Development of a counting-type neutron imaging detector for energy-resolved imaging at J-PARC/MLF

Joe Parker
CROSS-Tokai
BL22 Group
## RADEN/BL22 and µNID development members

<table>
<thead>
<tr>
<th>JAEA/J-PARC Center</th>
<th>Takenao Shinohara</th>
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<tr>
<td></td>
<td>Tetsuya Kai</td>
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<td></td>
<td>Kenichi Oikawa (BL10)</td>
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<td>Masahide Harada (BL10)</td>
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<td></td>
<td>Takeshi Nakatani</td>
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<td>Mariko Segawa</td>
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<td>Kosuke Hiroi</td>
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<td>Yuhua Su</td>
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<tr>
<th>CROSS-Tokai</th>
<th>Hirotoshi Hayashida</th>
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<tr>
<td></td>
<td>Joe Parker (µNID Lead Developer)</td>
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<tr>
<td></td>
<td>Yoshihiro Matsumoto</td>
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<td>Shuoyuan Zhang</td>
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| Nagoya University  | Yoshiaki Kiyanagi  |
RADEN/BL22 – Neutron imaging instrument at the MLF

World’s first instrument dedicated to energy-resolved neutron imaging using pulsed neutrons!

- World-class, pioneering instrument for pulsed-neutron imaging
- Leading facility for conventional radiography in Japan
- Commissioning from Nov. 2014, user program from April 2015

First images from RADEN (7 Nov 2014)
Energy-resolved neutron imaging

Energy-dependent neutron transmission

- Energy-dependence → quantitative information on macroscopic distribution of microscopic quantities
- Pulsed neutrons → wide energy range, accurate energy determination by time-of-flight
- Requires detectors with:
  - Spatial resolution < 1 mm
  - Time resolution < 1 µs
  - Count rate > 1 Mcps
  - Strong background rejection
RADEN/BL22 – Neutron imaging instrument at the MLF

Properties of RADEN

| Conventional radiography/pulsed-neutron imaging | Large beam size (up to 30x30 cm²) |
| High flux (2.6x10⁷ n/s/cm² @ <0.5eV)          | Variable L/D (up to 7500)          |
| Wide bandwidth (~9Å, Δ λ / λ < 0.2%)          | Large experimental area             |
RADEN computer system

- Computer control of beam line components, sample stages, and detectors using IROHA2 (automated measurements)
- Large data storage capacity (24TB SSD primary, 100TB secondary)
- Fibre channel network (8 Gb/s) for fast data transfer
- GPGPU cluster (12 CPUs, 24 GPGPUs) for data analysis
Detectors available at RADEN

**Camera type**

- Andor iKon-L
  - Cooled CCD
  - 300µm
  - No TOF
  - Automated system for CT

**Counting type**

- nGEM
  - Micro-pattern w/ $^{10}$B (10% eff.)
  - FOV: 10 x 10 cm$^2$
  - $\Delta x=1$mm, $\Delta t=15$ns, < 1 Mcps

- LiTA12
  - Li-glass scint. (40% eff.)
  - FOV: 5 x 5 cm$^2$
  - $\Delta x=3$mm, $\Delta t=40$ns, 6 Mcps

- μNID
  - Micro-pattern
  - $^{3}$He (18% eff.)
  - FOV: 10 x 10 cm$^2$
  - $\Delta x=0.3$mm, $\Delta t=0.6$µs, < 1 Mcps

**Neutron Color I.I.**

- High-resolution (200 µm)
- High-speed (10k, 30k, 100k fps)
Current performance of counting-type detectors at RADEN
µPIC-based Neutron Imaging Detector (µNID)
µPIC-based neutron imaging detector (µNID)

**Neutron detection via $^3$He**

- Track length ~8 mm in gas

- 3-dimensional tracking of decay pattern
- Energy via time-over-threshold (TOT)
- Compact ASIC+FPGA data encoder

→ Good spatial resolution, strong background rejection, high data rates possible

**Digital encoder with time-over-threshold (TOT)**

- Time-above-threshold ($\propto$ energy dep.)

- TOT for proton-triton track

**µPIC**

- $400 \mu m$

- $9.0 \text{ cm}$

- $32.8 \text{ cm}$
µPIC-based neutron imaging detector (µNID)

- FPGA-based data encoders
- FPGA-based DAQ controller
- Data transfer via Ethernet
μNID performance

- Strong gamma rejection using TOT information
- Template fit for position analysis

μNID performance characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Area</td>
<td>10 x 10 cm²</td>
</tr>
<tr>
<td>Spatial res.</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Time res.</td>
<td>0.6 μs</td>
</tr>
<tr>
<td>ΔTOF/TOF</td>
<td>&lt; 0.07% @18m</td>
</tr>
<tr>
<td>γ-sensitivity</td>
<td>&lt; 10⁻¹²</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Up to 26%</td>
</tr>
<tr>
<td>Count rate</td>
<td>0.6 Mcps</td>
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Image data taken at NOBORU in Feb. 2011
Development of μNID

- Objectives:
  - Improve count rate and spatial resolution
  - Improve data analysis; reduce processing time
  - Integration into RADEN control system

- Count rate
  - Throughput of data encoder modules
  - Drift velocity, stopping power of filling gas
  - Readout geometry

- Spatial resolution
  - Electron diffusion, stopping power of filling gas
  - Readout strip pitch

- Improvement of count rate and data analysis is most pressing
Data encoder

- FPGA-based encoder modules
  - CMOS ASICS
  - Spartan6 FPGA
  - Ethernet transfer (SiTCP)
  - 128 ch/encoder (4 encoders total)
- Original encoder throughput limited by 100BASE-T Ethernet transfer
- Upgrades
  - Gigabit Ethernet PHY (1\textsuperscript{st} revision)
  - On-board DDR3 memory (2\textsuperscript{nd} revision, not yet tested)

Originally developed by Kyoto U. and KEK (Open-it)
Gas optimization

- Change to CF$_4$-based mixture
  - Increased drift velocity (count rate)
  - Decreased electron diffusion (spatial resolution)
  - Increased stopping power (both)

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<thead>
<tr>
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<th>Previous gas</th>
<th>New gas</th>
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<tr>
<td>Mixture</td>
<td>Ar-C$_2$H$_6$-$^3$He (67:7:30 @ 2atm)</td>
<td>CF$_4$-iC$<em>4$H$</em>{10}$-$^3$He (45:5:50 @ 2atm)</td>
</tr>
<tr>
<td>Drift velocity</td>
<td>23 µm/ns</td>
<td>58 µm/ns</td>
</tr>
<tr>
<td>Diffusion</td>
<td>275 µm/cm$^{1/2}$</td>
<td>80 µm/cm$^{1/2}$</td>
</tr>
<tr>
<td>Efficiency @25.3meV</td>
<td>18%</td>
<td>26%</td>
</tr>
<tr>
<td>Proton-triton track length</td>
<td>8 mm</td>
<td>5 mm</td>
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</table>

Gas characteristics simulated with MAGBOLTZ, GEANT4
Rate testing at RADEN

- Control incident intensity using $\text{B}_4\text{C}$ slits
- Testing of
  - rate capacity of hardware
  - rate linearity of detector
Rate testing at RADEN

- Test of revised encoders with GbE
- Ar-Ethane gas mixture
- Compared with original encoder
  - Rate capacity increased by more than factor of 6
- Mostly linear up to more than 3 Mcps
Rate testing at RADEN

- Test of CF$_4$-based gas mixture
- Encoders with GbE
- Rate capacity over 8 Mcps
- Nearly factor of 2 increase over Ar-based gas mixture

Neutron rates vs slit area

![Graph showing neutron rates vs slit area for Ar-C$_2$H$_6$ and CF$_4$-iC$_4$H$_{10}$ gas mixtures.](image)
Spatial resolution with CF$_4$

- Image of Gd test pattern
- L/D: 5000
- Exposure time: 1.5 hours
- 16% contrast at 2.5 lp/mm (200µm line width)
- Improvement over Ar-Ethane mixture

Transmission

Distance from top (mm)
Remaining issues

- Data analysis: performance of event clustering
  - Event ‘pile-up’ at rates above 100~300 kcps
  - Developing new algorithm
- Working with software company to improve speed and ease-of-use of analysis software

Efficiency of analysis determined by comparing numbers of raw hits and reconstructed neutron events
Other ongoing development

- New μPIC readout geometry
  - Additional strip plane at 45° to x,y strips
  - Aid in reconstruction of simultaneous events
  - Now testing at Kyoto U.
- Reduced strip pitch
  - Manufactured using MEMS (structures down to 10μm)
  - μPIC with 280, 215μm pitches
  - Performed preliminary testing at RADEN
First on-beam test of MEMS µPIC at RADEN

- 280µm pitch (192×192 strips)
- 215µm pitch (64×64 strips)

**Neutron TOF spectrum measured on 215µm section**

- No signal measured on 280µm section (gain too low)
- Signal confirmed on 215µm section
- Further testing to study gain stability, imaging capability
μNID with Boron converter
μNID with Boron converter

- $^{10}$B-coated drift cathode ($t=1\mu$m)
- 3-axis μPIC
- Encoder with on-board memory
- CF$_4$-based gas at 2 atm
- On-beam test at RADEN early next year

**Expected performance**

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<tbody>
<tr>
<td><a href="mailto:Efficiency@25.3meV">Efficiency@25.3meV</a></td>
<td>3~5%</td>
</tr>
<tr>
<td>Time resolution</td>
<td>10 ns</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>200~400 µm</td>
</tr>
<tr>
<td>Peak count rate</td>
<td>20~30 Mcps</td>
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</tbody>
</table>
Current and projected performance

- **Boron µNID**
  - (GbE/memory and reduced pitch)

- **µNID**
  - (GbE and optimized gas)

- **GEM**

- **LiTA12**

**Graph:**
- **Y-axis:** Count rate (Mcps)
- **X-axis:** Spatial resolution (mm)

Legend:
- Blue square: Boron µNID
- Blue circle: µNID (GbE/memory and reduced pitch)
- Red square: µNID (GbE and optimized gas)
- Green circle: GEM
- Black circle: LiTA12
Summary

- Development of µNID detector is proceeding
  - Increased rate capacity to 8 Mcps through hardware upgrades, optimization of gas mixture
  - Need to adapt analysis algorithms to higher rate, new gas characteristics
  - Testing of new µPIC readout boards for increased rate, higher spatial resolution has begun
  - Starting development of faster off-line data processing software
- µNID with Boron converter
  - Expect greatly improved rate (20~30 Mcps) and similar spatial resolution thanks to smaller event size
  - Will perform on-beam test at RADEN in 2016B