Neutron Imaging Detector based on the µPIC

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Neutron Imaging Detector based on the μPIC

* Prototype system and basic operation.
* Demonstration measurements.
* Future improvements.
Neutron imaging detector prototype (μNID)

- High-rate FPGA-based DAQ.
- TPC measures 3D proton-triton tracks.
- Energy deposition estimated by time-above-threshold method.
- Gas gain < 1000 for neutron imaging.
- Efficiency up to ~30%, position res. of ~120 µm, time res. of ~1 µs.
DAQ and FPGA logic

Amplifier-Shaper-Discriminators (ATLAS, KEK)

μPIC

FPGA
encoder

32 bits:
orientation,
time,
position,
edge

VME
memory

PC

33-bit LVDS
(× 2)

External
gate

Digital out
(256 ch × 2)

DATA ENCODING

• Two words per pulse.
• ‘edge bit’ saved with each data word.

µPIC

Threshold

0

1

ASD

Time-above-threshold
(∝ energy deposit)

VME bus

PROTON-TRITON TRACKS

Simultaneous measurement of position and ‘energy deposit’ at high rates.

Excellent background rejection capability.
DATA ENCODING

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- ‘edge bit’ saved with each data word.

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32 bits: orientation, time, position, edge

VME memory

33-bit LVDS (× 2)

External gate

PC

VME bus

Digital out (256 ch × 2)

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

ENERGY DEPOSITION

- Simultaneous measurement of position and ‘energy deposit’ at high rates.
- Excellent background rejection capability.

PROTON-TRITON TRACKS

Position

Energy Deposition

Time-above-threshold (clocks)

0 1

Time-above-threshold (∝ energy deposit)
DATA ENCODING

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

Simultaneous measurement of position and ‘energy deposit’ at high rates.
Excellent background rejection capability.
Test experiments at J-PARC

- Beam power ~120 kW.
- Carried out at NOBORU beam line.
- Fill gas: Ar-C$_2$H$_6$-$_3$He (63:7:30) at 2 atm, efficiencies ~28%(5 cm), ~13%(2.5 cm).

Moderator-to-detector distance of ~14.5 m.
Max. beam size: 10 × 10 cm$^2$.
25 Hz pulse rate, 10 Å bandwidth.
Long term operability and $^3$He usage

- Same gas filling used for first two experiments (separated by 8 months).
- No degradation in performance seen in June experiment.
- Gain recovered by increasing anode voltage.
- Detector remained operable after more than 1 year on single gas filling.

<table>
<thead>
<tr>
<th>Time after filling</th>
<th>Gain (% of initial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Exp (2009)</td>
<td>100</td>
</tr>
<tr>
<td>2nd Exp (2010)</td>
<td>67</td>
</tr>
<tr>
<td>Dec 2010</td>
<td>30</td>
</tr>
</tbody>
</table>

Strategies to extend operation

- Annealing of vessel and $\mu$PIC against outgassing.
- Careful selection of materials.
- Gas purification or $^3$He reclamation system.
DAQ performance at NOBORU

- Time-averaged data rates from 200 kHz ~ 9.4 MHz (neutron rate of 80~100 kHz).
- Large dead time (40 ~ 85%).
- Encoder limits DAQ rate.
- VME-to-PC transfer creates dead time.
- Limitations can be reduced with further hardware development.

EXTERNAL TOF GATE

Ex: Bragg transmission measurement (2010).

<table>
<thead>
<tr>
<th></th>
<th>Ungated</th>
<th>TOF &gt; 3 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of pulses</td>
<td>8948</td>
<td>191389</td>
</tr>
<tr>
<td>Total time (min)</td>
<td>34.5</td>
<td>226.2</td>
</tr>
<tr>
<td>Dead time (%)</td>
<td>82.7</td>
<td>43.6</td>
</tr>
</tbody>
</table>

~70% decrease in measurement time.

- Reduction in incoming data means fewer VME readouts.
- Effectiveness depends on details of TOF distribution and gate.
- Useful for Bragg transmission, resonance absorption.
Neutron-gamma separation

- Both neutrons and gammas are detected ($\gamma$ efficiency $\sim 10^{-3}$).
- Neutrons selected by cuts in total time-above-threshold and 3D track length.
- Fraction of detected $\gamma$'s surviving neutron cuts $< 10^{-6}$ (effective gamma sensitivity of $< 10^{-9}$).

- Gamma rejection studied using RI sources.
- Data taken over 24 hours.

Pulse-width sum after track-length cut

<table>
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<th>Track length + PID</th>
<th>Contamination fraction (95% CL)</th>
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<td>&lt; 5.5 $\times$ 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>&lt; 2.9 $\times$ 10^{-6}</td>
<td></td>
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</table>
Position resolution with PID

Cd TEST CHART

2 mm slits

5 cm

No PID

With PID

Resolution: ~1 mm ($\sigma$)

Resolution with PID: $349 \pm 36 \mu m$ ($\sigma$)
(Includes beam dispersion.)

Data taken at NOBORU, J-PARC in Nov. 2009.

Proton direction from shape of distribution

Corrected position

Mid-point

Entries 29
Entries 29

Position from mid-point of track.
Refining position resolution

- Two methods: End-Point Extrapolation (EPE) and Peak Interpolation (PI).
- Combining both methods produces best result of $\sigma = 118.4 \pm 0.2 \, \mu m$.

Data taken at NOBORU, J-PARC in Feb. 2011.
Image of a wristwatch

μPIC (29 MIN.)

- Bin size: 200 µm × 200 µm.
- Bin size can be decreased with higher statistics.
- Image processing techniques could improve image.

Data taken at NOBORU, J-PARC in Feb. 2011 (μPIC).

IMAGING PLATE (200 MIN.)

Resolution 50~60 µm.

Courtesy of Ohi, J-PARC.
Demonstration measurements

- Resonance absorption.
- Bragg-edge transmission.
Resonance absorption

- Sheets of In, Ta, Ag, Mo, and Mn.
- Typical area of 10 cm × 10 cm.
- Thicknesses from 10 µm to 1 mm.

- Resonance absorption occurs when neutrons of a particular energy are absorbed preferentially by a target nucleus.
- Large samples to accumulate statistics quickly (~16 min/sample).
- Good time resolution and background rejection allows us to see resonances near beginning of pulse.

Data taken at NOBORU, J-PARC in Feb. 2011.
Bragg-edge transmission

Edges appear when neutron wavelength is twice crystal plane spacing (Bragg’s law at $2\theta = 180^\circ$).

Edge spacing is consistent with expected BCC crystal structure.

Precise measurement of edge positions determines lattice parameter.

Data taken at NOBORU, J-PARC in Feb. 2011.

Fe powder (> 99% purity, grain size < 325 µm).

Fe CRYSTAL STRUCTURE

Body-centered cubic (BCC)

$a$ is referred to as the lattice parameter.

$$a = d_{lmn} \sqrt{l^2 + m^2 + n^2}$$
Bragg-edge transmission

78 \times 40.5 \times 10 \text{ mm}^3 \text{TIG-WELDED 316L STAINLESS STEEL PLATE}

19 \text{ mm}

78 \text{ mm}

Edge spacing is consistent with FCC crystal structure.

Data taken at NOBORU, J-PARC in June 2010.
Bragg-edge transmission

- Variation in edge positions may be related to internal strain.
- Full strain tensor requires measurements from at least six independent directions.
- Only one direction observed in this measurement.

* Fit procedure based on Santisteban, et al. (2001)

Divide image into 4.8 x 4.8 mm² ‘pixels’ and fit edge positions.

\[ d = \frac{\lambda}{2} \]

d-spacing from wavelength

\[ \epsilon = \frac{d - d_0}{d_0} \]

strain component in beam direction

Data taken at NOBORU, J-PARC in June 2010.
Future improvements

- Optimization of gas mixture.
- Smaller pitch μPIC.
- New ASICs and encoder for more compact DAQ.
## Gas optimization and pixel pitch

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<th>Drift velocity (µm/ns)</th>
<th>Transverse diffusion (µm/cm(^{1/2}))</th>
<th>Longitudinal diffusion (µm/cm(^{1/2}))</th>
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Gas parameters determined by MAGBOLTZ. Resolutions estimated with GEANT4.

- Shorten p-t track lengths by increasing pressure or changing to gas with higher stopping power.
- Reduce diffusion of drift electrons.
- Moderate reductions in pixel pitch produce corresponding reduction in position resolution.
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**DAQ improvements**

- Replace ASDs with CMOS chips (developed with KEK for SMILE project).
- 16 channels/chip (increased from 4).
- Power per channel reduced by factor of more than 3.

- Combine CMOS chips with FPGA on single board.
- Four boards replace ASD racks, encoder, cables.
- Each board writes to memory, increasing max. data rate.
- New boards now under testing.

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**Diagram:**

- ASDs
- FPGA
- Encoder
- 10-cm prototype in lab at Kyoto Univ.

- New CMOS ASIC
- 4 mm
- Power per channel reduced by factor of more than 3.

- 16 channels/chip (increased from 4).
- Each board writes to memory, increasing max. data rate.
- New boards now under testing.

**Dimensions:**

- 118mm × 220mm
- Control
- Analog
- Data & Trig.
- CMOS ASICS
- ADC
- FPGA
- CR board

**Analog Signal 128ch**

**To memory board**
Summary

- TPC based on micro-pattern gaseous detector and FPGA DAQ system.
  - Position resolution of 118 µm; time resolution of ~1 µs.
  - FPGA-based DAQ with high data rates.
  - Strong rejection of gammas and fast neutrons.

- Detector remains operable over long time.
  - Annealing to reduce outgassing for increased long-term stability.
  - Gas filtration system could extend operation considerably.

- Development of compact DAQ and optimization of gas mixture are ongoing.

- µPIC manufactured using standard, inexpensive PC board manufacturing processes.
  - µPIC sizes up to 30 × 30 cm² are currently available.
  - Tiling of detectors to cover large area.