Development of counting-type detectors for energy-resolved neutron imaging at RADEN

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CROSS
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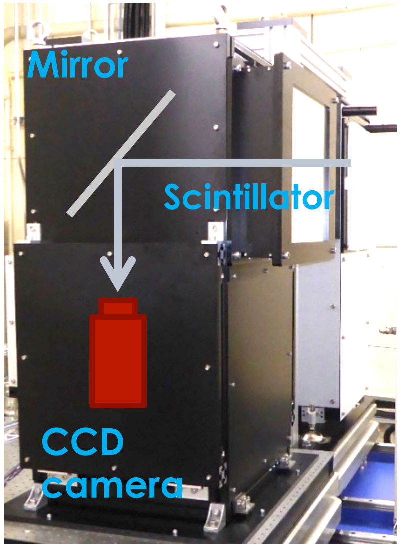
平成29年度中性子イメージング専門研究会　京都大学原子炉実験所　29 Dec 2017

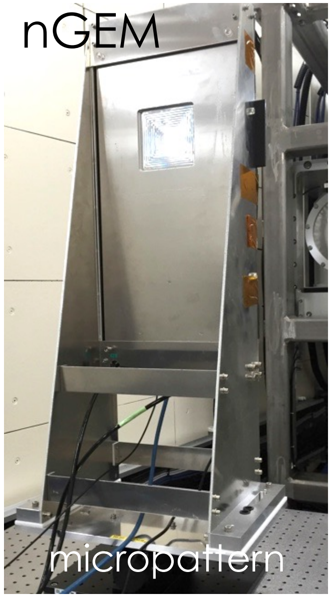
Neutron imaging detectors at RADEN

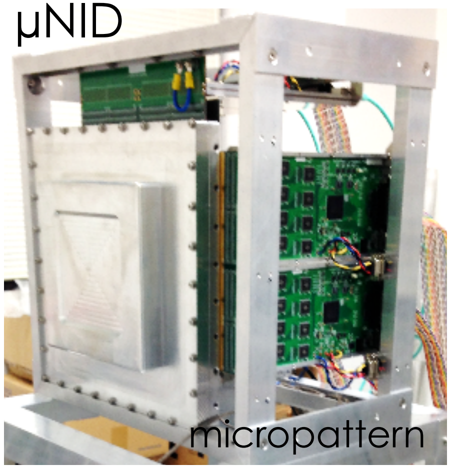
Camera type



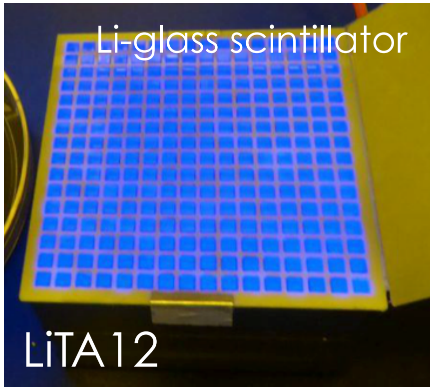
- Single-mirror CCD system (Andor iKon-L, EMCCD)
- Neutron color I.I. (high-res, high-speed)

Counting type

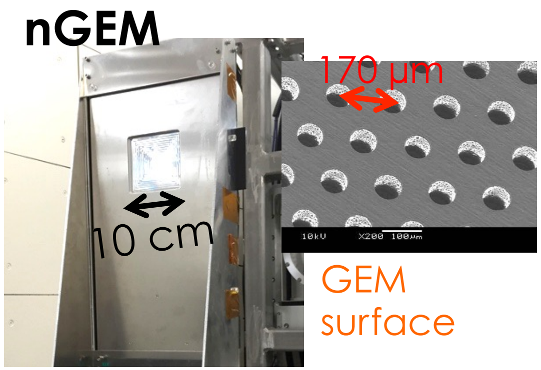


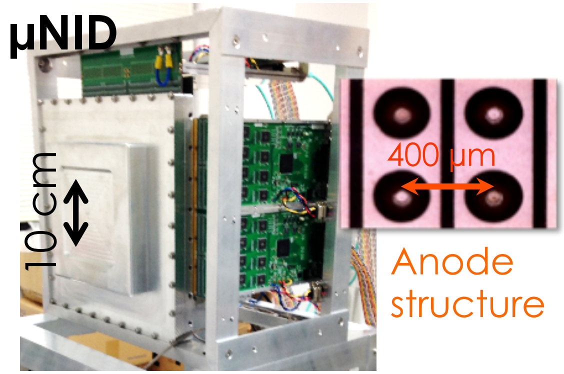


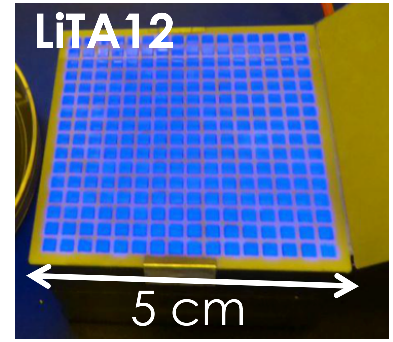
- nGEM (^{10}B)
- μNID (^{3}He)
- LiTA12 (^{6}Li)



Counting-type detectors at RADEN

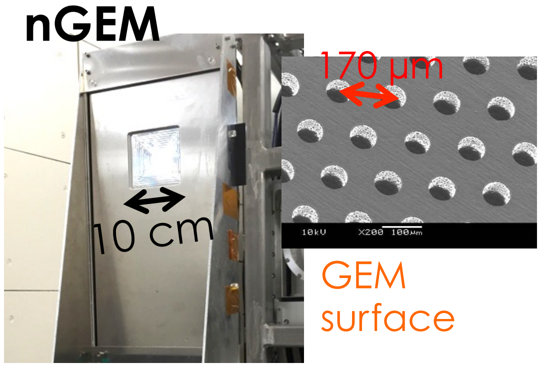


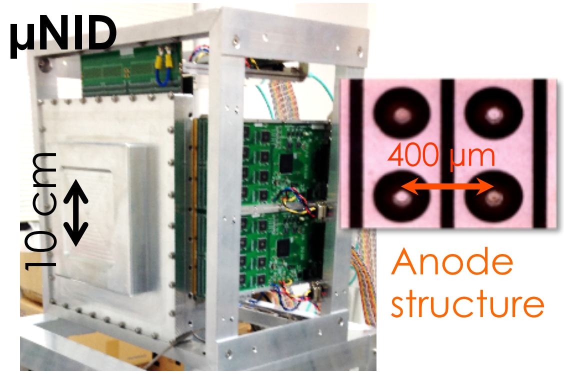


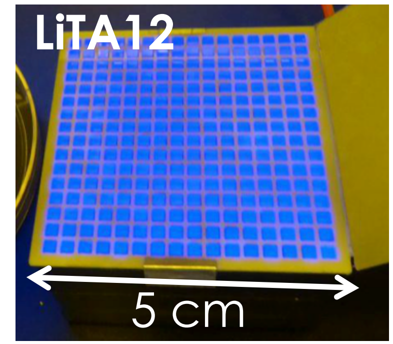


	nGEM	μNID	LiTA12
Detector type	Micropattern	Micropattern	Scintillator
Converter material	^{10}B	^{3}He	^{6}Li
Active area	100 x 100 mm^2	100 x 100 mm^2	50 x 50 mm^2
Spatial resolution	1 mm	0.1 mm	3 mm
Time resolution	10 ns	0.25 μs	40 ns
Efficiency (thermal)	10%	26%	23%
Count rate	< 0.5 Mcps	1 Mcps	6 Mcps
Gamma sensitivity	10^{-4}	$< 10^{-12}$	low

Counting-type detectors at RADEN







Focus of development at RADEN

	nGEM	μNID	LiTA12
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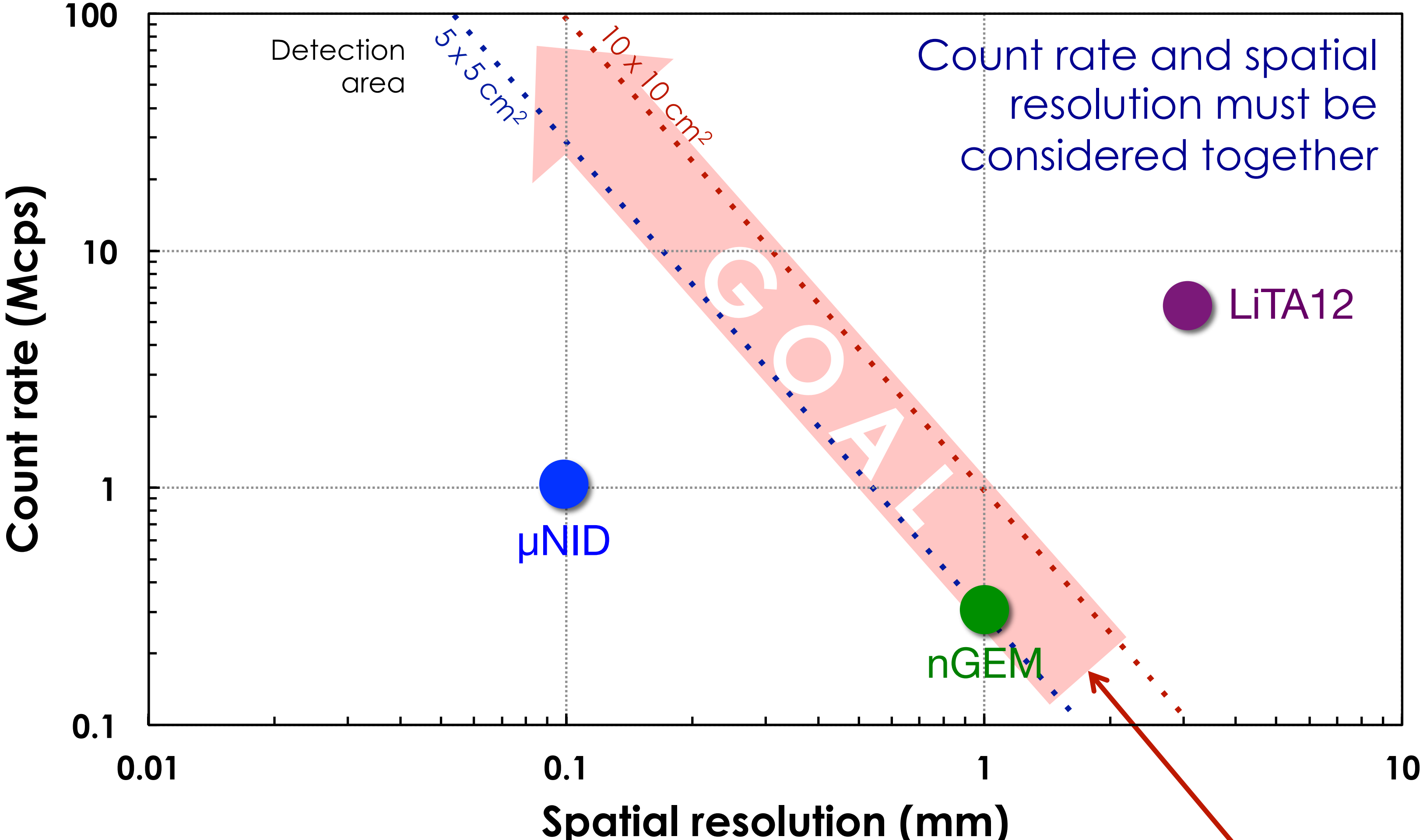
Current performance



Count rate required at given spatial resolution
for Bragg-edge measurement time of 10 hours

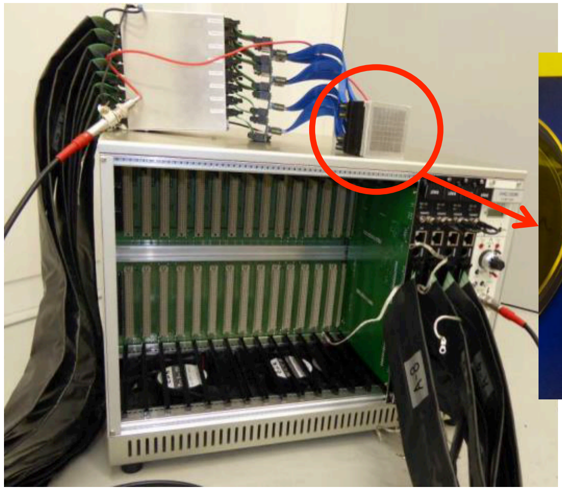
Development of counting-type detectors

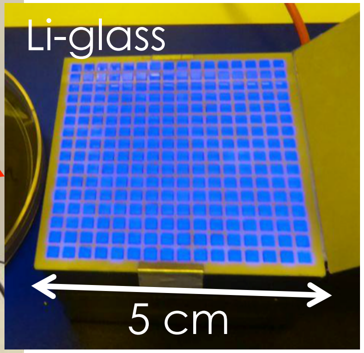
- Optimization of Li-glass detector
  - Improve spatial resolution using super resolution techniques
- Continuing development of μNID
  - Optimization of detector hardware/analysis algorithms
  - Small-pitch MEMS μPIC
  - μNID with boron converter
- Improvement of control/analysis software for Li-glass and μNID
  - Integration into RADEN control system
  - Optimization of analysis code, improve ease-of-use

LiTA12

Li-6 time analyzer 2012 (LiTA12)

- Li-glass scintillator with Ce activator (GS20) (2.1 x 2.1 x 1mm^3 x 256)
- Hamamatsu H9500 multi-anode PMT
- Improve spatial resolution with super resolution techniques
  - Charge centroiding with single, flat scintillator
  - Composite multiple images with sub-pixel shifts

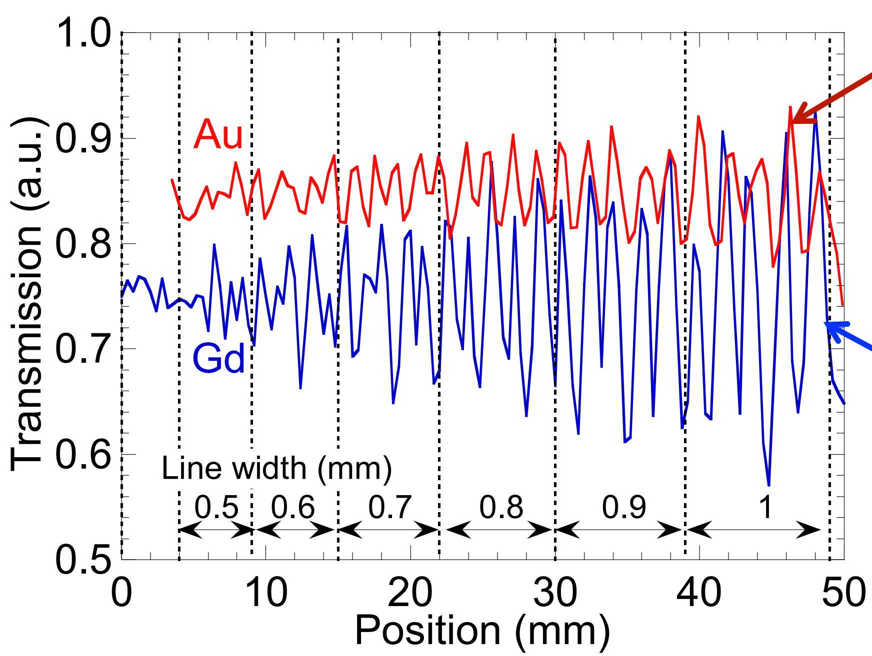


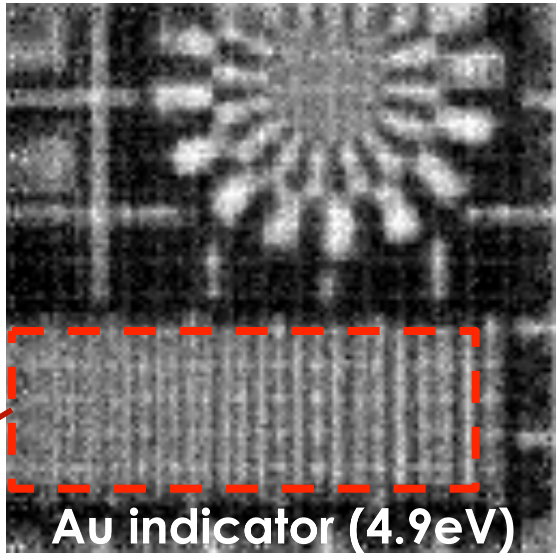


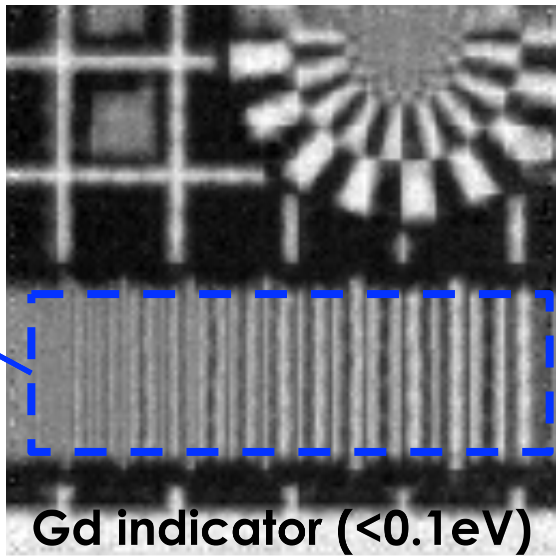
Li-glass detector parameters	
Area	5 x 5 cm^2
Spatial resolution	3 mm
Time resolution	40 ns ~
Efficiency (thermal)	23%
Count rate	6 Mcps

LiTA12 with charge centroiding

- 1mm thick ^{6}Li-glass plate in place of pixels
- Spatial resolution improved by the centroid computation
- ~0.7 mm was obtained for both Au, Gd indicators



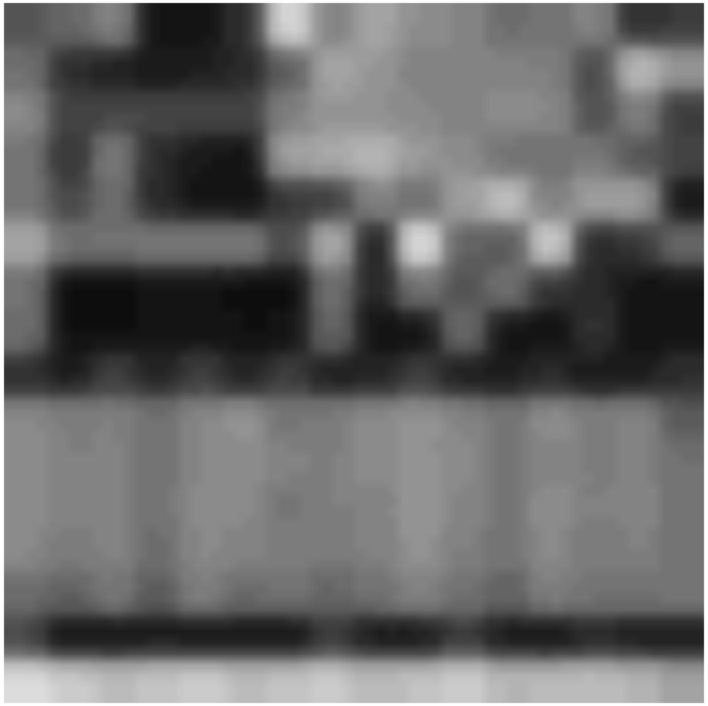




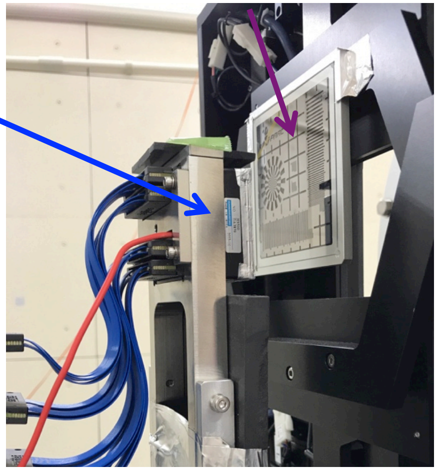
LiTA12 with multi-image compositing

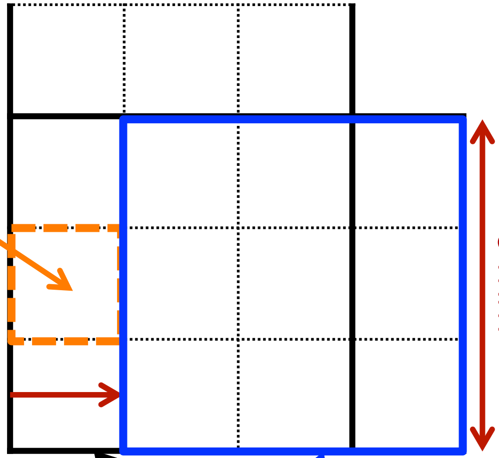
6 x 6 scan of Gd test chart

- 0.5 mm step size
- 36 images total



FOV: 50 x 50 mm^2





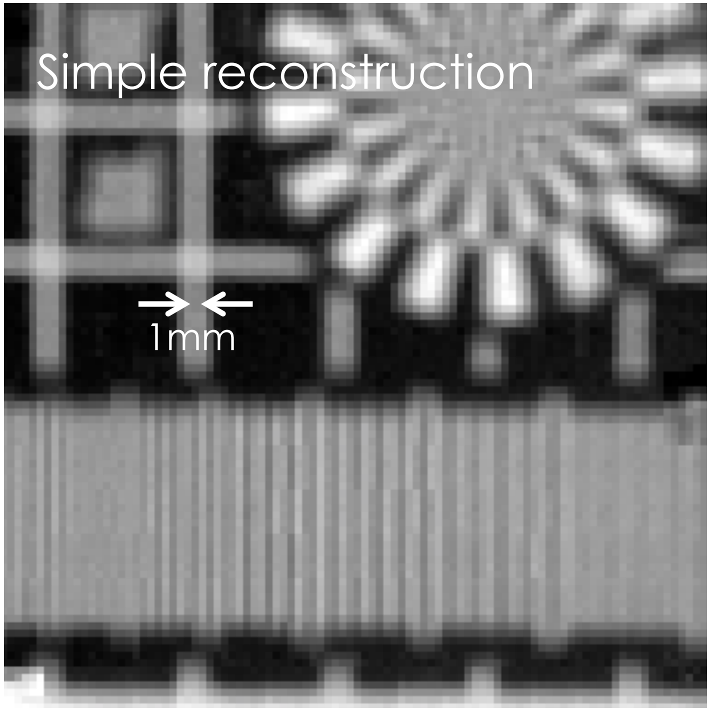
LiTA12 with multi-image compositing

6 x 6 scan of Gd test chart

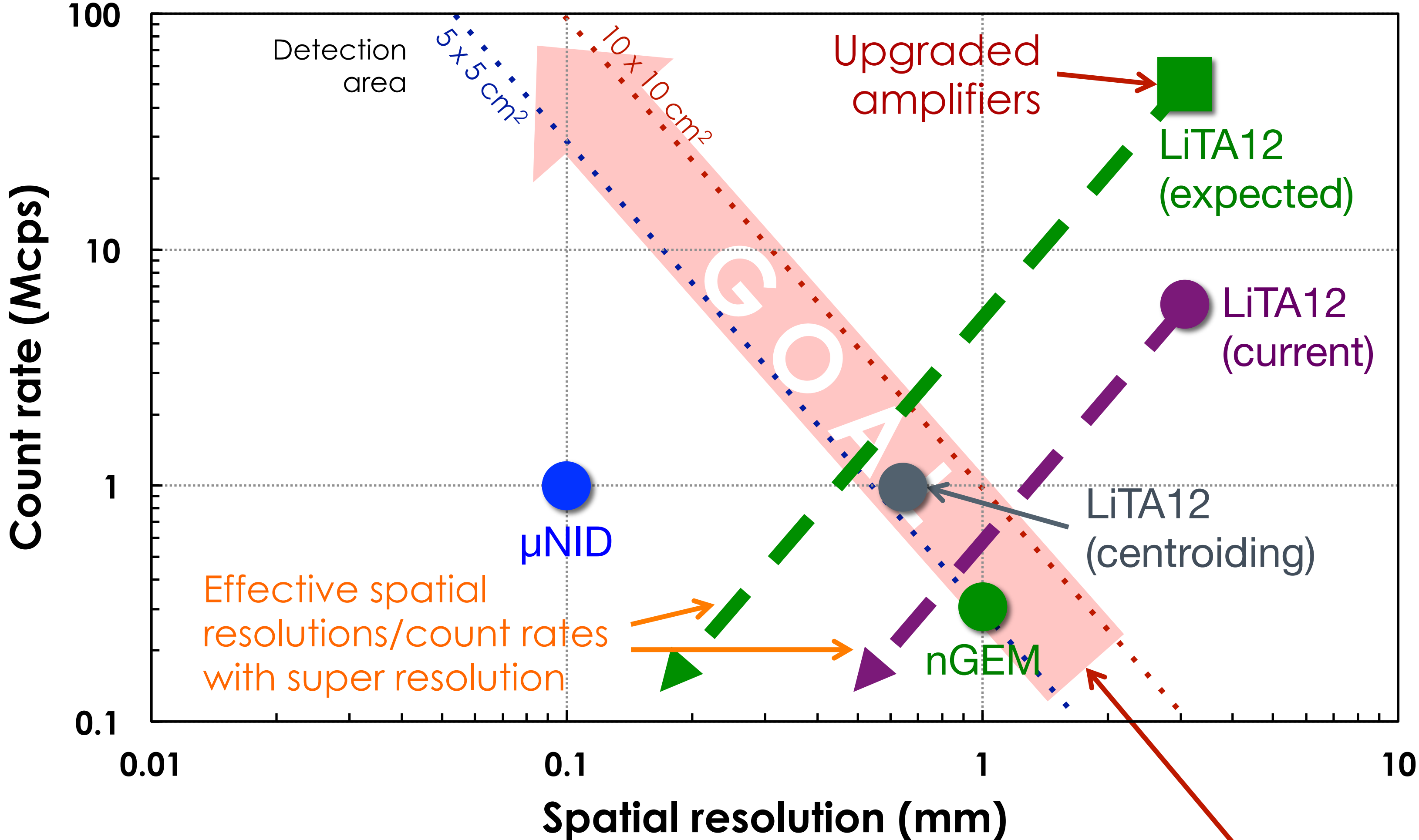
- 0.5 mm step size
- 36 images total

Simple reconstruction indicates it should be possible to extract sub-pixel features

FOV: 50 x 50 mm²



LiTA12: current and expected performance

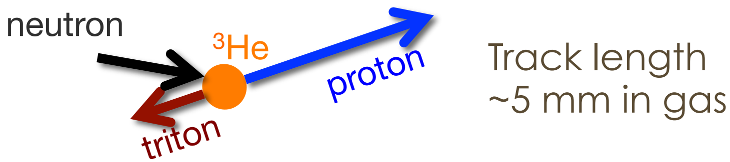


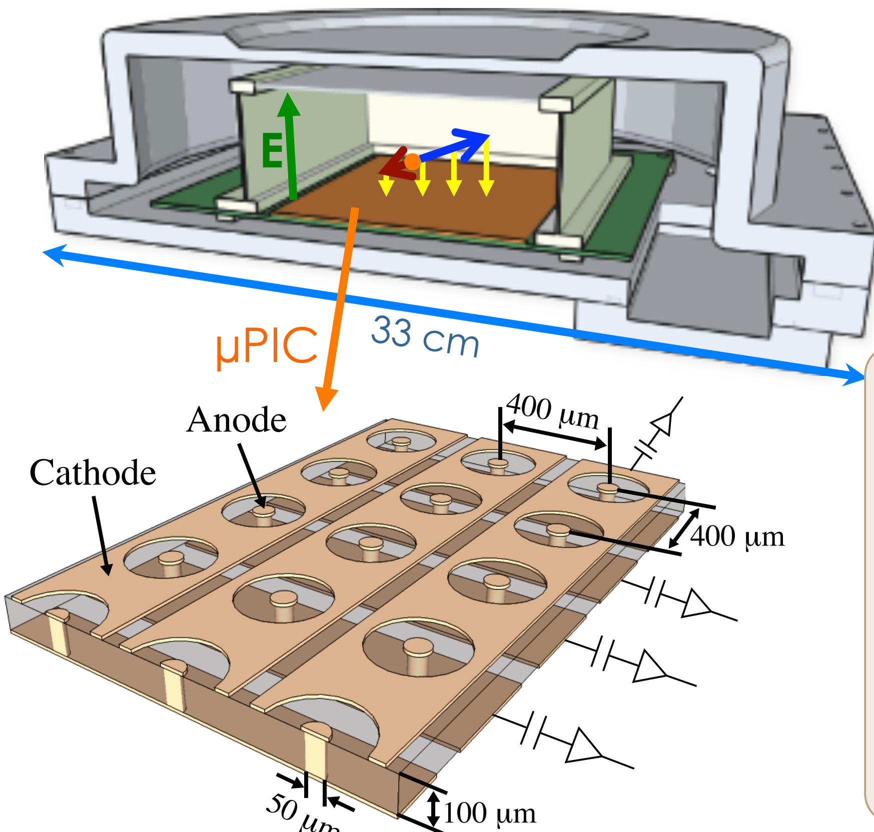
Count rate required at given spatial resolution for Bragg-edge measurement time of 10 hours

Standard μNID

μPIC-based neutron imaging detector (μNID)

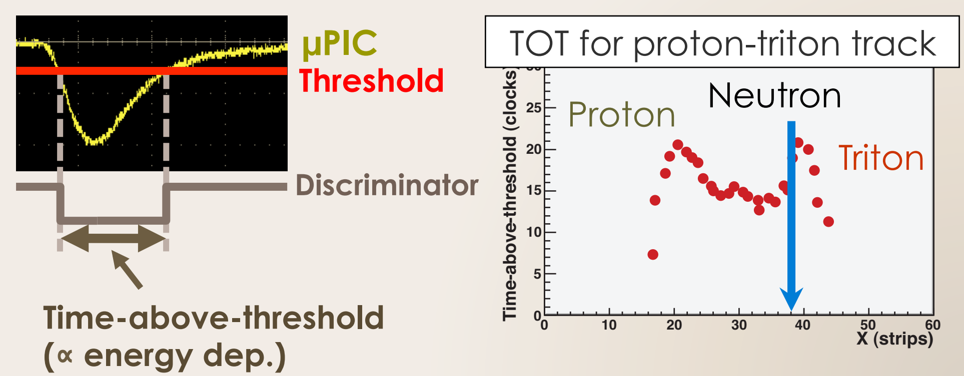
Neutron detection via ^{3}He



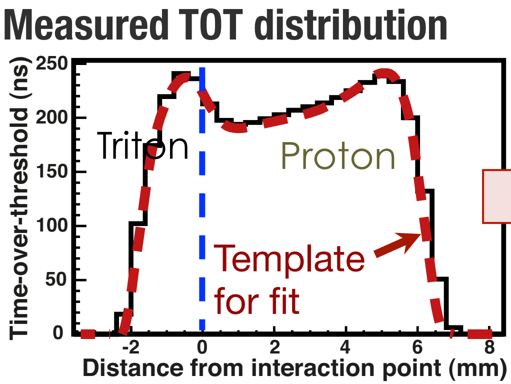


- CF_4-isobutane-^{3}He (45:5:50) gas mixture at 2 atm
- 3-dimensional tracking of decay pattern
- Energy via time-over-threshold
- Compact ASIC+FPGA data encoder

Digital encoder with time-over-threshold (TOT)



Performance of standard μNID



Fine spatial resolution from fit to TOT distribution

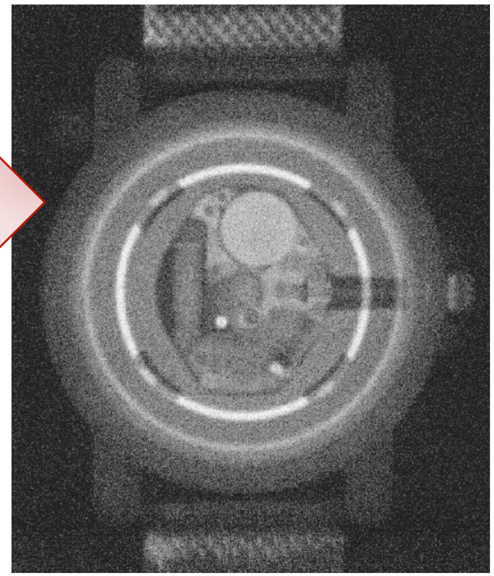
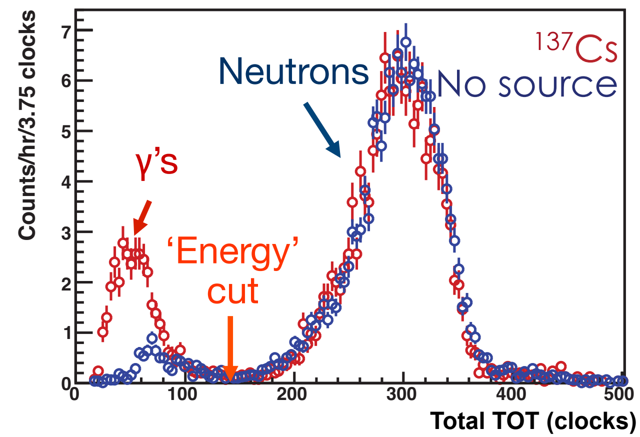


Image taken at NOBORU (2011)

Strong gamma rejection using sum of TOT



Performance characteristics						
Active area	Spatial resolution	Time resolution	γ-sensitivity	Efficiency @25.3meV	Rate capacity	Effective max. rate
10 x 10 cm^2	0.1 mm	0.25 μs	< 10^{-12}	26%	8 Mcps	1 Mcps

Spatial resolution at RADEN

- Refinement of neutron position reconstruction algorithm
- Image of Gd test pattern
- L/D: 5000, Exposure: 1.5 hours
- 10% contrast at 5 lp/mm (100μm line width)

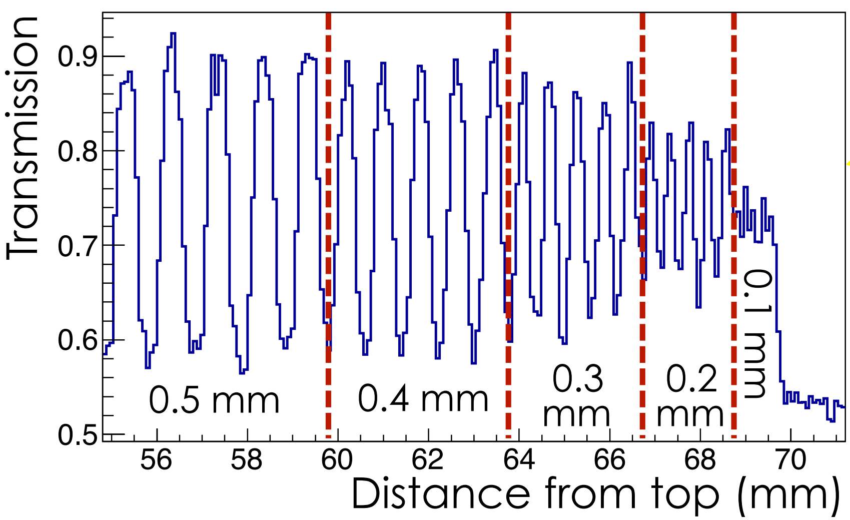
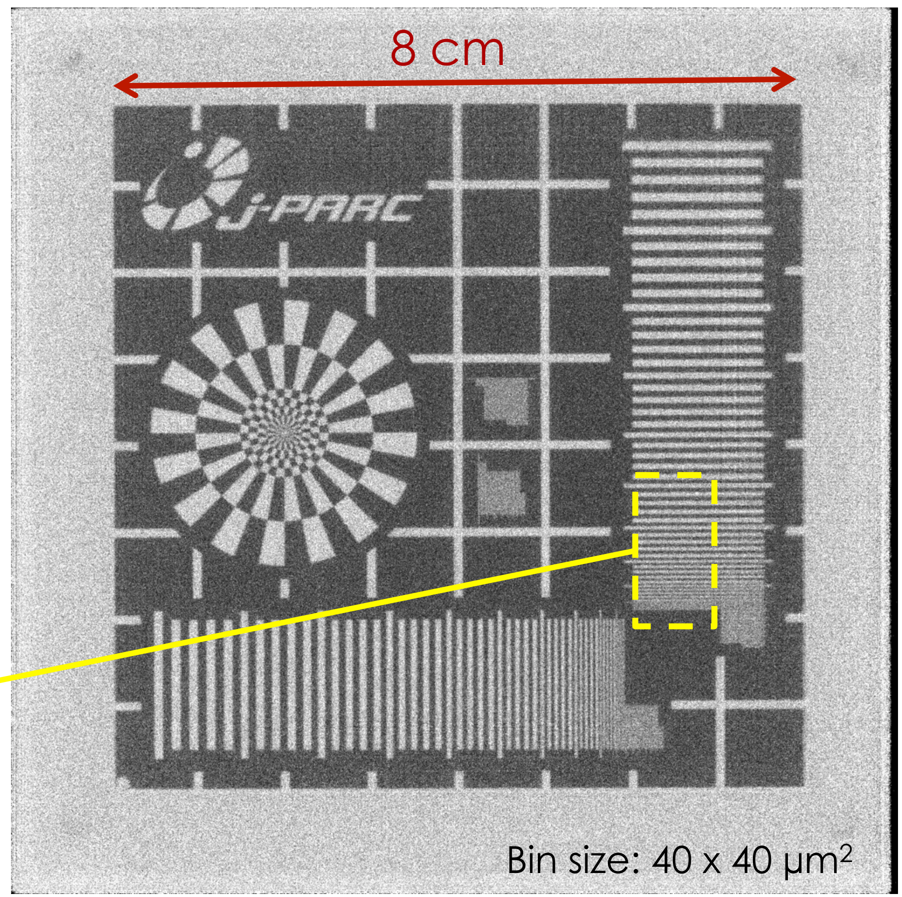
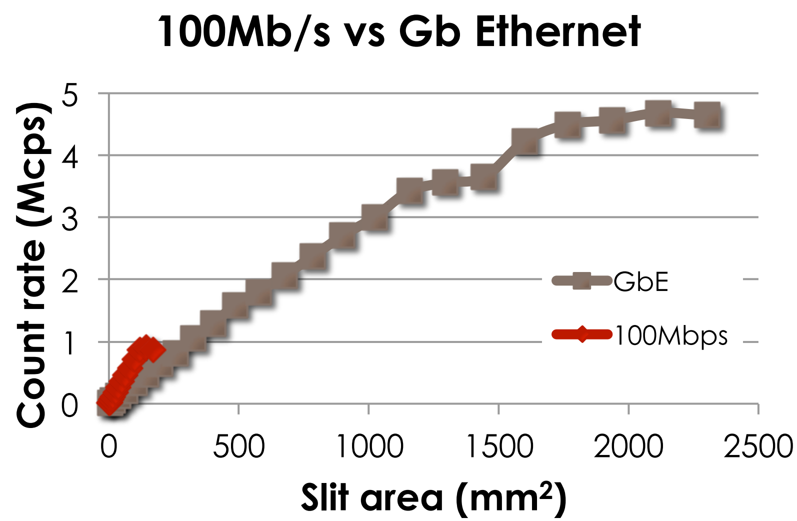


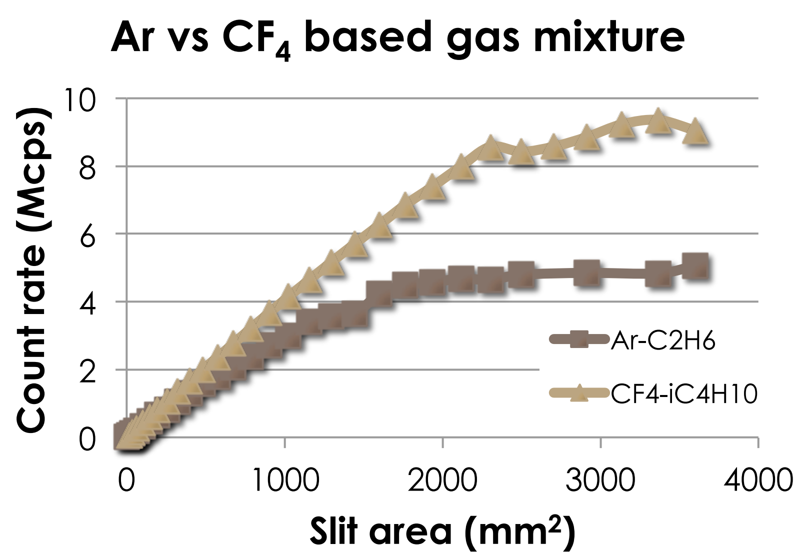
Image of Gd test target



Optimization of rate performance

- Revised data encoder hardware (100BASE-T → Gigabit Ethernet)
  - → About 7 times increase in rate capacity
- Change from Ar to CF_4 based gas mixture
  - → About 2 times increase due to smaller event size
- Total increase in count rate capacity from 0.6 to 8 Mcps
- Usable rate limited by offline analysis

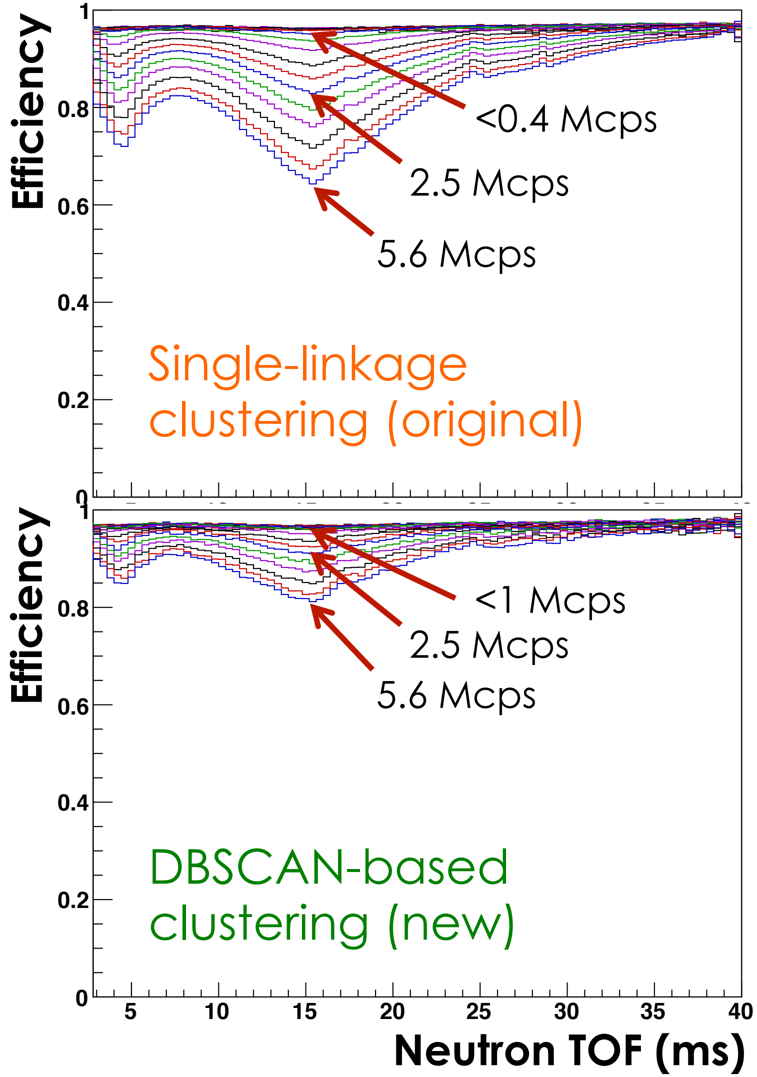




Improvement of clustering algorithm

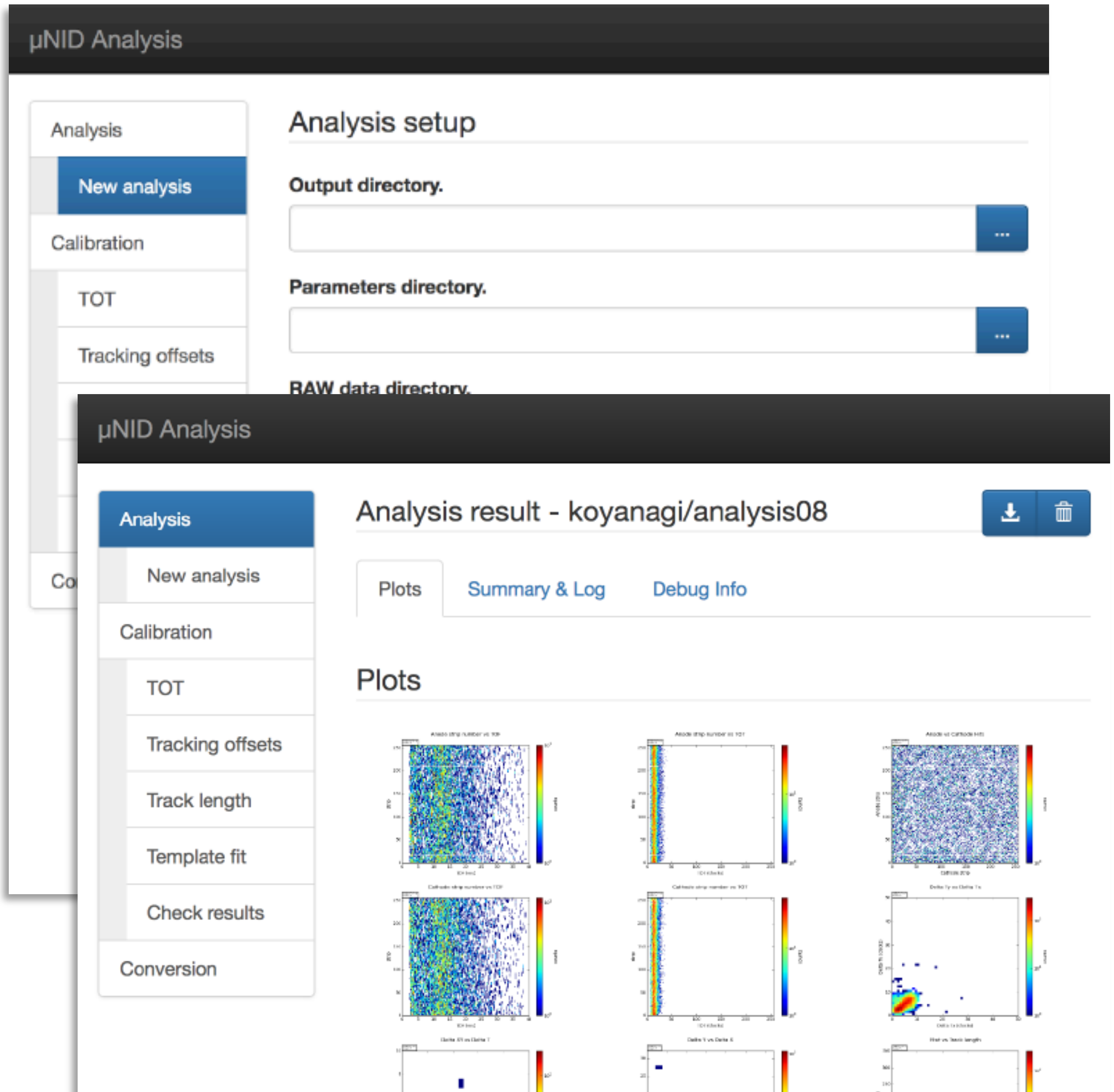
- Raw hits are clustered into neutron events (~14 hits/ event)
- Change from single-linkage algorithm to DBSCAN-based algorithm with explicit pile-up event resolution
- Event loss improved from 2% at 400 kcps to 2% at 1 Mcps
    - Data taken with fixed area and increasing neutron flux
    - Efficiency of analysis determined by comparing numbers of raw hits and reconstructed neutron events

Event reconstruction efficiency



μNID analysis GUI/control software

- Preparing new GUI for offline analysis
  - Focus on ease-of-use
- Preparing new control software
  - Based on DAQ middleware
  - Integration into beam line control system (IROHA2)

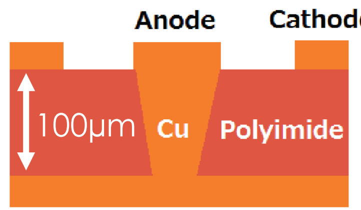


Small-pitch MEMS μPIC

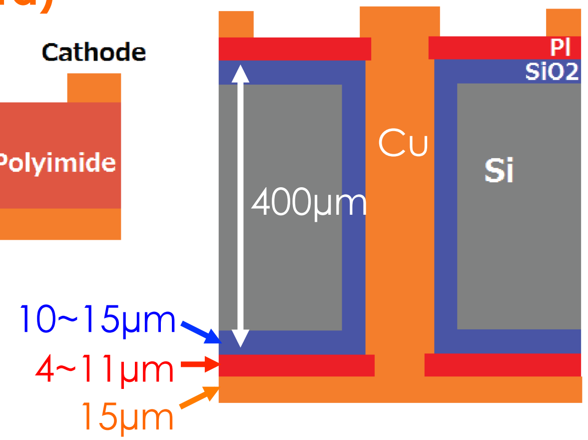
Small-pitch MEMS μPIC

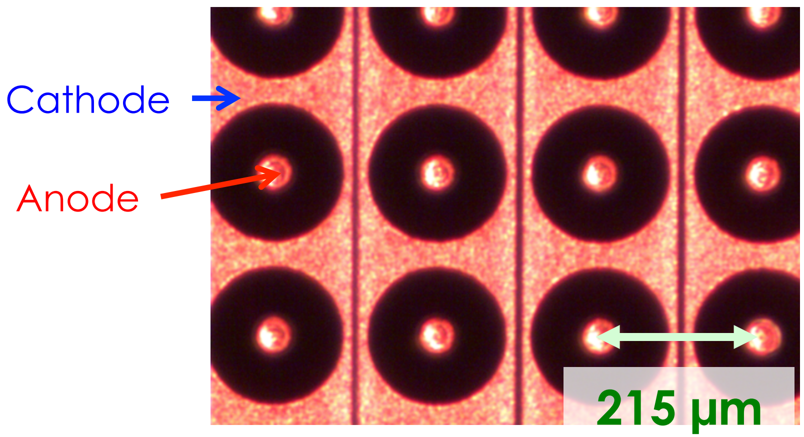
- Improve spatial resolution by reducing strip pitch
- Develop small-pitch μPIC
  - Standard μPIC (400μm) → limit of printed circuit board process
  - Manufacture using MEMS on silicon substrate (大日本印刷)
  - Started with small test element (14 x 14 mm^2); now preparing larger MEMS μPICs (55 x 55 mm^2)
- Initial tests found issue with gain stability
  - Steady increase under neutron irradiation → effect of Si substrate

PCB μPIC (standard)



MEMS μPIC

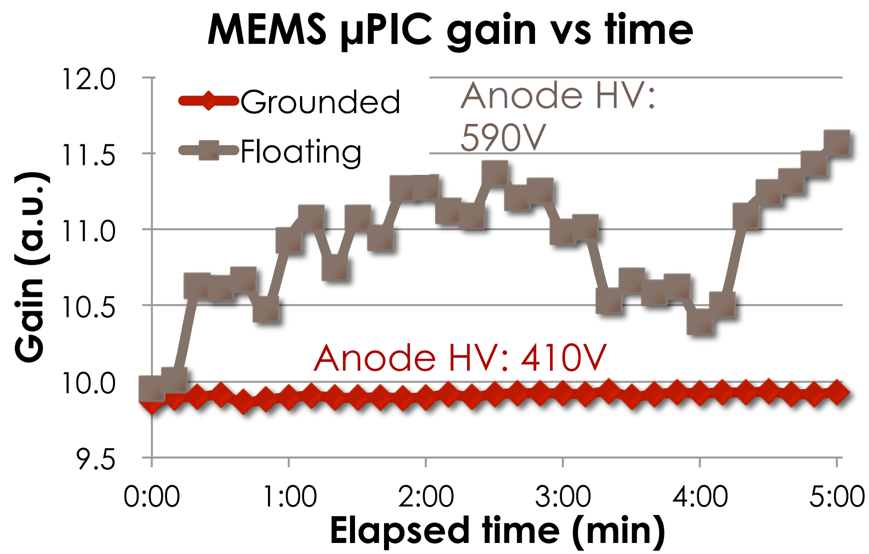


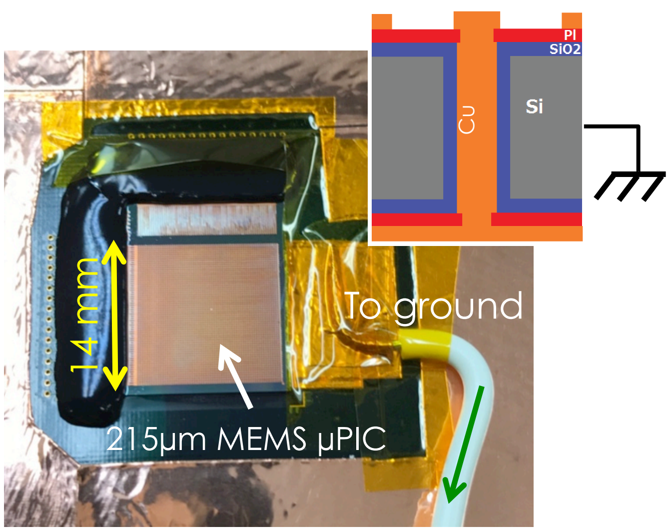


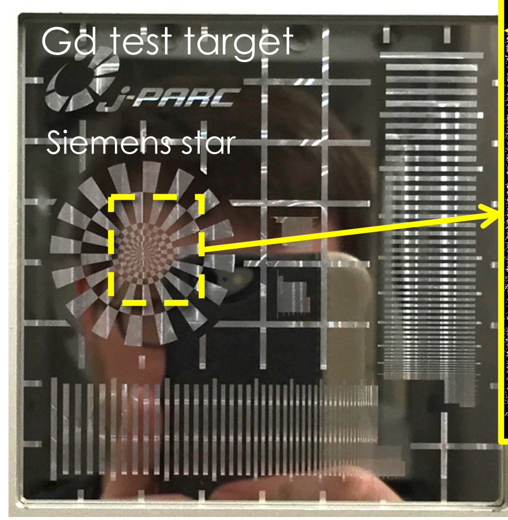
Surface of MEMS μPIC (digital microscope)

MEMS μPIC tests at RADEN

- MEMS μPIC gain observed to increase with neutron exposure
- Grounding Si substrate appeared to stabilize gain
- First image successfully taken after stabilizing gain







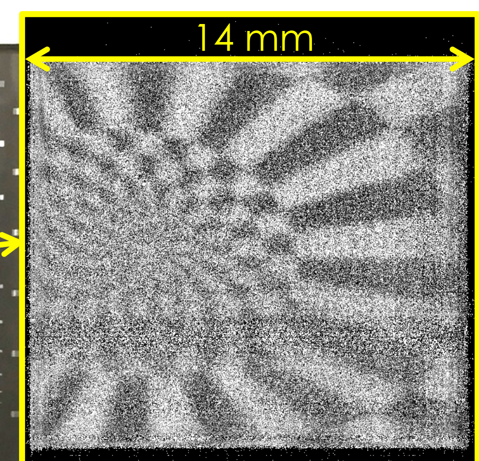
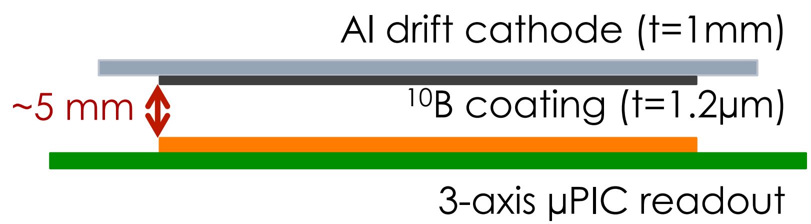


Image taken with 215μm pitch MEMS μPIC at BL22

μNID with boron converter

μNID with boron converter (B-μNID)

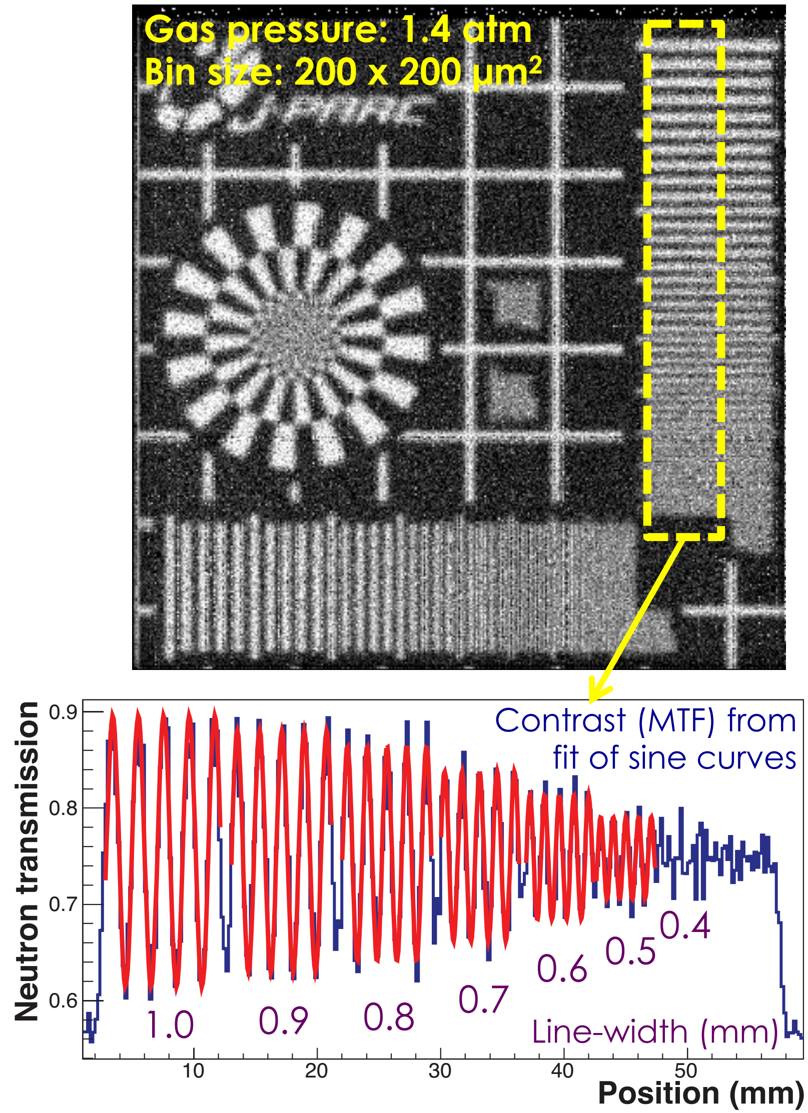
- Increase count rate capacity by reducing event size
  - Switch from ^{3}He (p,t) to ^{10}B (α,Li) for 3x smaller event size
  - Trade-off in spatial resolution
- μNID with flat boron converter (for initial testing)
  - Thin ^{10}B layer → low efficiency (3~5%)
- Consider ways to improve detection efficiency



Expected performance	
Efficiency@25.3meV	3~5%
Time resolution	10 ns
Spatial resolution	0.4~0.5 mm
Peak count rate	20~30 Mcps

Spatial resolution study at RADEN

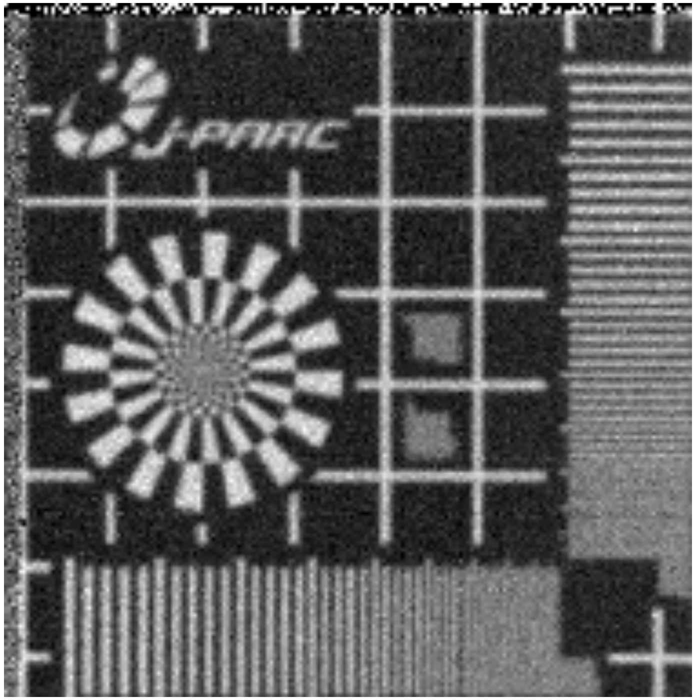
- Study of spatial resolution, event size vs. gas pressure (1.2 ~ 1.6 atm)
- L/D:1000, Exposure time: 15 mins
- Spatial resolution estimated from contrast of line-pairs (MTF)
- Maximum count rate estimated from event size: 22 Mcps



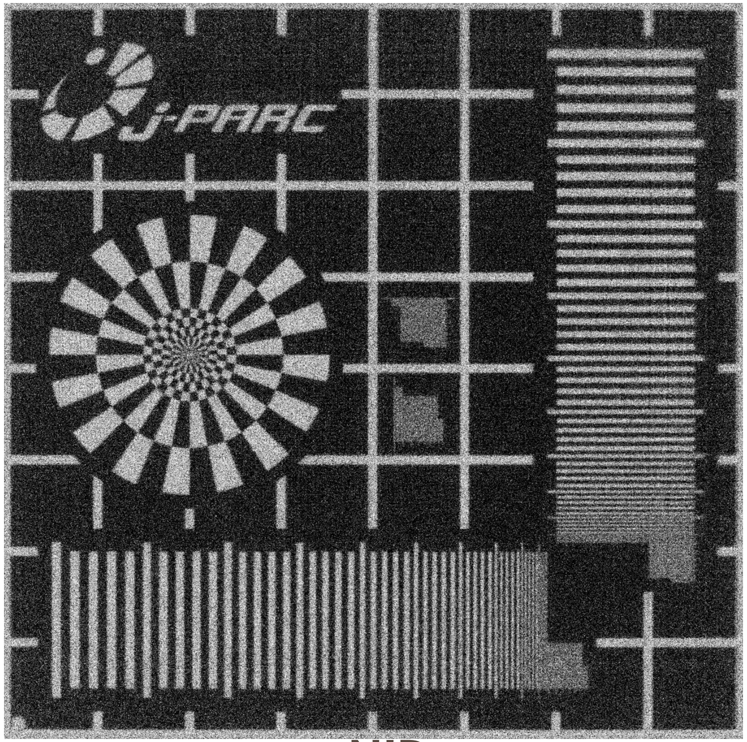
Pressure (atm)	1.2	1.4	1.6
Average hits/ event	5.86	5.42	4.82
MTF @0.6mm	27%	36%	41%
Spatial resolution @10% MTF (mm)	0.50	0.48	0.45

B-μNID and μNID

- μNID：^{3}He converter
- Larger event size but better position reconstruction



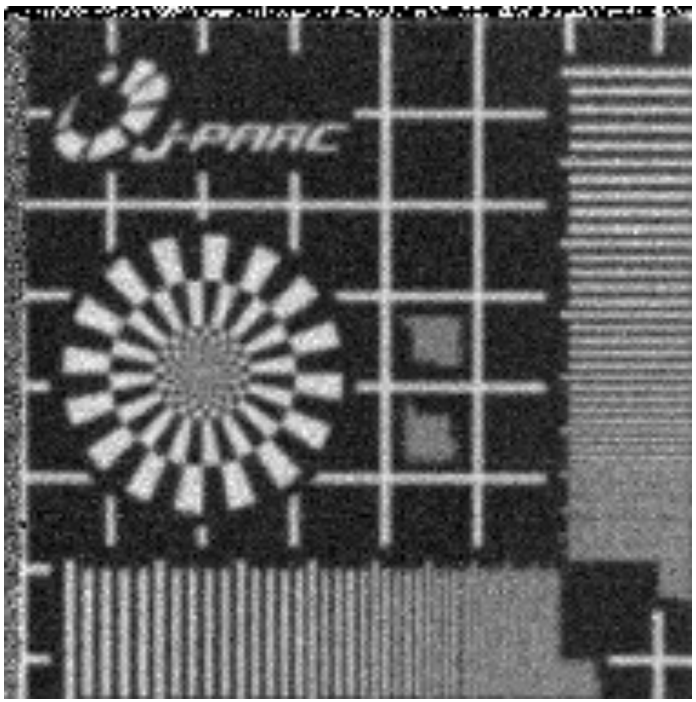
B-μNID (1.6atm)
Spatial resolution: 0.45 mm



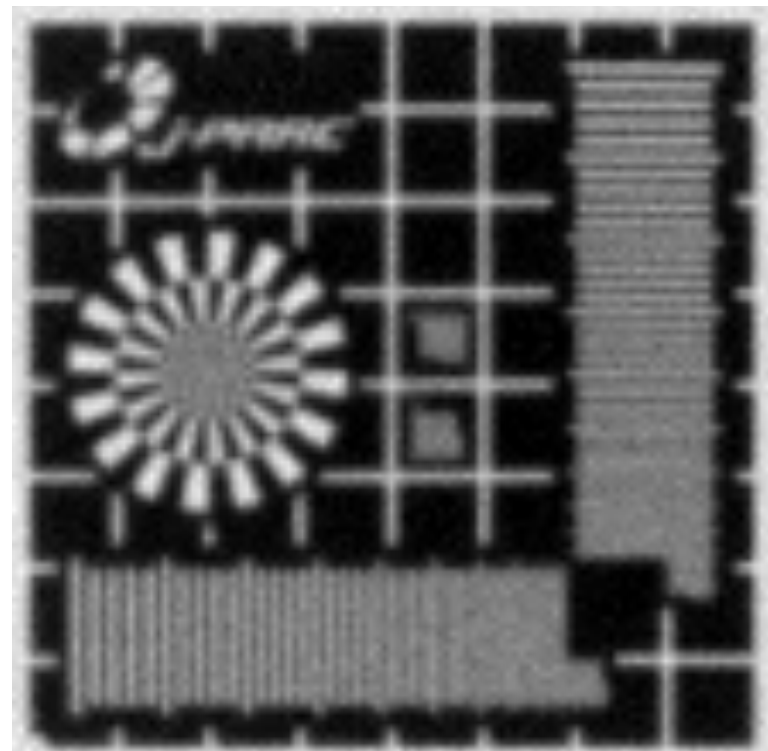
μNID
Spatial resolution: 0.1 mm

B-µNID and nGEM

- nGEM: similar boron-coating
- Ar:CO_2 (90:10) at 1 atm
- 128 x 128 strips, 0.8 mm pitch
- Spatial resolution about 1 mm



B-µNID (1.6atm)
Spatial resolution: 0.45 mm

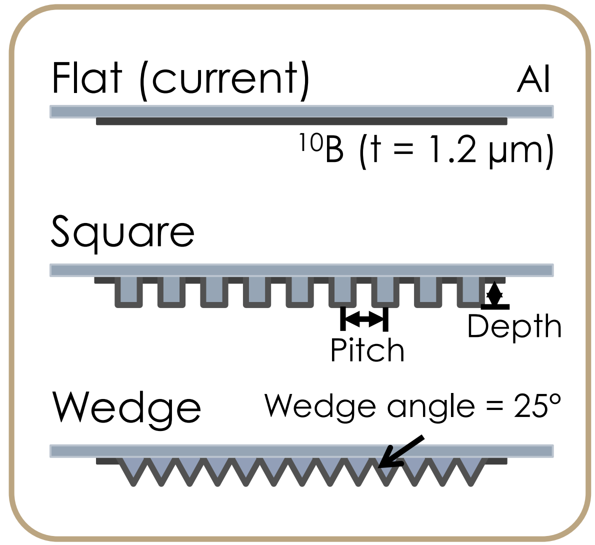


nGEM
Spatial resolution: 1 mm

Increase efficiency of B-μNID

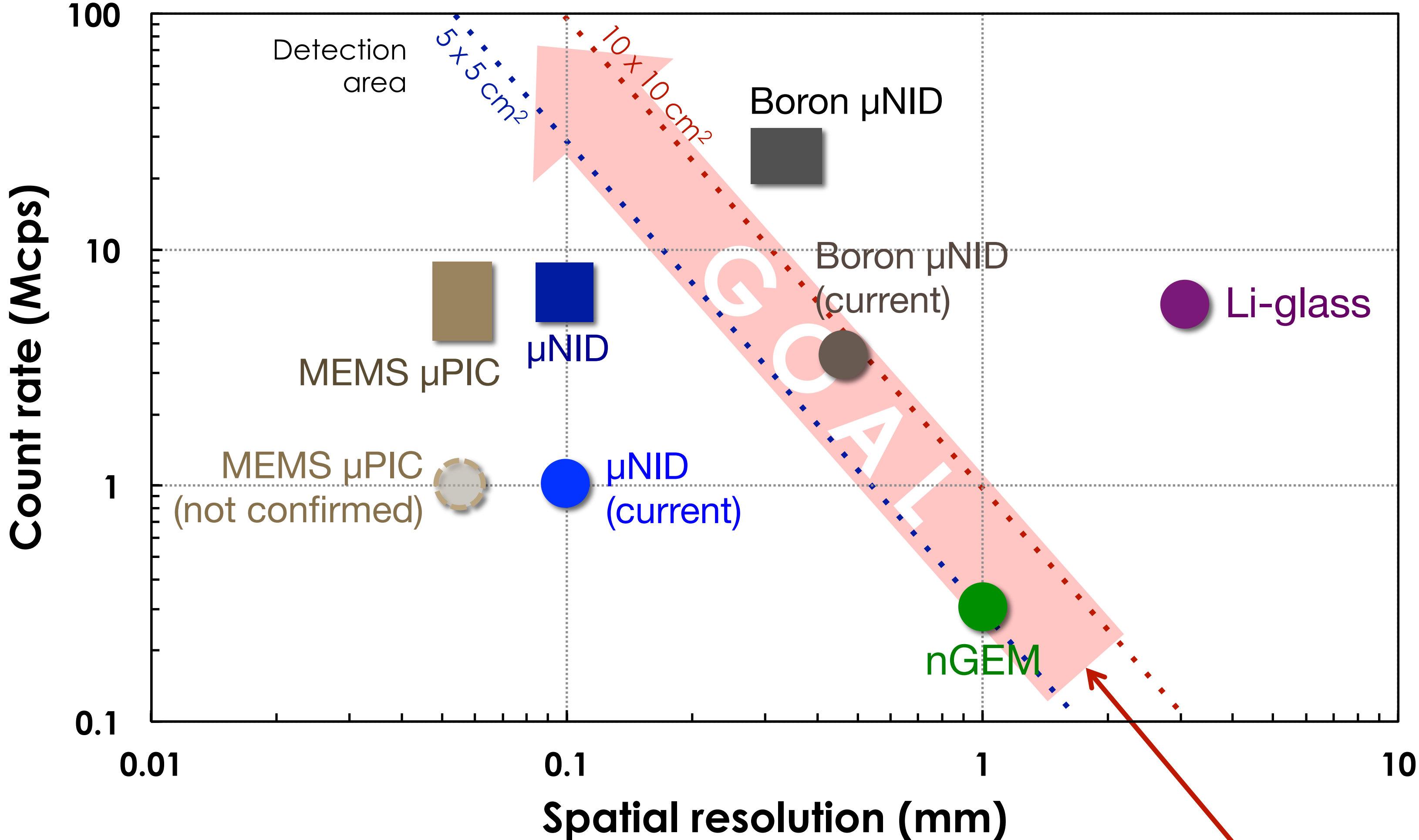
- Options for increasing efficiency
  - Insert additional boron layers (GEM, mesh, etc.)
  - Use micro-patterning of converter to increase surface area
- Preliminary simulations of patterned converters
  - Show improved efficiency and reduced event size

Simulation of boron converters



	Pitch (mm)	Depth (mm)	Event size	Eff. ratio
Flat	-	-	4.9	1
Square	0.4	0.2	3.8	1.1
Wedge	0.2	0.2	3.4	1.6

µNID: current and expected performance



Count rate required at given spatial resolution
for Bragg-edge measurement time of 10 hours

Summary

- Development of detectors to meet the needs of conventional and energy-resolved neutron imaging at RADEN is ongoing
- Optimization of the LiTA12
  - Improved spatial resolution with flat scintillator and charge centroiding, promising results with multi-image compositing
- Standard μNID
  - Refining analysis for improved spatial resolution/image quality and improved rate performance
  - Preparing easy-to-use analysis GUI and control software
- Continuing μNID development
  - Developing small-pitch μPIC for improved spatial resolution
  - Started testing of μNID with boron converter