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

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BL22 Group

RADEN/BL22 and μNID development members

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RADEN/BL22 – Neutron imaging instrument at the MLF

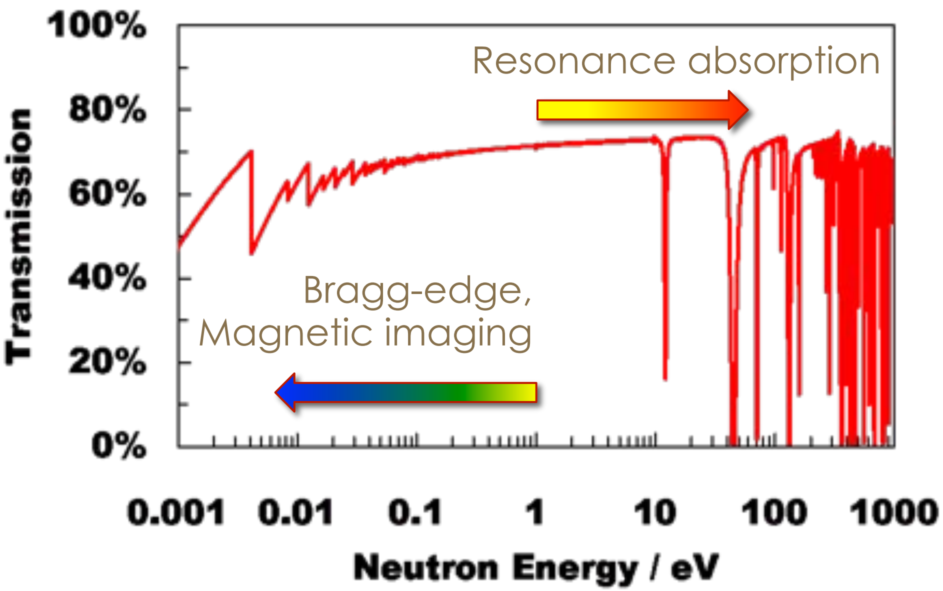
World's first instrument dedicated to energy-resolved neutron imaging using pulsed neutrons!

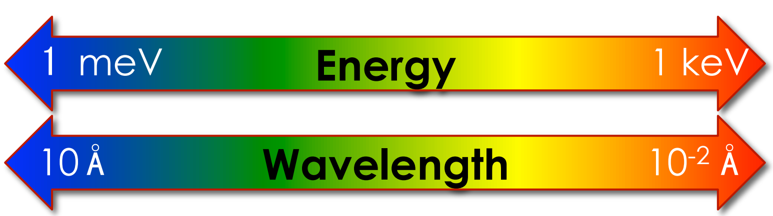
- World-class, pioneering instrument for pulsed-neutron imaging
- Leading facility for conventional radiography in Japan
- Commissioning from Nov. 2014, user program from April 2015

First images from RADEN (7 Nov 2014)

Energy-resolved neutron imaging

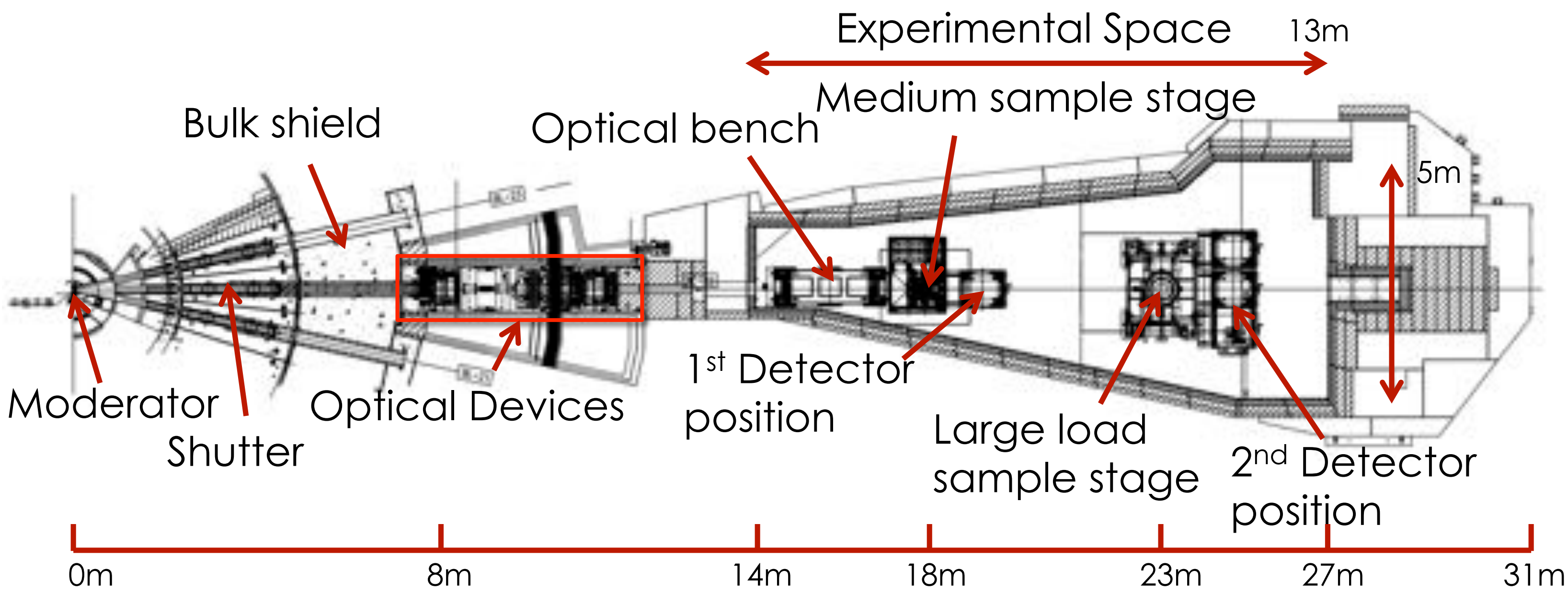
Energy-dependent neutron transmission





- 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

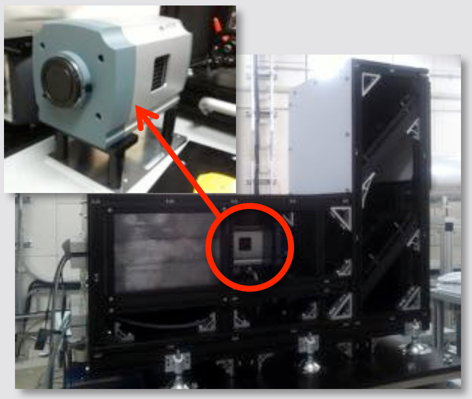
Conventional radiography/pulsed-neutron imaging	Large beam size (up to 30x30 cm^2)
High flux ($2.6x10^7$ $n/s/cm^2$ @ <0.5eV)	Variable L/D (up to 7500)
Wide bandwidth (~9Å, $\Delta \lambda / \lambda$ < 0.2%)	Large experimental area

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

Neutron Color I.I.

- High-resolution (200 μm)
- High-speed (10k, 30k, 100k fps)

Counting type

nGEM

- Micro-pattern w/ ^{10}B (10% eff.)
- FOV: 10 × 10 cm^2
- **Δx=1mm**, Δt=15ns, < 1 Mcps

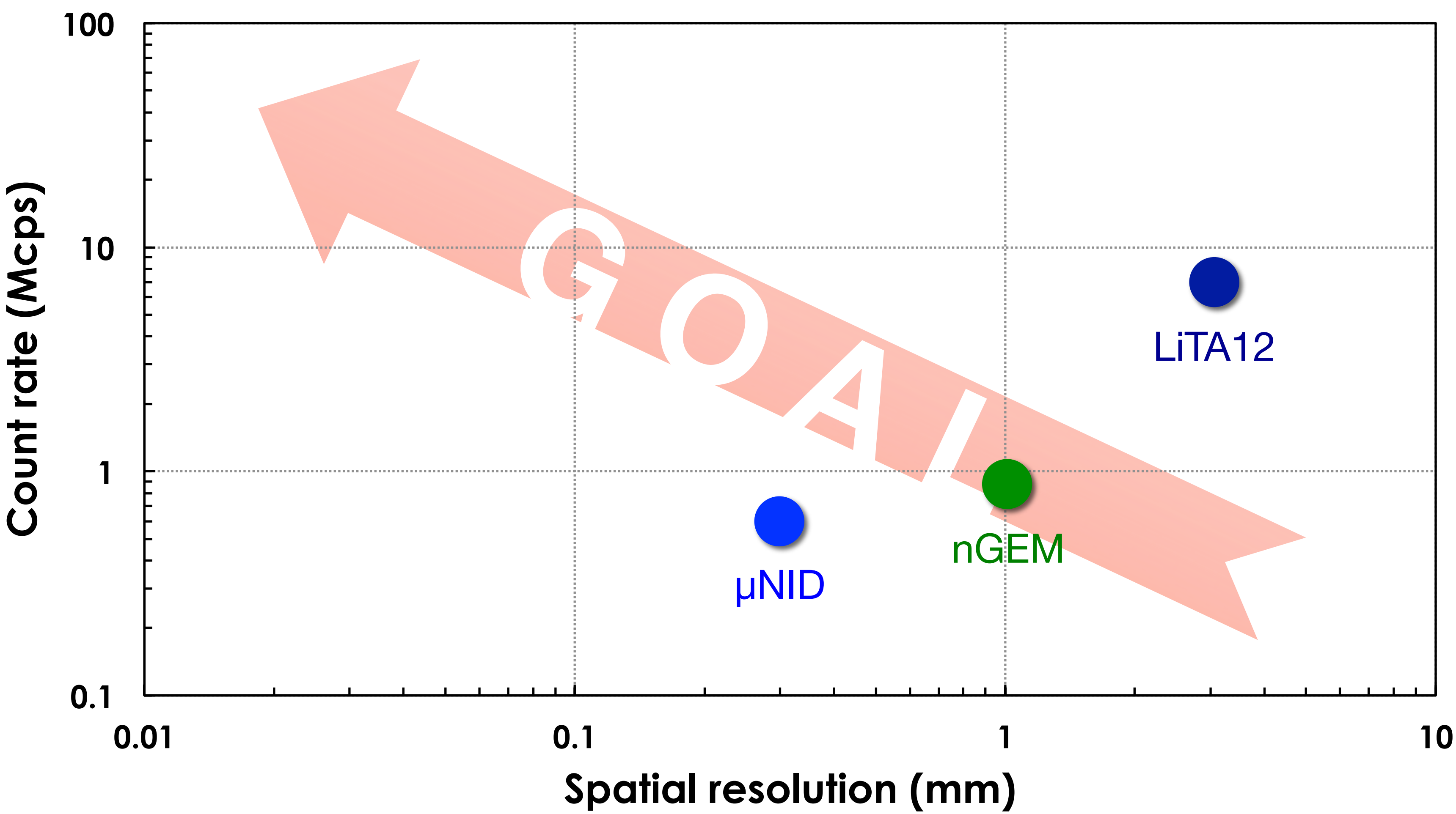
LiTA12

- Li-glass scint. (40% eff.)
- FOV: 5 × 5 cm^2
- **Δx=3mm**, Δt=40ns,6 Mcps

μNID

- Micro-pattern
- ^{3}He (18% eff.)
- FOV: 10 × 10 cm^2
- **Δx=0.3mm**, Δt=0.6μs, < 1 Mcps

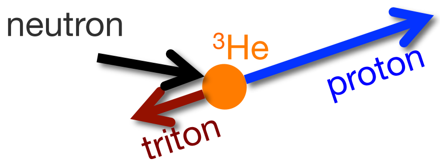
Current performance of counting-type detectors at RADEN



μPIC-based Neutron Imaging Detector (μNID)

μPIC-based neutron imaging detector (μNID)

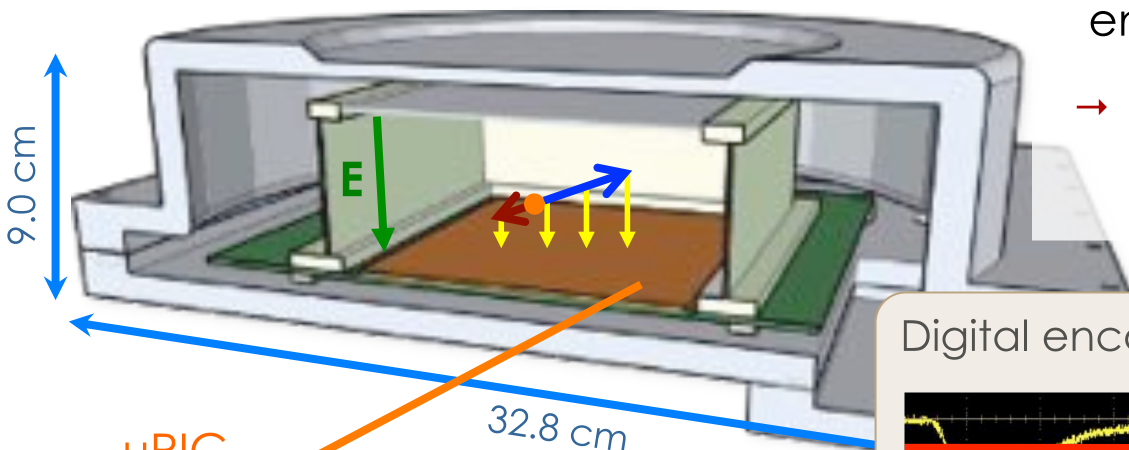
Neutron detection via ^{3}He



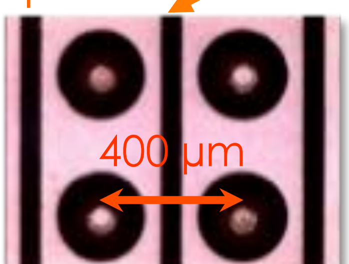
Track length
~8 mm in gas

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

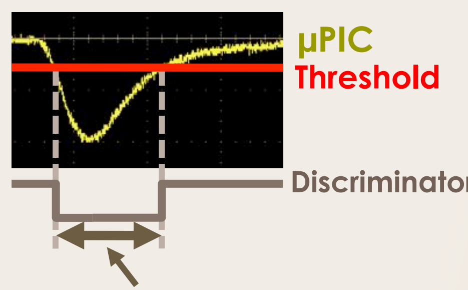
→ Good spatial resolution, strong background rejection, high data rates possible



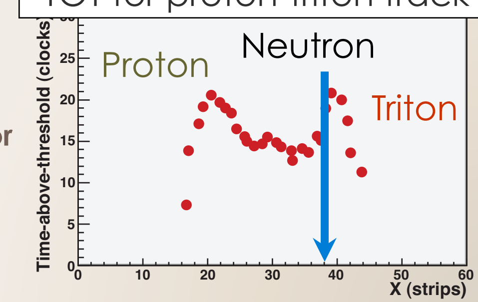
μPIC



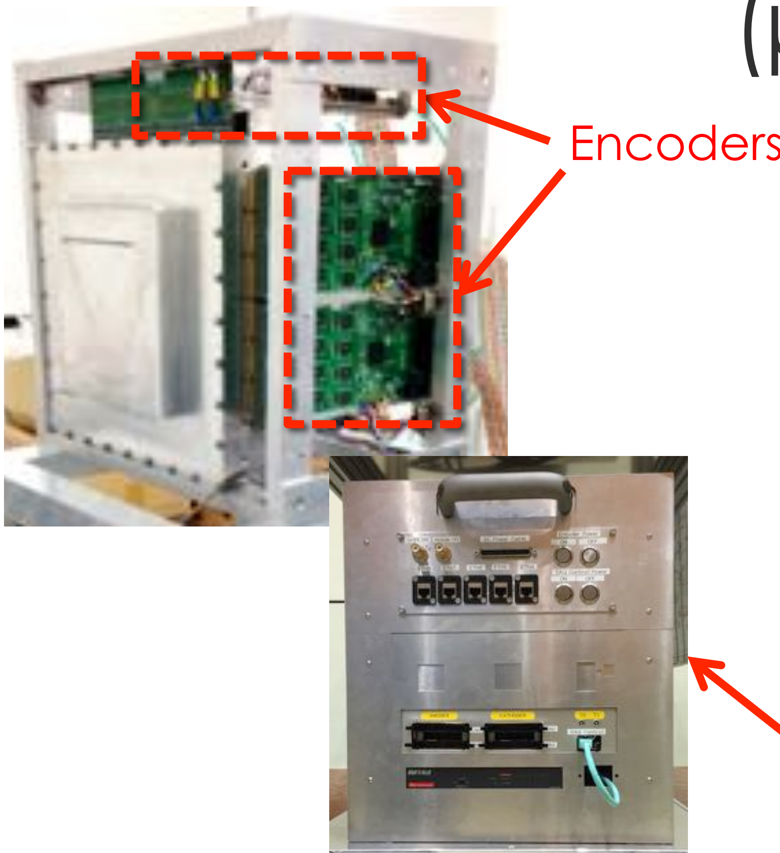
Digital encoder with time-over-threshold (TOT)

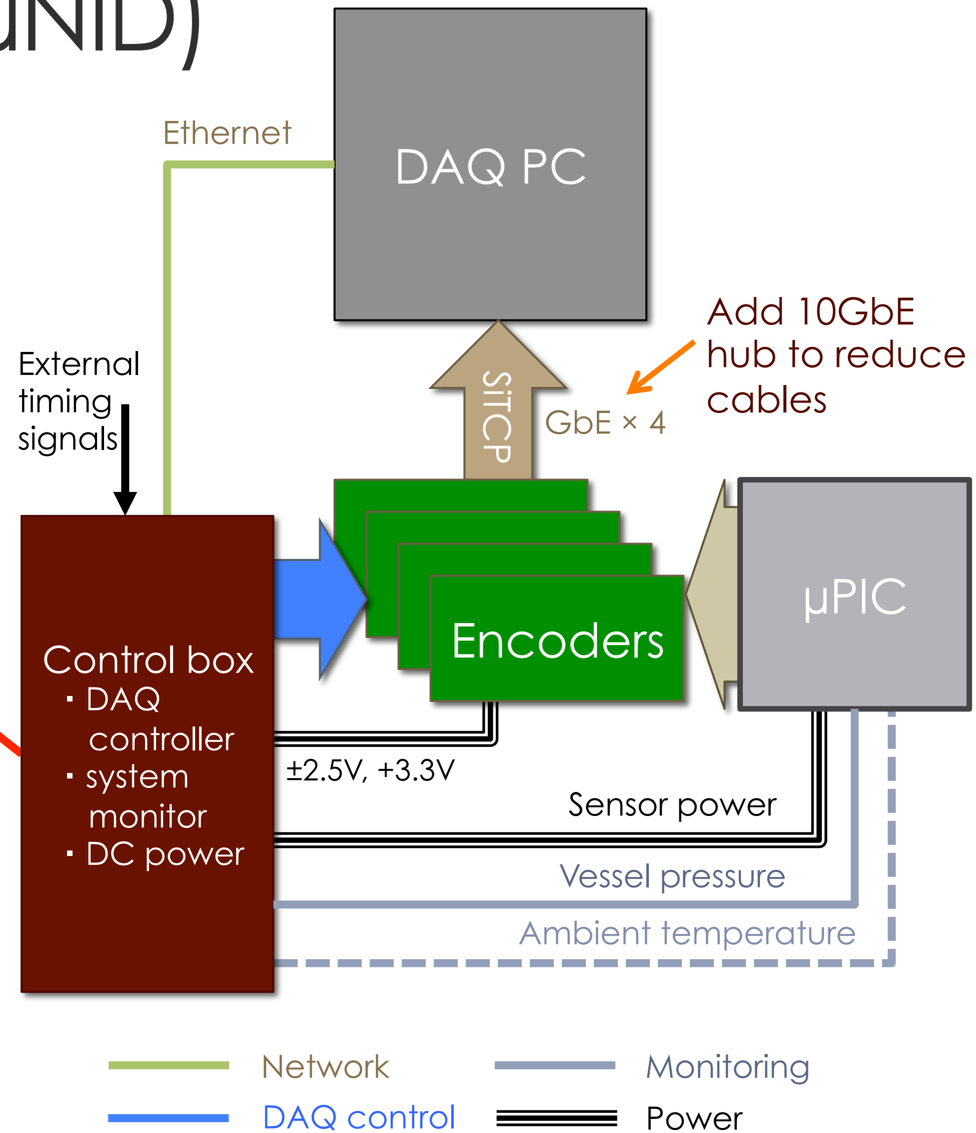


TOT for proton-triton track



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

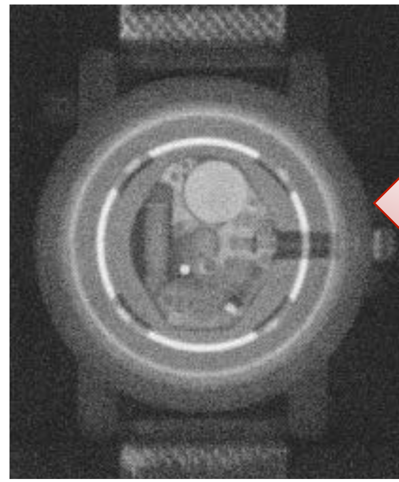
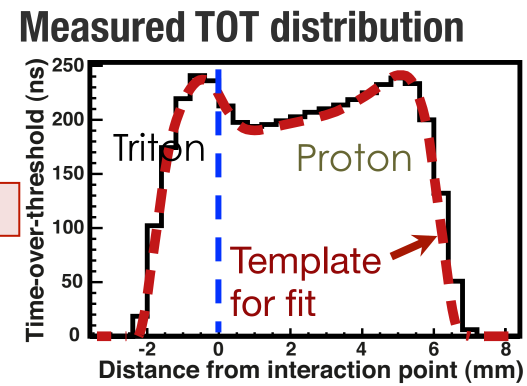
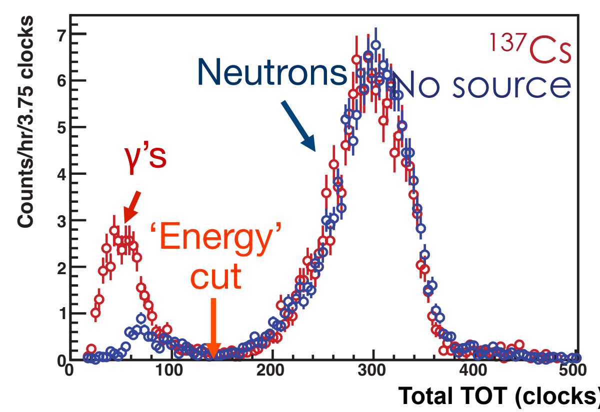


Image data taken at NOBORU in Feb. 2011





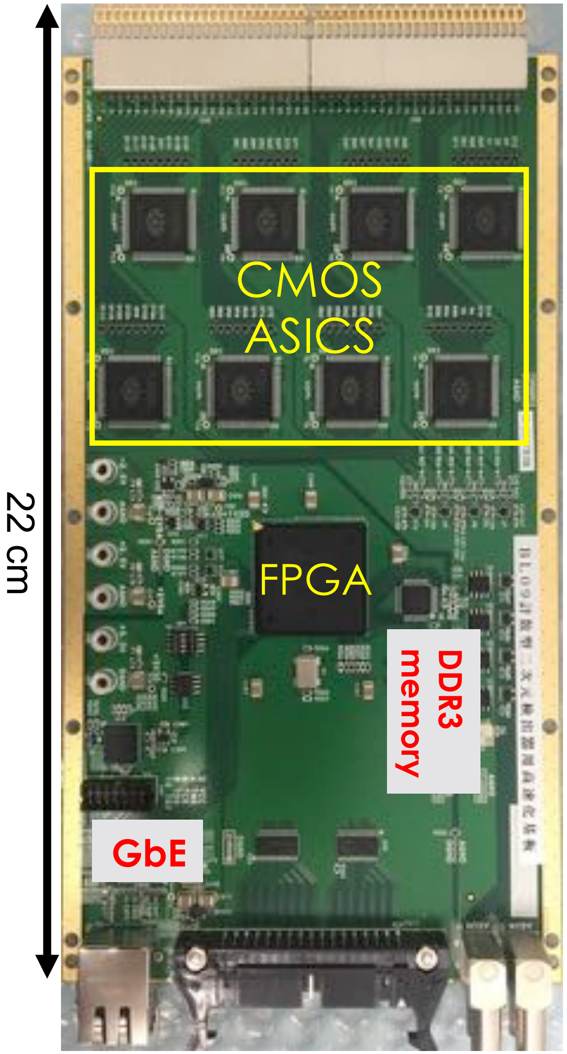
μNID performance characteristics	
Area	10 x 10 cm^2
Spatial res.	0.3 mm
Time res.	0.6 μs
Δ TOF/TOF	< 0.07% @18m
γ -sensitivity	< 10^{-12}
Efficiency	Up to 26%
Count rate	0.6 Mcps

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 (1st revision)
  - On-board DDR3 memory (2nd 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)

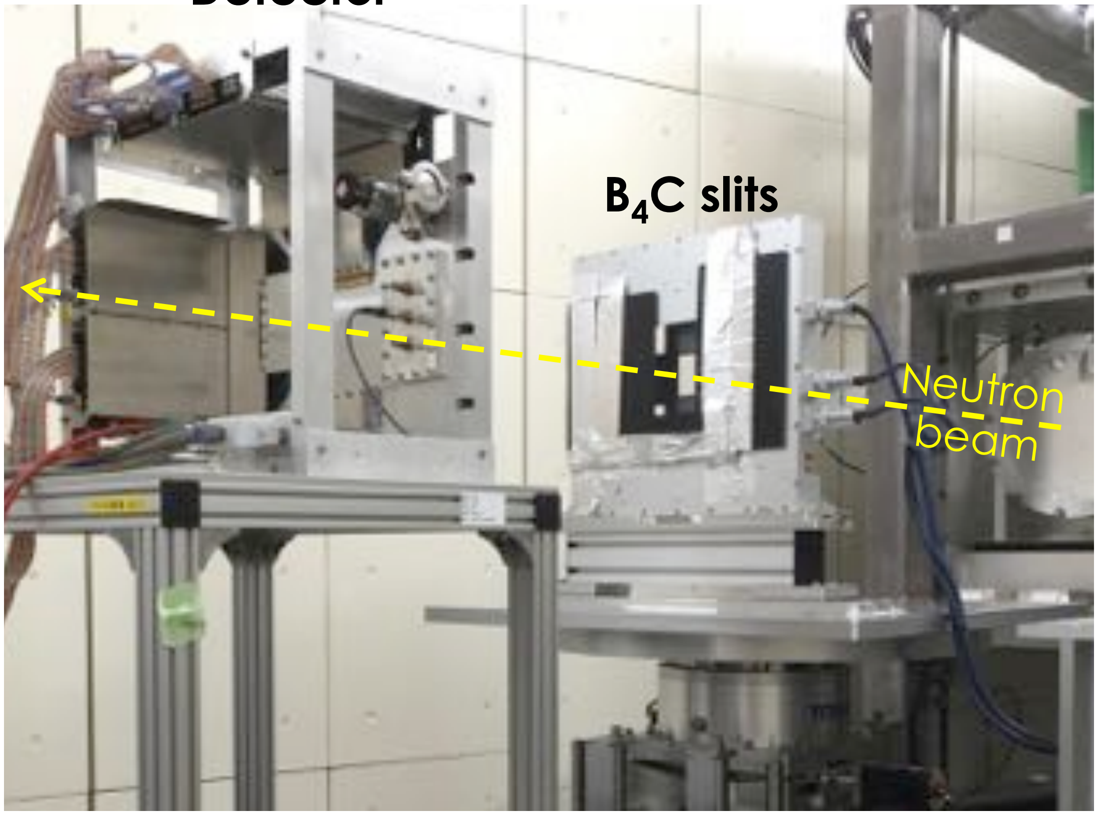
	Previous gas	New gas
Mixture	Ar-C_2H_6-^3He (67:7:30 @ 2atm)	CF_4-iC_4H_{10}-^3He (45:5:50 @ 2atm)
Drift velocity	23 μm/ns	58 μm/ns
Diffusion	275 μm/cm$^{1/2}$	80 μm/cm$^{1/2}$
Efficiency @25.3meV	18%	26%
Proton-triton track length	8 mm	5 mm

Gas characteristics simulated with MAGBOLTZ, GEANT4

Rate testing at RADEN

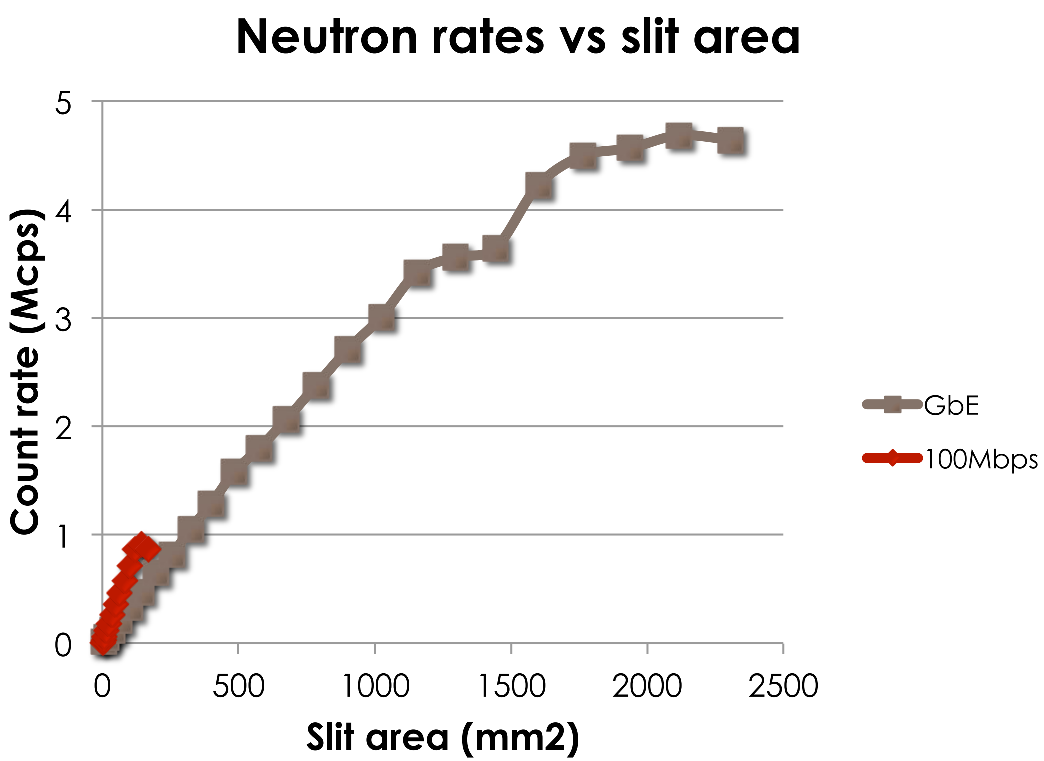
- Control incident intensity using B_4C slits
- Testing of
  - rate capacity of hardware
  - rate linearity of detector

Detector



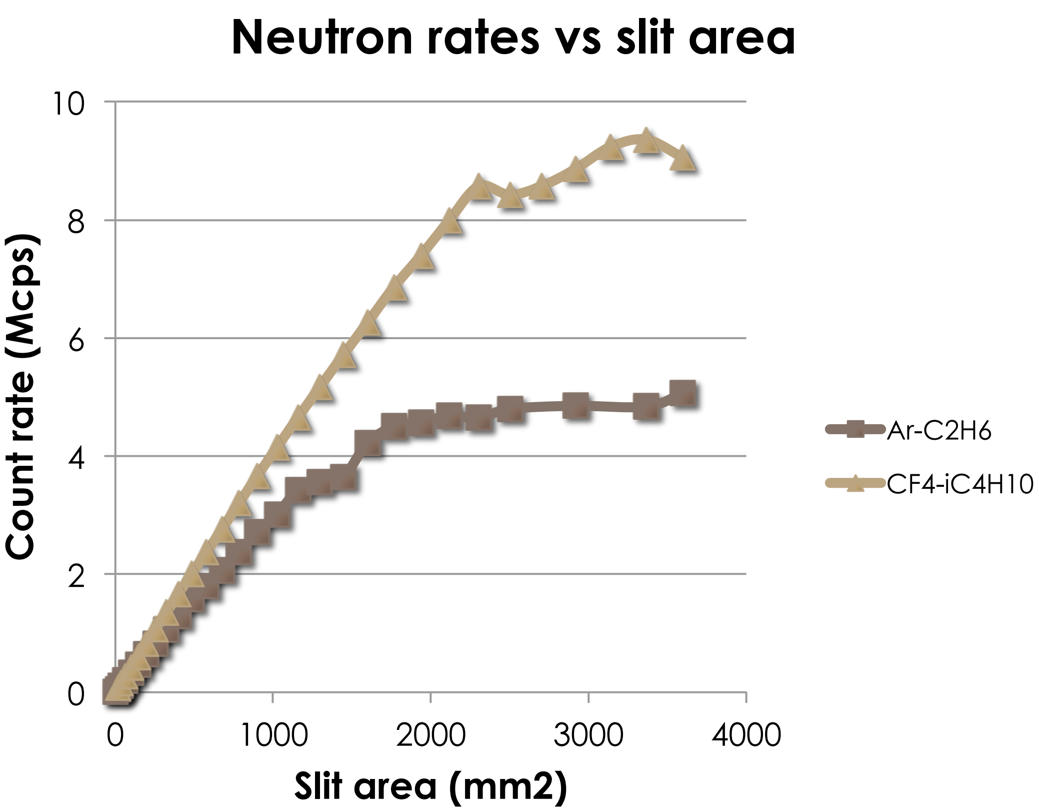
Rate testing at RADEN

- 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



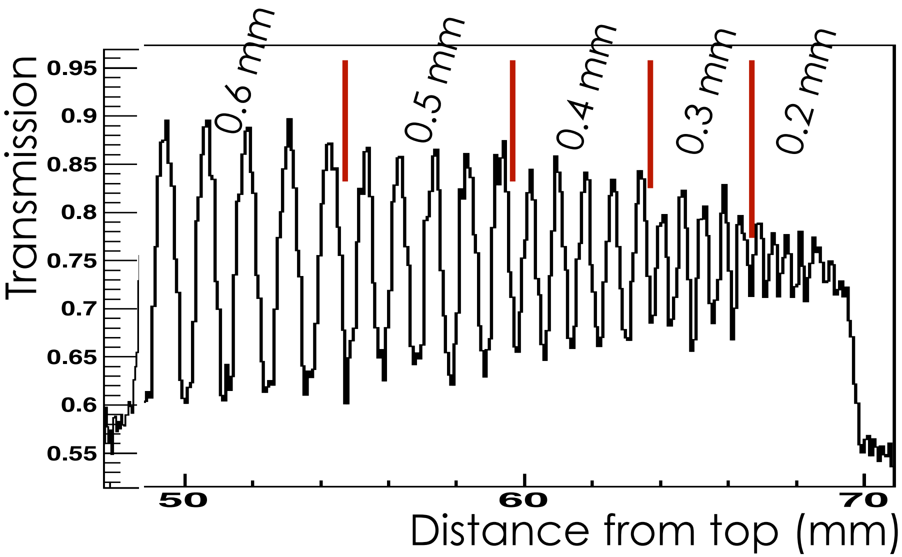
Rate testing at RADEN

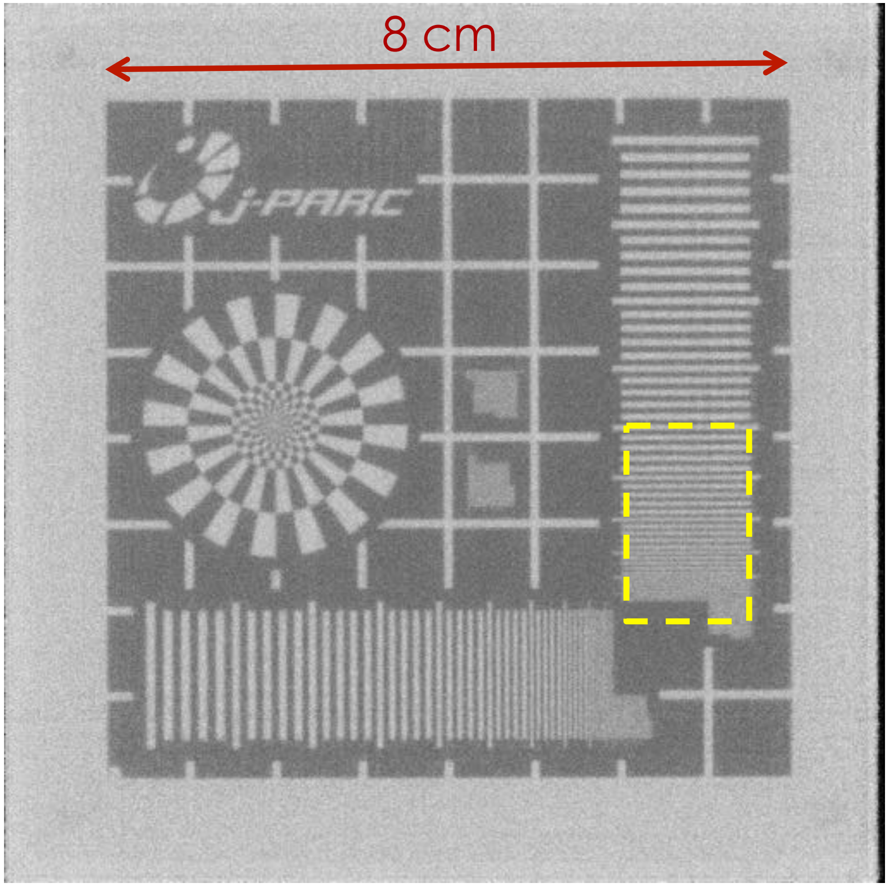
- Test of CF_4-based gas mixture
- Encoders with GbE
- Rate capacity over 8 Mcps
- Nearly factor of 2 increase over Ar-based gas mixture



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

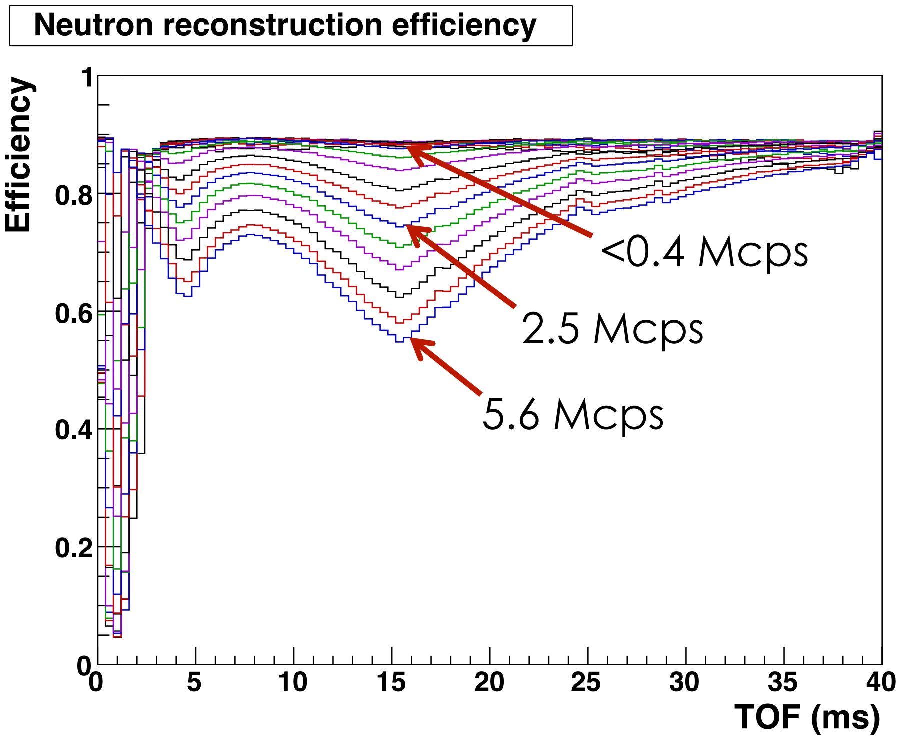




Bin size: 40 x 40 μm^2

Remaining issues

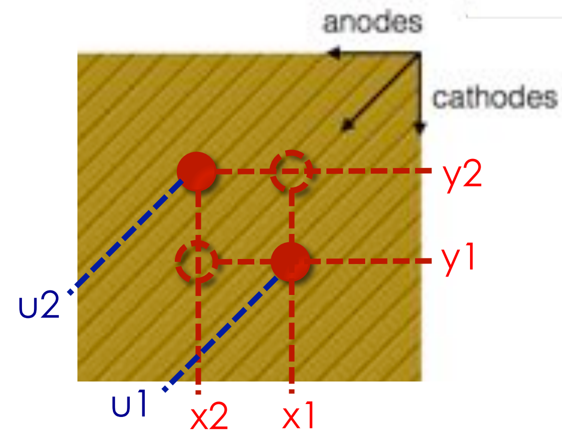
- Data analysis: performance of event clustering
  - Event 'pile-up' at rates above 100~300 kcps
  - Developing new algorithm
- Working with software company to improve speed and ease-of-use of analysis software

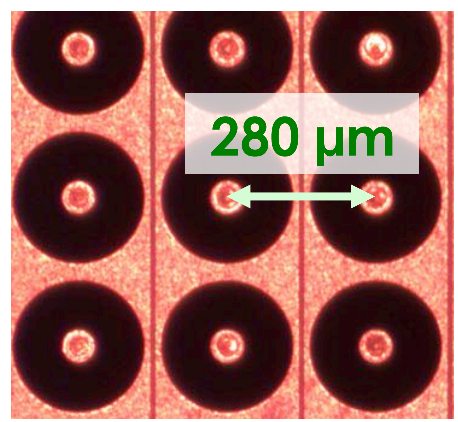


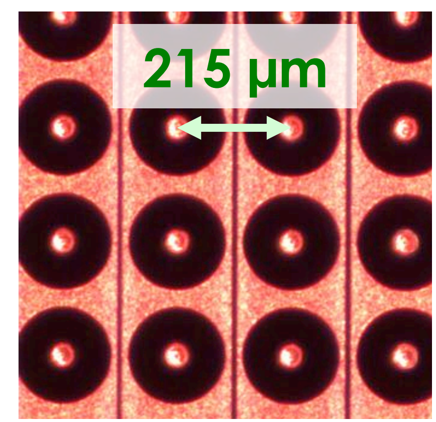
Efficiency of analysis determined by comparing numbers of raw hits and reconstructed neutron events

Other ongoing development

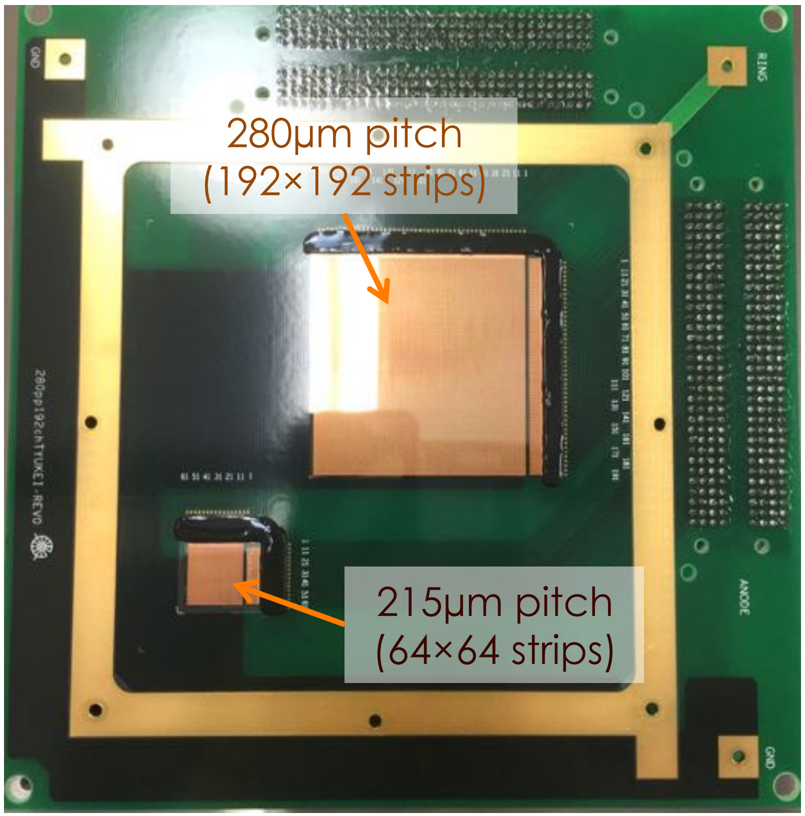
- New µPIC readout geometry
  - Additional strip plane at 45° to x,y strips
  - Aid in reconstruction of simultaneous events
  - Now testing at Kyoto U.
- Reduced strip pitch
  - Manufactured using MEMS (structures down to 10µm)
  - µPIC with 280, 215µm pitches
  - Performed preliminary testing at RADEN



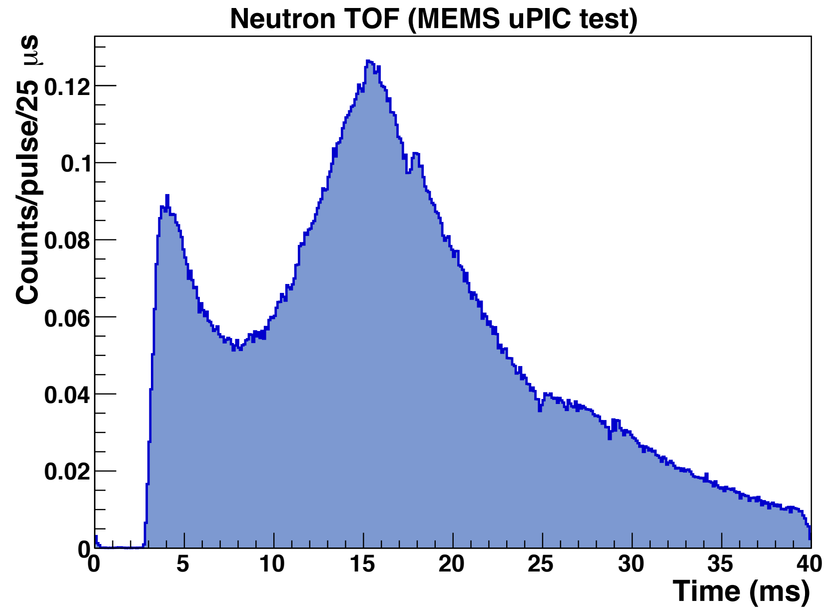




First on-beam test of MEMS µPIC at RADEN



MEMS µPIC test board



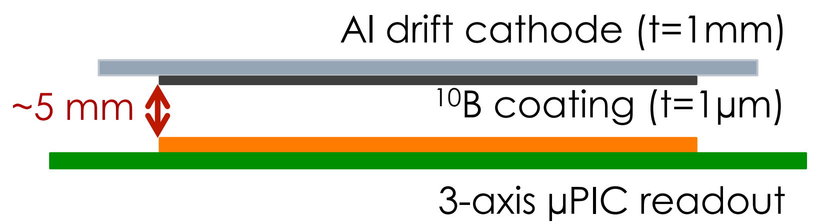
Neutron TOF spectrum measured on 215µm section

- 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

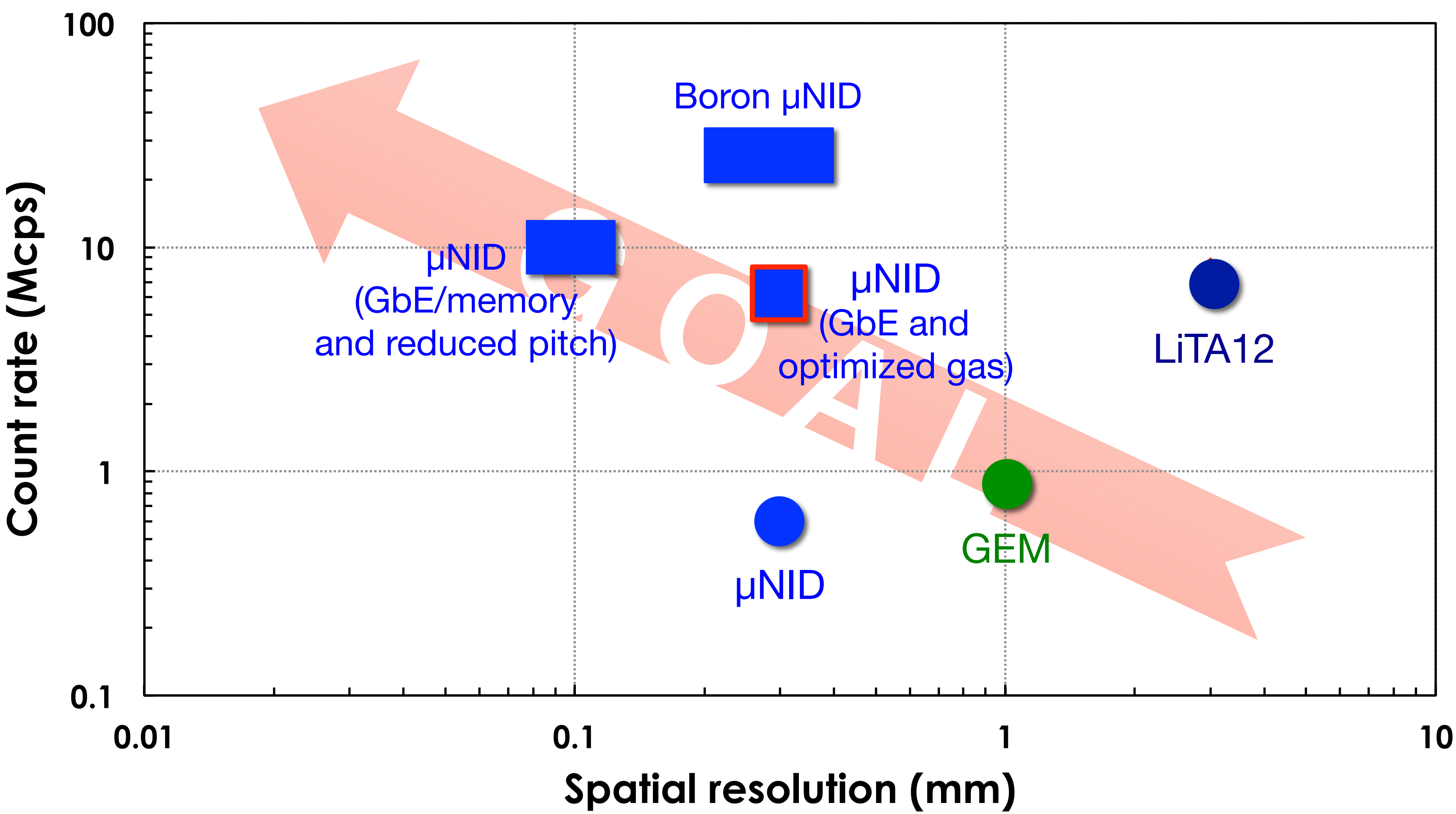
μNID with Boron converter

- ^{10}B-coated drift cathode (t=1μm)
- 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	
Efficiency@25.3meV	3~5%
Time resolution	10 ns
Spatial resolution	200~400 μm
Peak count rate	20~30 Mcps

Current and projected performance



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