# Neutron Imaging Detector Based on the µPIC Micro-Pixel Chamber

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## Introduction

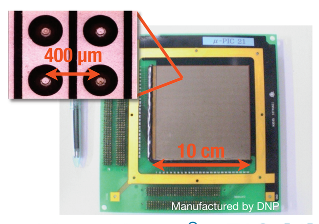
We have developed a prototype time-resolved neutron imaging detector which employs the micro-pixel gaseous chamber (µPIC), a micropattern gaseous detector, coupled with a field programmable gate array (FPGA)-based data acquisition system for applications in small-angle neutron scattering and neutron radiography at high-intensity neutron sources [1-3]. Good spatial resolution and excellent background rejection are achieved by measuring both the energy measurement (via time-over-threshold) and 3D track of the resultant proton-triton pair. Using time-over-threshold allows us to keep the system simple and compact, while preserving the high-rate capability.

Main features of our µPIC-based detector

| | |
|---|---|
| **Gas mixture** | Ar-$C_2H_6$-$^3$He (63:7:30) at 2 atm |
| **Gas gain** | 200~500 in normal operation |
| **Longevity** | ~2 years on single gas filling |
| **Efficiency** | 18% at 25.3meV, 65% at 0.35meV peak (for 2.5cm gas depth) |
| **Neutron rate** | ~200 kcps (to ~1 Mcps after hardware upgrade) |
| **Resolutions** | <120µm (spatial), 0.6µs~ (time) |
| **γ sensitivity** | $<10^{-12}$ @ gas gain 250~300 |
| **µPIC area** | 10x10cm²(prototype), 20x20cm², 30x30cm² |

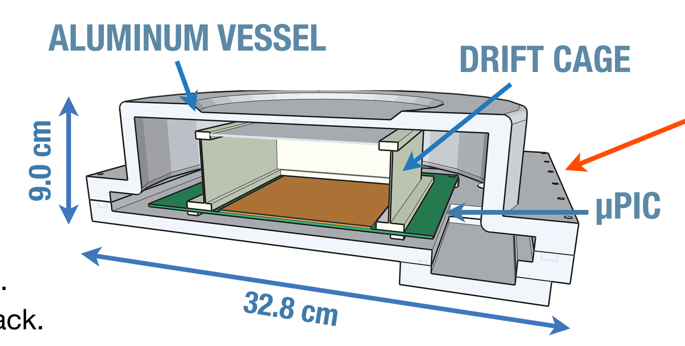
## Prototype detector

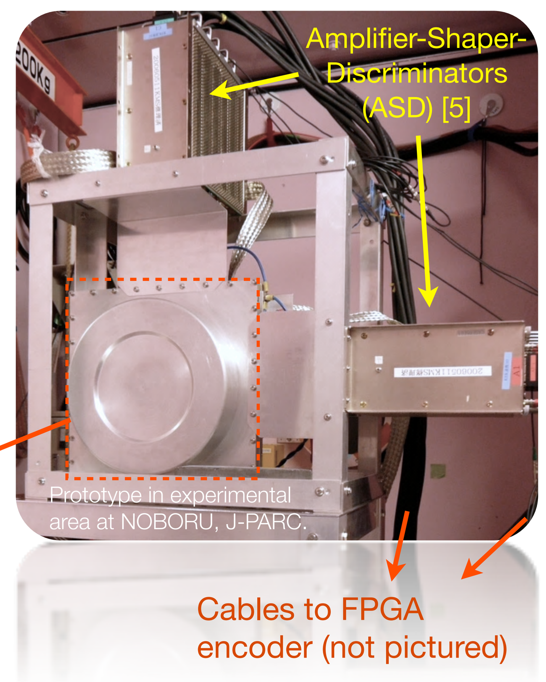
The prototype detector uses a time projection chamber (TPC) based on a 10 × 10 cm² µPIC. The TPC is contained within a sealed aluminum vessel capable of withstanding pressures up to 2 atm. The µPIC itself was developed in our group at Kyoto University [4] and is manufactured by DaiNippon Printing Co., Ltd., using inexpensive printed circuit board (PCB) technology.



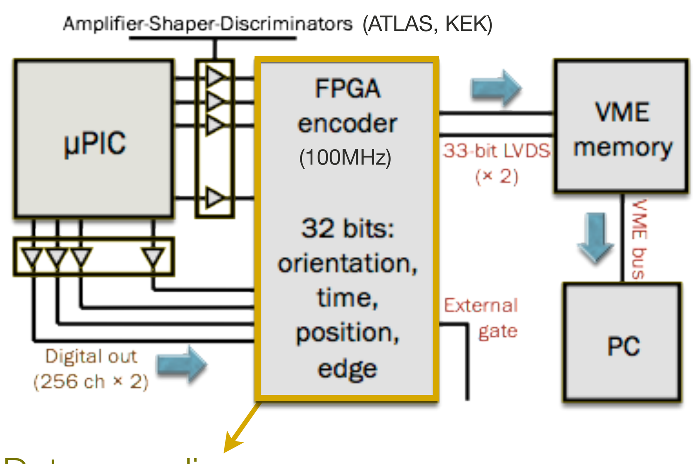

10 × 10 cm² µPIC [4]

- 400-µm pitch with 2D strip readout.
- 2D readout + drift-time gives 3D track.
- Stable operation at gains up to 6000.



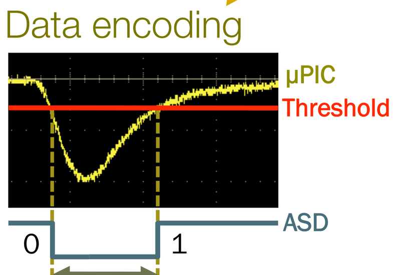




## Data acquisition system




The heart of the data acquisition system (DAQ) is the FPGA encoder module [6]. For high-intensity neutron measurements, all incoming data is streamed to the VME memory with no per-event trigger. Individual events are later isolated in the offline analysis using a clustering algorithm. Additionally, by recording both the leading and trailing edge of the signals, we are able to estimated the energy deposition using the time-over-threshold (TOT) method with no added cost or complexity for the DAQ hardware.

Data encoding

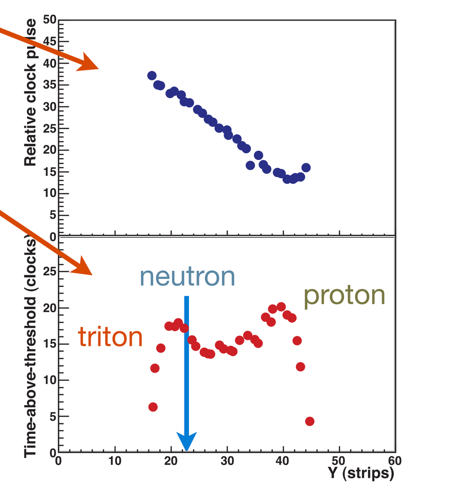



- Two data words per pulse (labeled 0 and 1).
- Time between words (or TOT) is proportional to energy deposit.

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

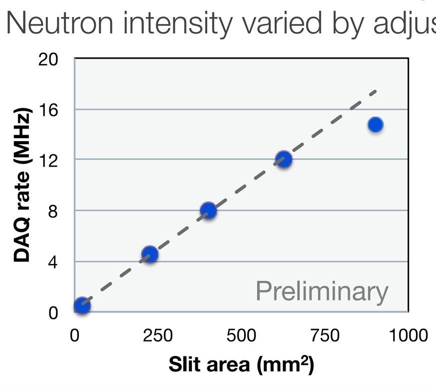
Proton-triton separation by shape of TOT distribution.

**Proton-triton track recorded with FPGA encoder.**




Improved position accuracy and background rejection via detailed tracking.

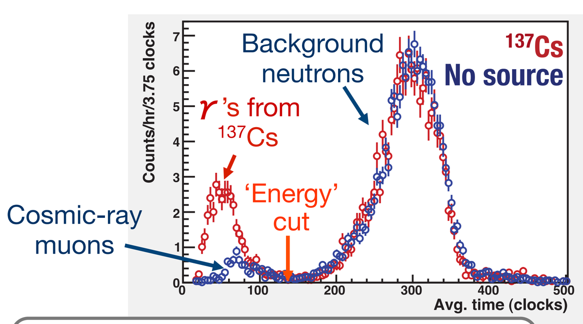
**Rate test at NOBORU, J-PARC (2012)**
Neutron intensity varied by adjusting slit opening




- DAQ shows good linearity up to a data rate of 10~12MHz (neutron rate of ~200kcps).
- Deviation at higher rates due to overflow of internal FIFOs of FPGA.
- Max. rate will be increased to 1Mcps level with DAQ upgrade.

## Gamma and fast neutron rejection

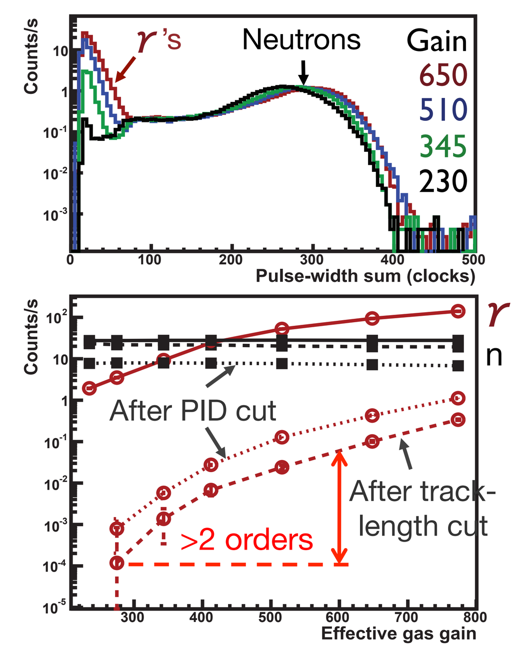
**Event-by-event TOT sum (1-MBq $^{137}$Cs)**
Gas gain ~600, track-length cut




Effective gamma sensitivity of $<10^{-9}$ was achieved at gain of 600.

**Neutron-gamma separation** is achieved by combining information about energy deposition (via time-over-threshold) and track length. Neutrons produce proton-triton tracks with essentially the same energy and track lengths, while gamma events deposit much less energy and produce a range of track lengths.

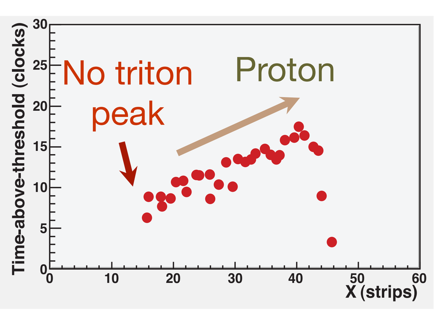
**TOT sum and n/γ event rates as a function of gas gain ($^{137}$Cs + $^{252}$Cf)**




Effective gamma sensitivity of $<10^{-12}$ for gains below 300.

**Fast neutrons** scatter with protons in the gas, with a small fraction producing a proton with energy and track length similar to a proton-triton event. Such events can be distinguished by the shape of the TOT distribution.

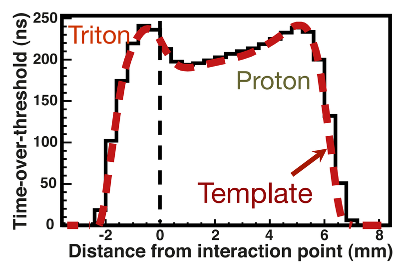
**TOT distribution for scattered proton**
Fast neutrons from $^{252}$Cf source




## Spatial resolution

As the range of the proton is ~3 times the triton, it is essential to separate the two particles for an accurate determination of the neutron position. This is accomplished by comparing the measured TOT distributions with the expected distributions generated by a GEANT4 simulation of our detector.

**Measured and expected TOT distributions**

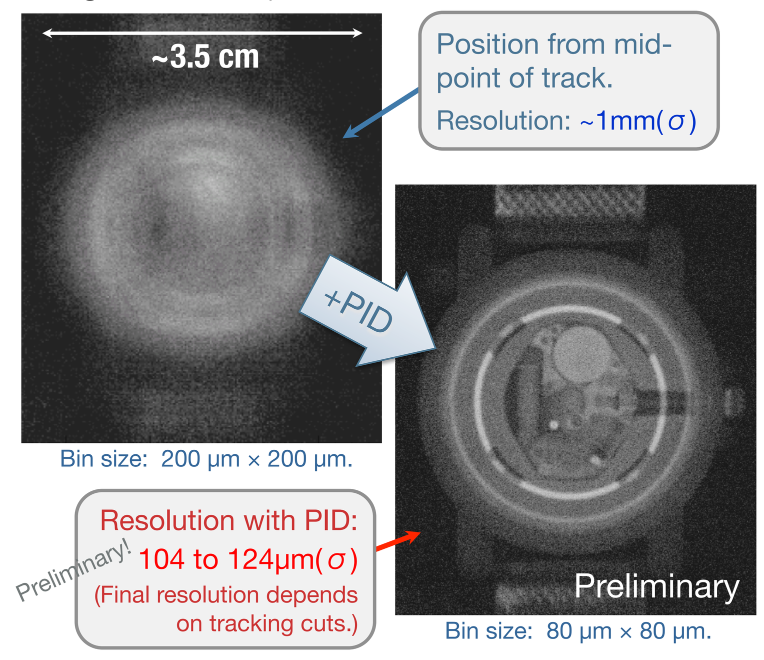



- Template shapes generated with GEANT4 simulation.
- Proton direction, neutron position determined by fit.

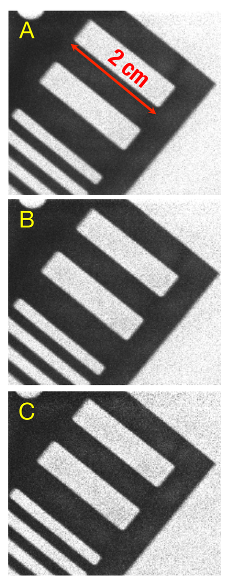
$$\mathrm{TOT}(x,m) = A\,\mathrm{Template}_m(\hat{x}\,a_w(x-x_N))$$

Normalization; Template index (from track angle); Proton direction (= ±1); Overall width scale factor; Neutron position

**Data taken at NOBORU, J-PARC in Feb 2011**
Gas gain ~470, exposure time ~29 minutes



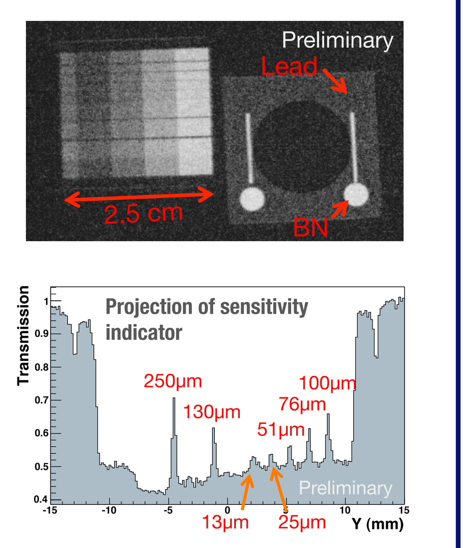

**Dependence of resolution on cut conditions**
Cadmium test chart, knife-edge test




| | Res (µm) | Cut fraction (%) |
|---|---|---|
| A | 124 | 100 |
| B | 117 | 66 |
| C | 104 | 32 |

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.

**Sensitivity and beam purity indicators**




Data taken at NOBORU, J-PARC in March 2012

**Improvement of spatial resolution**

Gas properties
- Shorten proton-triton track lengths.
- Reduce electron diffusion.
  → ~15% improvement

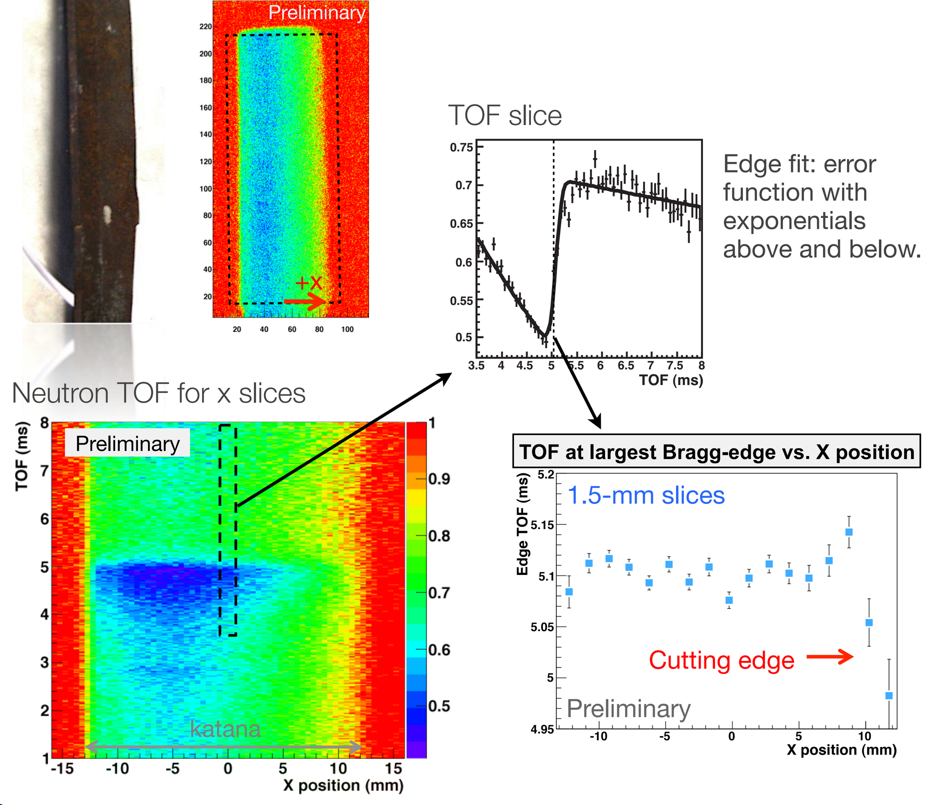
Improvements to µPIC
- Improve gain variation (through tighter manufacturing controls).
  → 5~10% improvement
- Finer pixel pitch.
  → >15% improvement

With reduced diffusion and gain variation: 80~90µm
Plus finer pixel pitch: <70µm

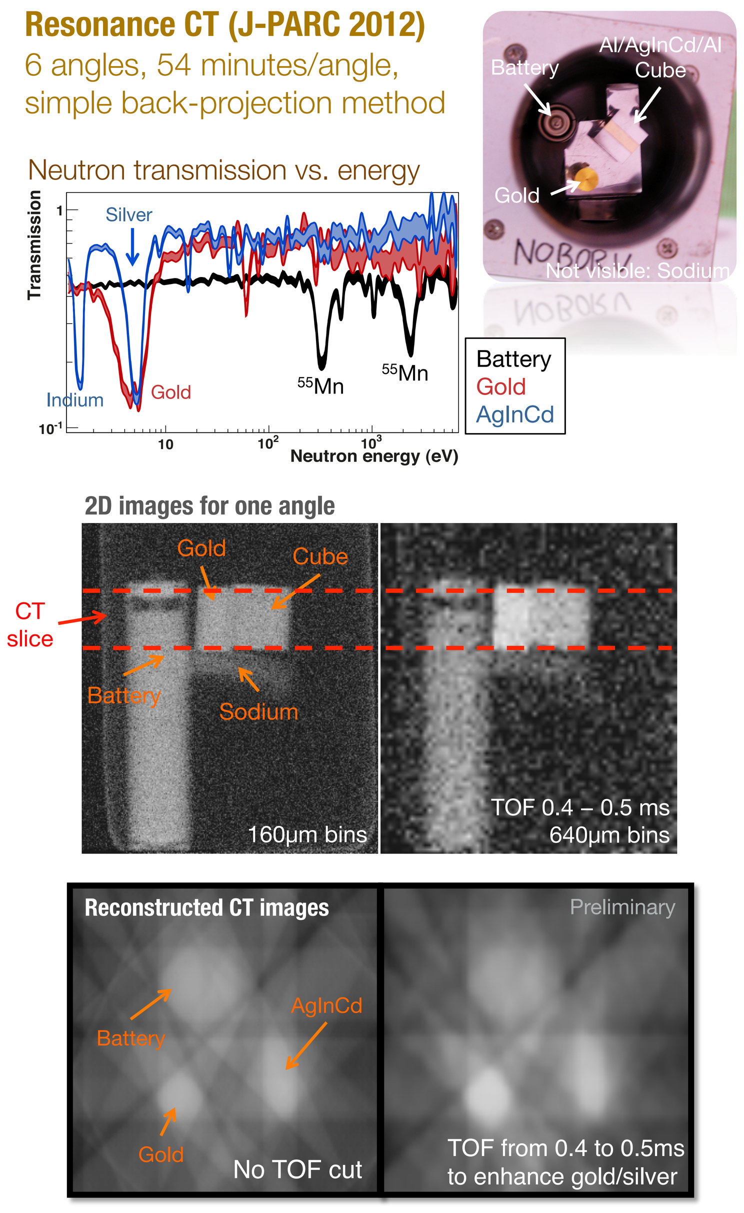
## Time-resolved radiographic techniques

A time resolution of ~0.6µs makes our prototype detector well-suited for time-resolved radiographic techniques such as Bragg-edge transmission and nucleon resonance absorption spectroscopy. The good spatial resolution allows us to easily measure detailed 2-dimensional distributions, and we can extend to 3D by utilizing computed tomography techniques.

**Bragg-edge transmission for katana fragment (北大, 2012)**

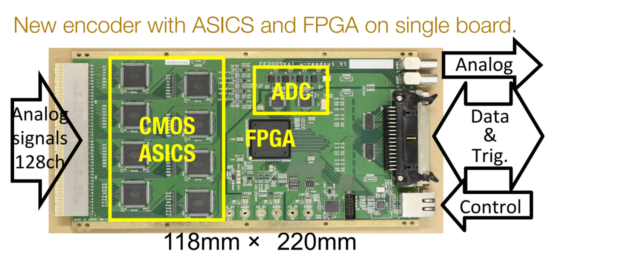



**Resonance CT (J-PARC 2012)**
6 angles, 54 minutes/angle, simple back-projection method



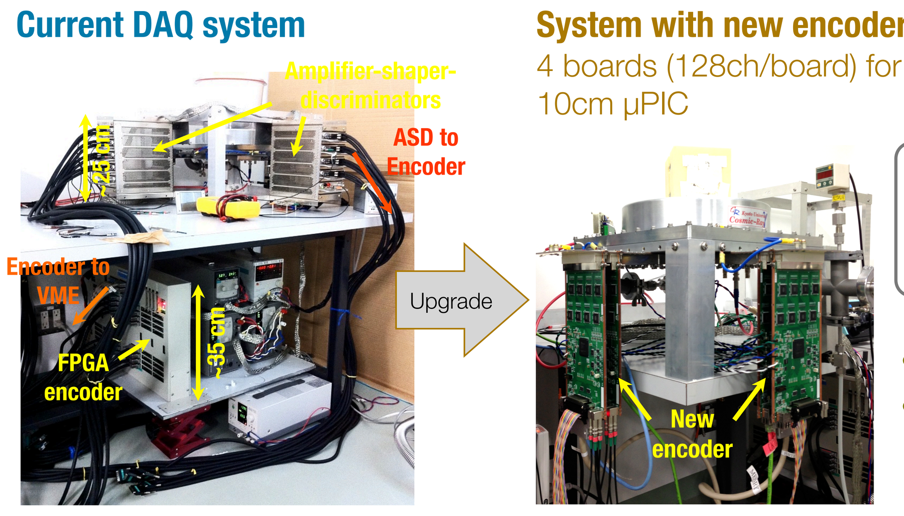

## DAQ upgrade

A new encoder module combines ASICs and FPGA on a single board. It also includes an on-board flash ADC. The new encoder greatly increases the compactness and ease of use of the DAQ system, while increasing the rate by eliminating bottlenecks.




**Current DAQ system**

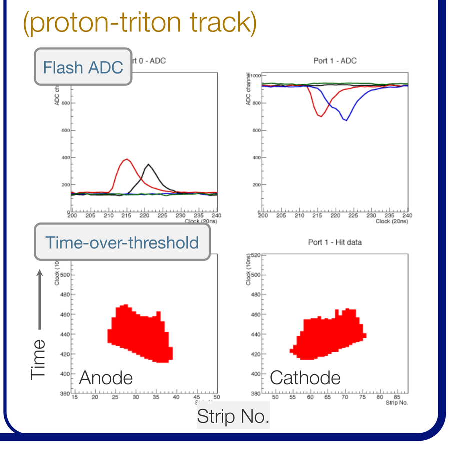
**System with new encoder**
4 boards (128ch/board) for 10cm µPIC




Expect increase in max. neutron rate by factor of 4 or more (to 1Mcps level).

- Preliminary test OK.
- Planned beam test at J-PARC in Feb. 2013.

**Neutron event with new encoder**
(proton-triton track)




## Conclusion

By measuring both the energy deposition (via time-above-threshold) and track positions, a position resolution of <120 µm and an effective gamma sensitivity of $<10^{-12}$ were achieved. The time resolution of ~0.6 µs, as determined by the electron drift velocity, enables clean separation of neutrons by time-of-flight at pulsed neutron sources. The detector was able to maintain its good operating characteristics for nearly two years on a single gas filling. The compact, high-speed FPGA-based DAQ is simple to setup and operate and will be capable of neutron rates approaching 1 Mcps after the encoder upgrade. Furthermore, the printed circuit board manufacturing process is inexpensive and allows for freedom in choosing the size and shape of the µPIC. These properties make the µPIC an attractive solution for neutron imaging applications in high-rate environments that require very low background, time-resolved measurements.

## References

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[6] H. Kubo et al., 2005 IEEE Nuclear Science Symposium Conference Record (©2005 IEEE) 371.

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