operate for ~2 years on a single gas filling.
  - After upgrading DAQ and optimizing gas, maximum neutron rate on order of 1 Mcps and spatial resolution <100 µm.

- Next
  - Develop and test new FPGA code for neutron imaging.
  - Beam test of new DAQ at NOBORU this February.
Extra slides
Neutron efficiency

- Neutron efficiency as a function of neutron energy.
- Determined from GEANT4 simulation.
- Loss of peak efficiency due to large dead layer in current configuration (2.5-cm).

<table>
<thead>
<tr>
<th>Drift cage configuration</th>
<th>Drift height</th>
<th>Dead layer</th>
<th>Efficiency at 25.3 meV</th>
<th>Peak efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-cm</td>
<td>5.0 cm</td>
<td>0.8 cm</td>
<td>0.35</td>
<td>0.75 (0.7meV)</td>
</tr>
<tr>
<td>2.5-cm</td>
<td>2.5 cm</td>
<td>3.3 cm</td>
<td>0.18</td>
<td>0.27 (3meV)</td>
</tr>
<tr>
<td>2.5-cm(2)</td>
<td>2.5 cm</td>
<td>0.8 cm</td>
<td>0.20</td>
<td>0.65 (0.35meV)</td>
</tr>
</tbody>
</table>
Gas study – Ar:CO₂-based mixtures

- Compared following mixtures at 2 atm:
  - Ar:C₂H₆:He (63:7:30)
  - Ar:CO₂:He (50:15:35)
  - Ar:CO₂:C₂H₆:He (50:10:5:35)
- C₂H₆ included to increase gain and stability.
- ⁴He used in place of ³He.

**CO₂-based mixtures require higher anode voltages.**

Next steps:
- Check gain variation.
- Add small amount of ³He and measure proton-triton tracks.
Resonance absorption: Ag-In-Cd alloy

- Plate thickness: 3 mm.
- Exposure: 2 hrs.
- TOF gate: 0 – 3 ms.
- Neutron rate: ~10 kcps.
- DAQ live time: 70%.

Data taken at NOBORU in March 2012.