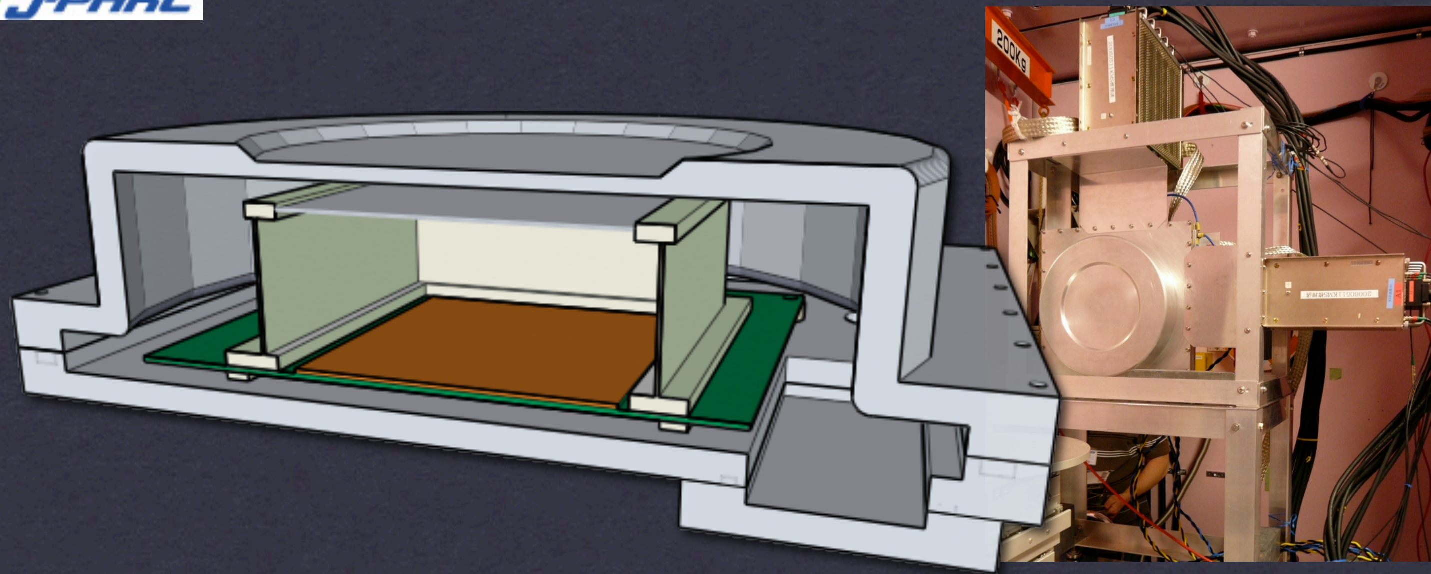
日本物理学会2012年秋季大会、20 September 2012



Recent Results for the μPIC Neutron Imaging Detector

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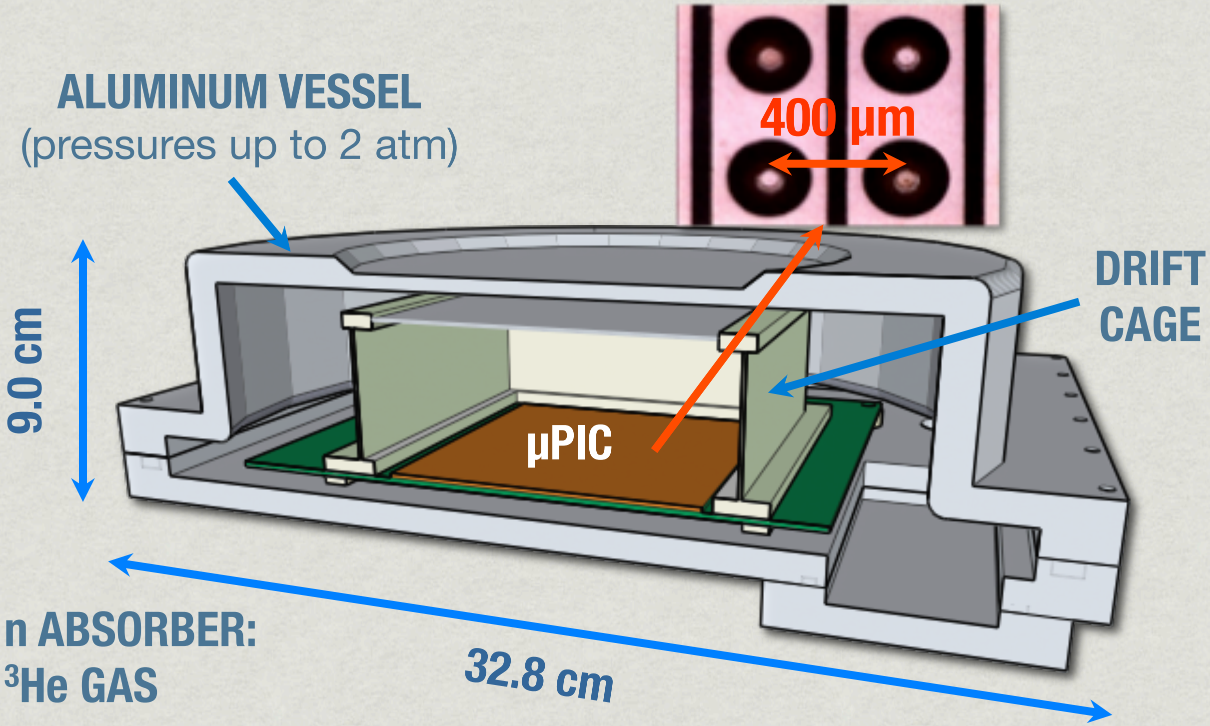
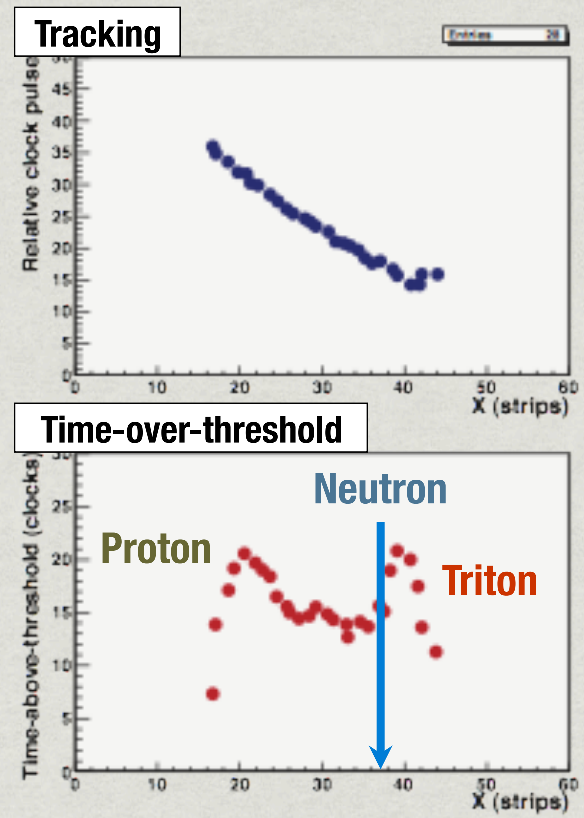
Neutron imaging detector prototype (μNID)



- TPC measures 3D proton-triton tracks.
- Time-over-threshold to estimate energy deposition.
- Gas gain < 1000 for neutron imaging.
- Efficiency up to ~30%, spatial res. of ~120 μm, time res. of ~1 μs.
- Detector remains operable for over 1 year on single gas filling.

FPGA Encoder with time-over-threshold

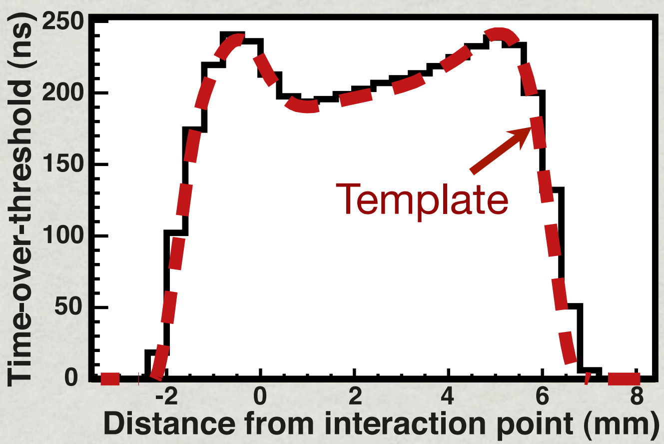


- Fast 3D tracking and 'energy' measurement
- Improved position accuracy and background rejection.

Spatial resolution with template fit

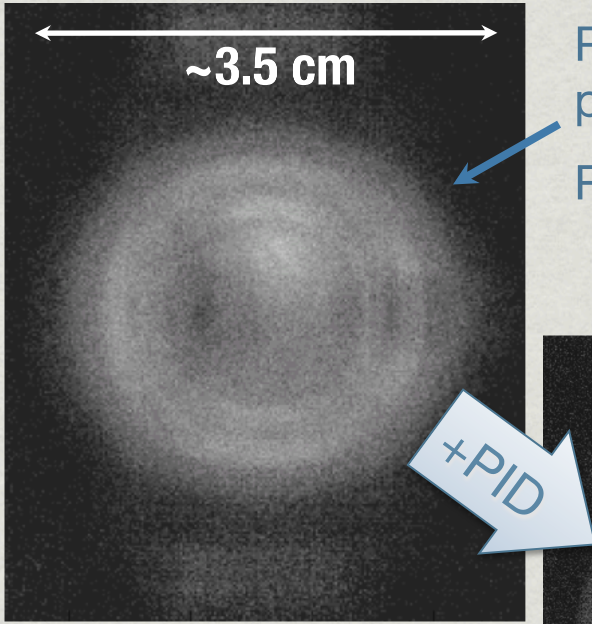
- Proton range ~3 times triton.
- Proton-triton separation, position correction essential for spatial resolution.
- Proton direction, neutron position determined by fit.

Measured TOT distribution



Templates generated with GEANT4 simulation of detector.

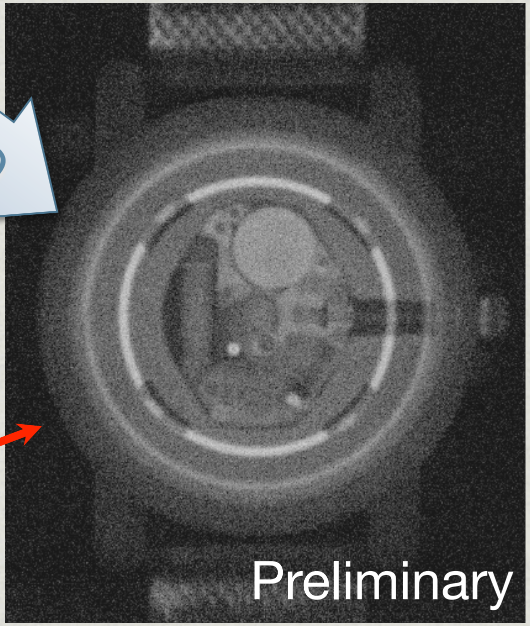
Data taken at NOBORU in Feb. 2011.



Bin size: 200 μm × 200 μm.

Position from mid-point of track.

Resolution: ~1 mm(σ)



Bin size: 80 μm × 80 μm.

Resolution with PID:
105~130 μm(σ)

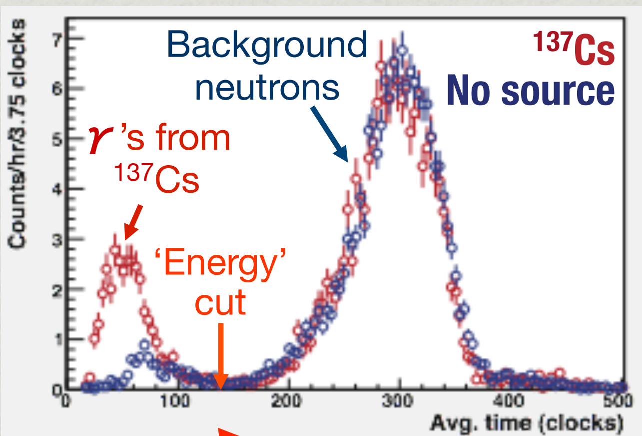
(Final resolution depends on tracking cuts.)

- Improvement possible (10~15%) by optimizing gas for reduced diffusion/shorter track-lengths.
- Recent data (NOBORU, March 2012) suggests some improvement (~5%) with lower gas gain.

Neutron-gamma separation

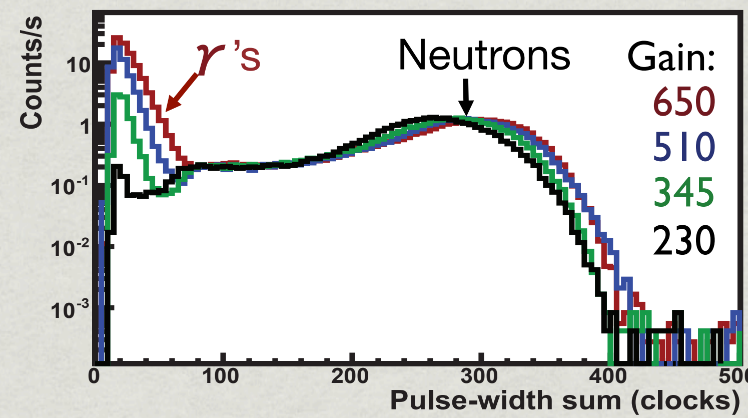
- Gamma rejection studied using 1-MBq ^{137}Cs source.
- Data taken over 24 hours at a gas gain of ~600.
- Both neutrons and gammas are detected (γ efficiency < 10^{-3}).
- Separation by total time-over-threshold and 3D track length.

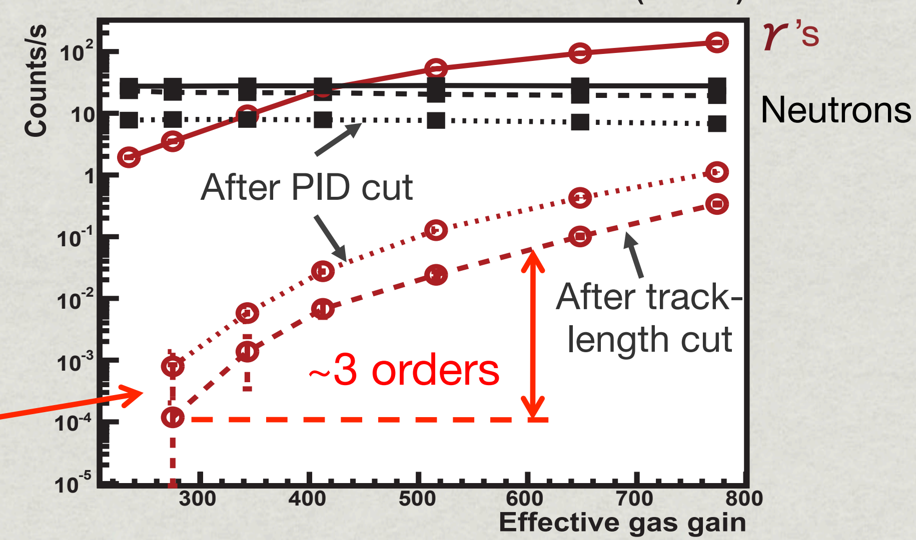
Pulse-width sum after track-length cut



Fraction of detected γ's surviving neutron cuts < 10^{-6} (effective gamma sensitivity of < 10^{-9} at gain of ~600).

n and γ event rates (^{137}Cs + ^{252}Cf)

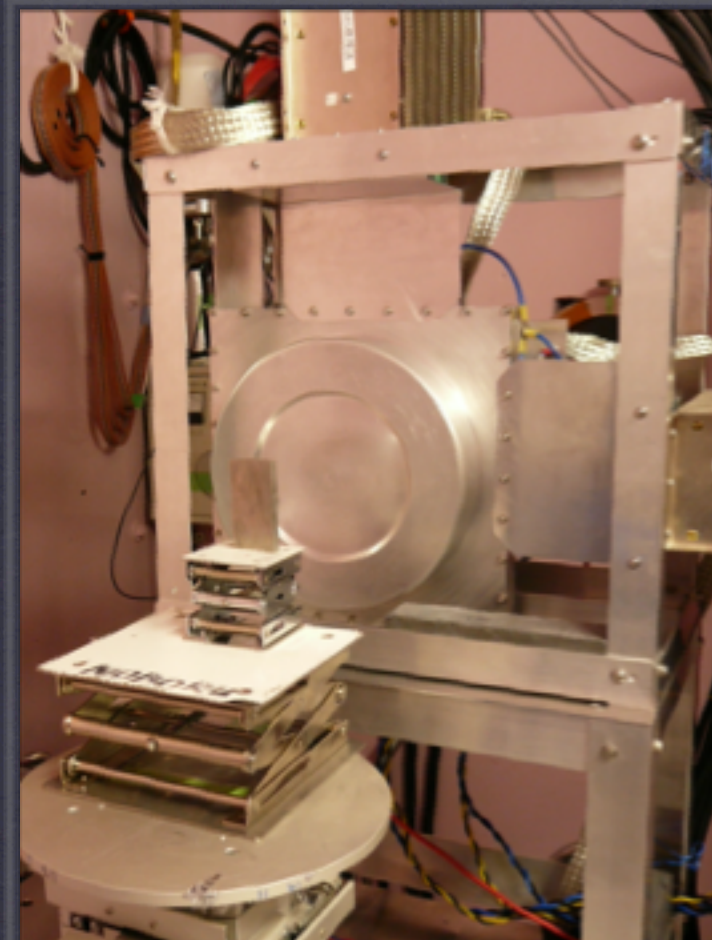




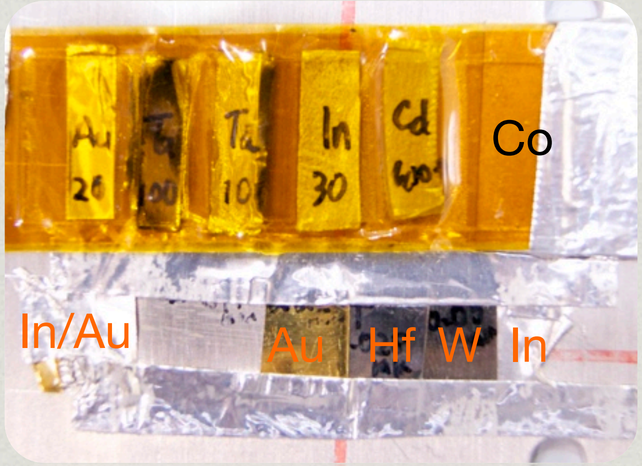
Sensitivity of < 10^{-12} can be achieved by reducing gain by half without loss of neutron efficiency.

Recent measurements

- Resonance absorption.
- Bragg-edge transmission.
- CT test measurement.



Neutron resonance absorption



- Exposure: 5 hrs.
- TOF: 0 – 2.2 ms.
- ~10 kcps.
- Live time: 60%.

- Measurement of neutron TOF allows selective imaging of nuclides via resonance absorption.
- Good time resolution is essential.

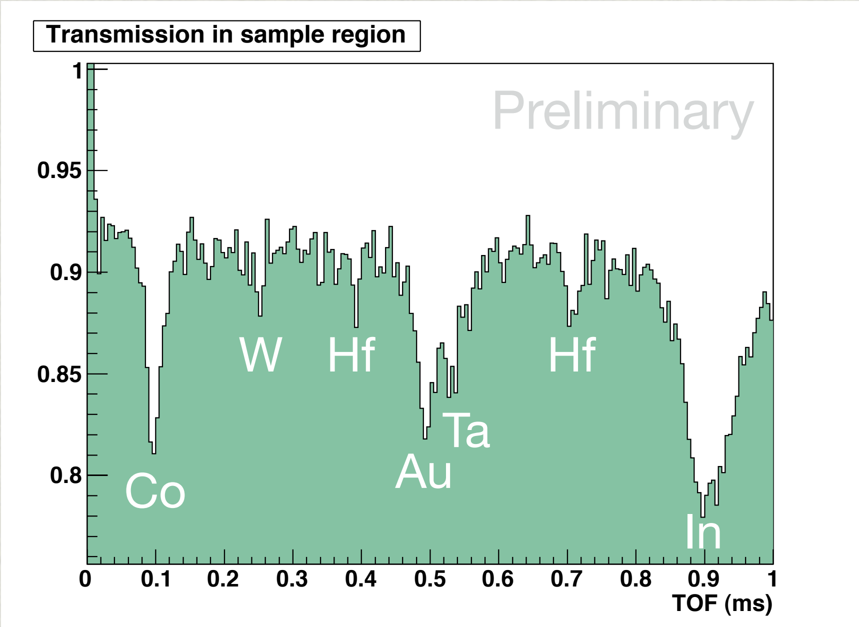
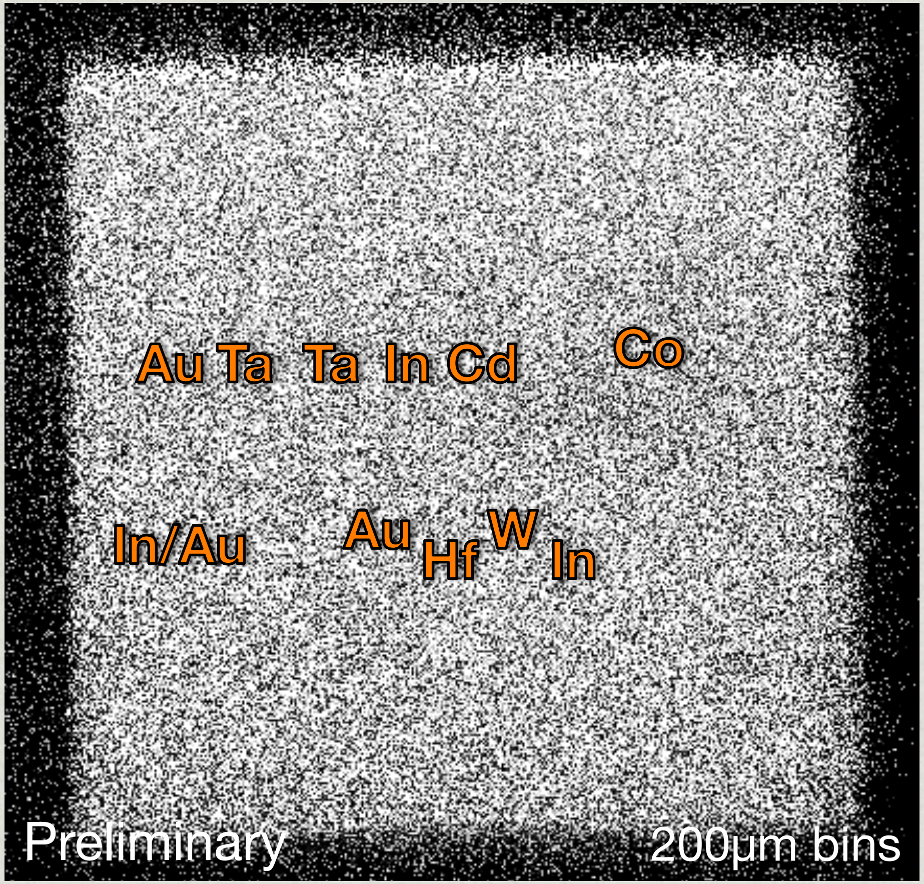


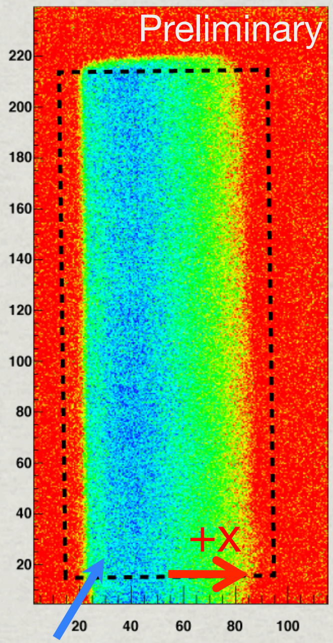
Image vs. TOF (0 ~ 1 ms)



Data taken at NOBORU in March 2012.

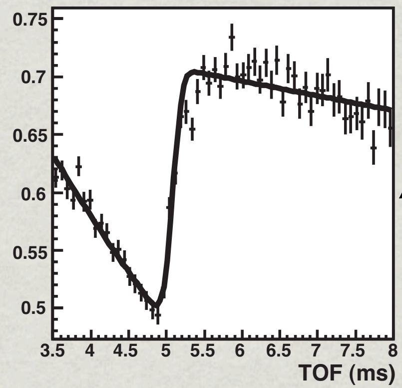
Bragg-edge transmission

2D image of katana



Region used for Bragg-edge study

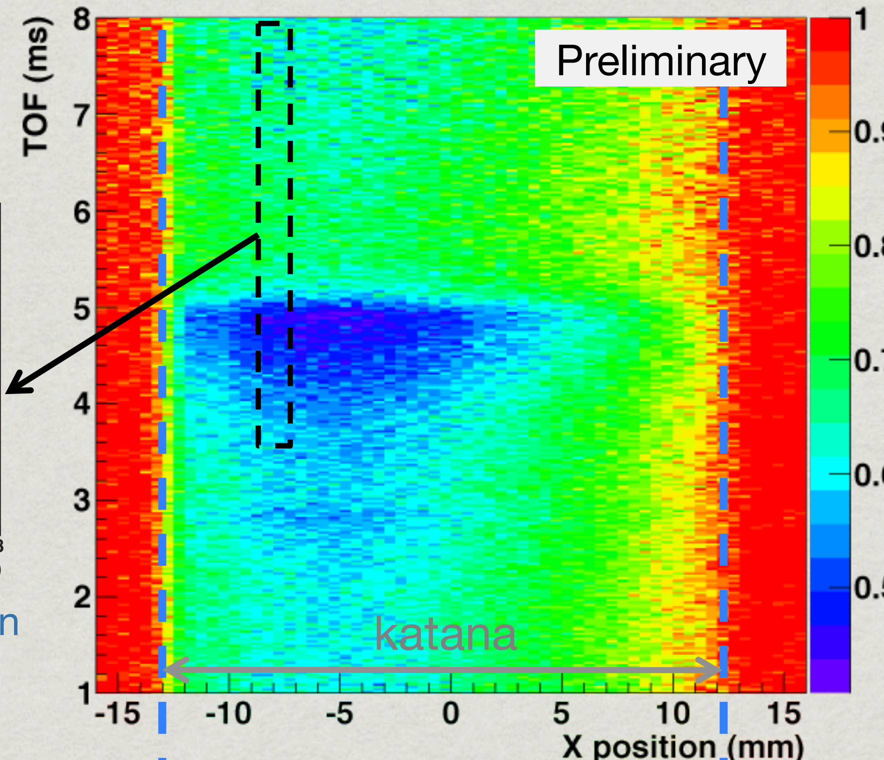
TOF projection for one slice

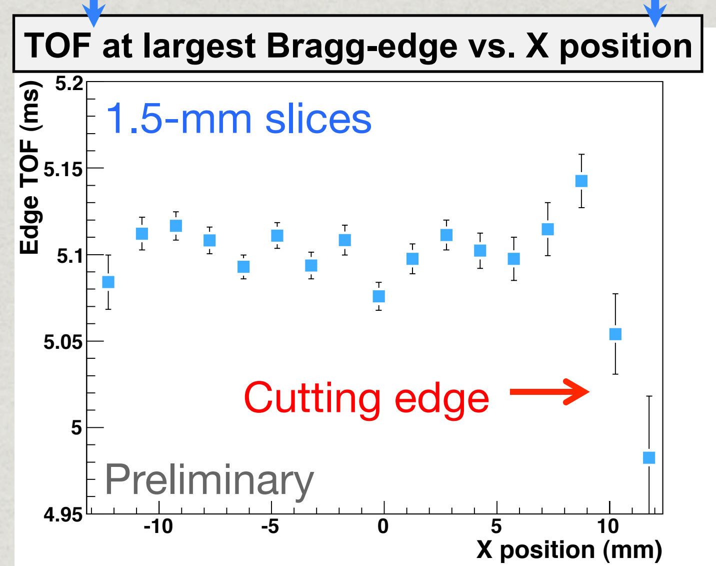


Edge fit: error function with exponentials above and below.

Simplified version of function from J.R. Santisteban *et al.*, J Appl Cryst **34** (2001).

Neutron TOF vs. X position

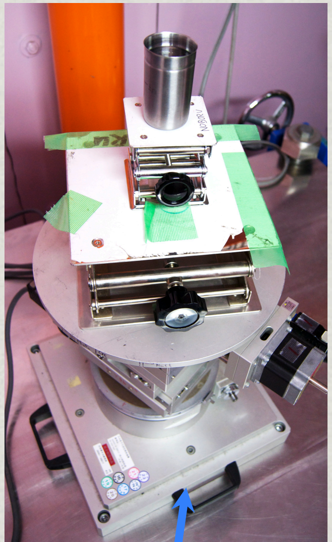


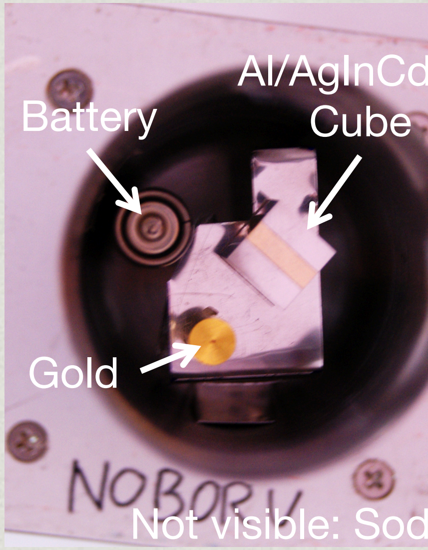


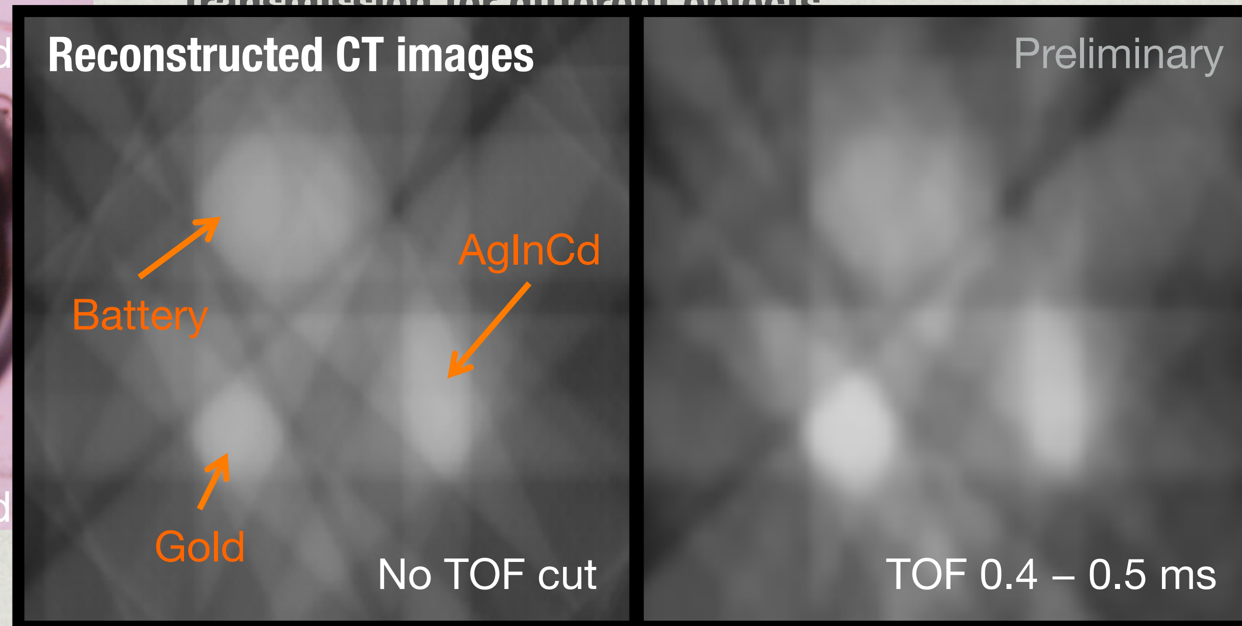
- Fragment of a katana (15th or 16th century).
- Bragg edge positions indicate some difference between cutting edge and spine.

Data taken at Hokkaido University in February 2012.

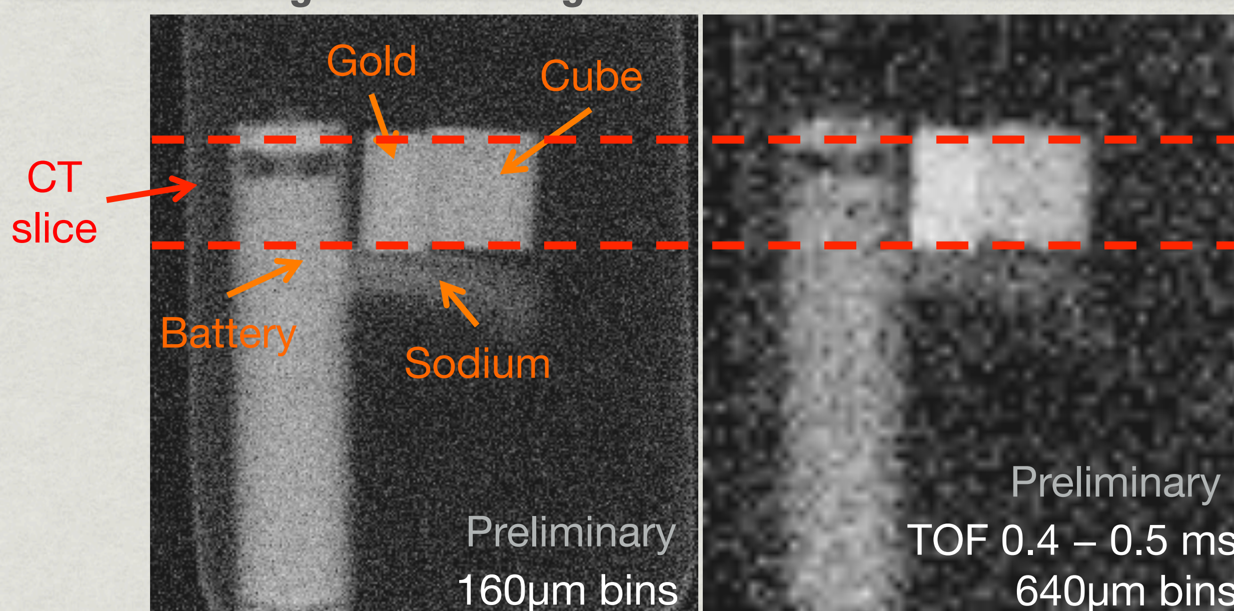
CT test measurement







Goniometer with θ-rotation from -155° to 155°.

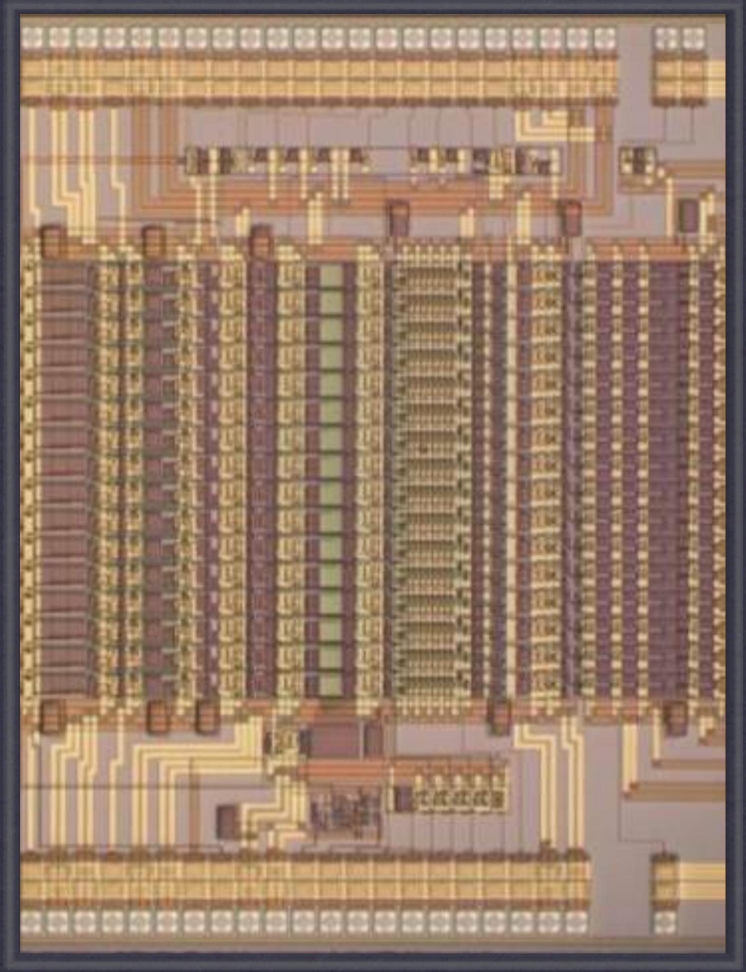


- 9 angles (6 independent), 1.5 hours/angle.
- TOF: 0 – 3 ms
- Neutron rate ~10 kcps, Live time 60%.
- CT reconstruction using simple back-projection method.

Data taken at NOBORU in March 2012.

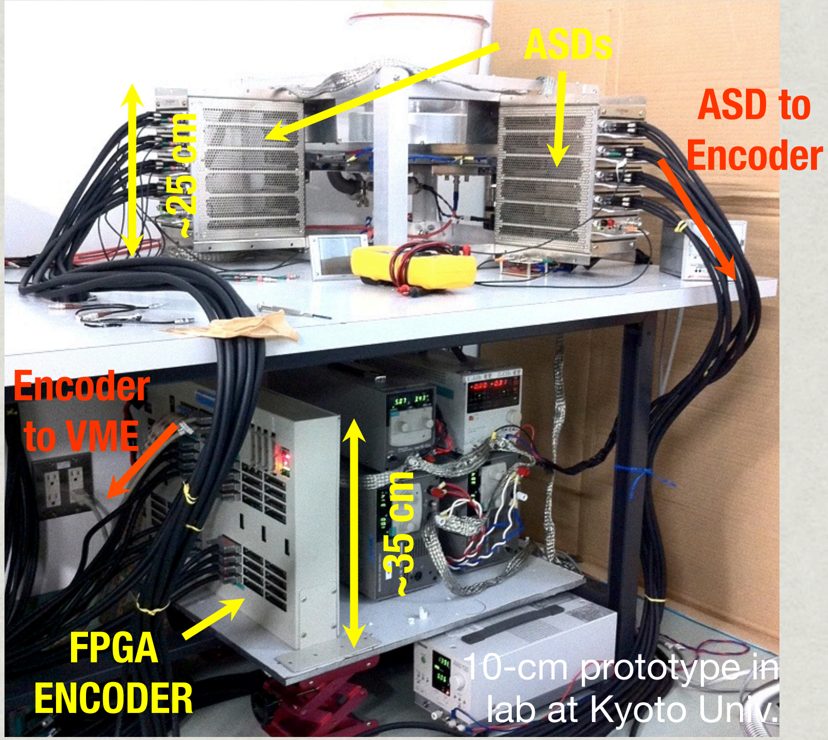
Improvements

- New ASICs and encoder for faster, more compact DAQ.



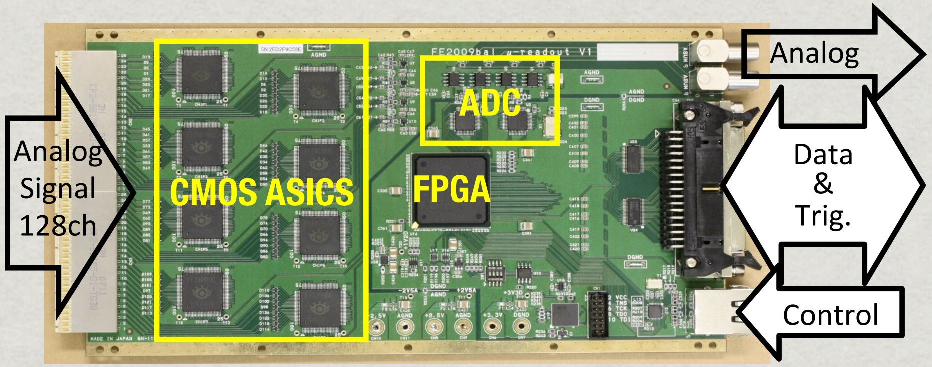
DAQ upgrade

Current DAQ setup



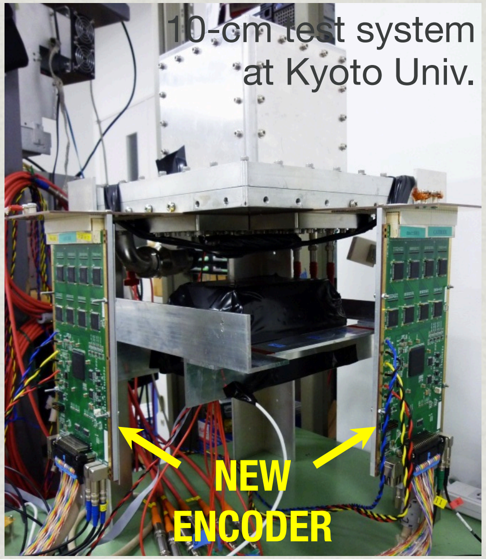
- ASD racks, cables, and encoder module.
- Output through single FPGA limits DAQ rate to ~10 MHz (neutron rate of ~150 kHz).
- Slow VME-PC transfer limits live time (15 ~ 60%).

New encoder module



118mm × 220mm

128 channels per board



- ASICs and FPGA on single board.
- Four boards replace ASDs, encoder, cables.
- DAQ rate increase by factor of 5 or more.
- Will begin testing with neutron system soon.

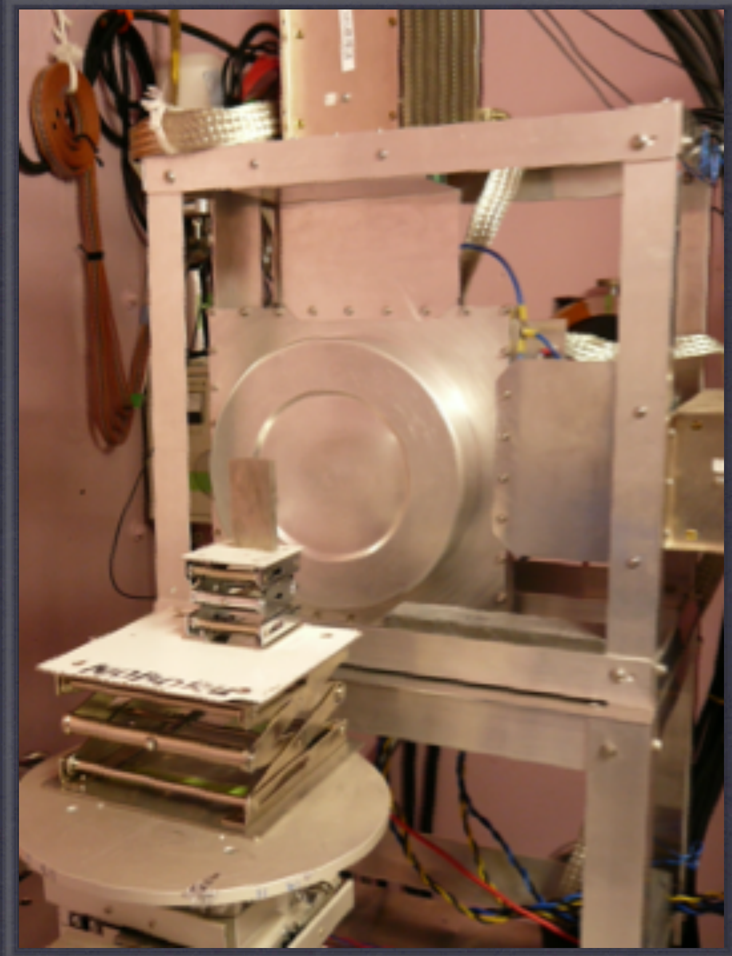
VME-PC transfer

- Implement faster VME readout (block transfer, double-buffer).
- Block transfer gives 1.5X increase; double-buffer not yet tested.
- For future, switch to SiTCP.

Summary

- μPIC-based time-resolved neutron imaging detector.
  - For radiography, neutron resonance absorption imaging/spectroscopy, Bragg-edge transmission, CT imaging, SANS.
- Detector performance.
  - Spatial resolution of 105~130 μm; time resolution of ~1 μs.
  - Very small effective gamma sensitivity of $< 10^{-12}$.
  - After upgrading DAQ and optimizing gas, maximum neutron rate up to 1 Mcps and spatial resolution < 100 μm.
- Next
  - Develop and test new FPGA code for neutron imaging.
  - Possible beam test of new DAQ at NOBORU this winter.
  - Consider design of next version of the detector.

Extra slides



Resonance absorption: Ag-In-Cd alloy

- Plate thickness: 3 mm.
- Exposure: 2 hrs.
- TOF gate: 0 – 3 ms.
- Neutron rate: ~10 kcps.
- DAQ live time: 70%.

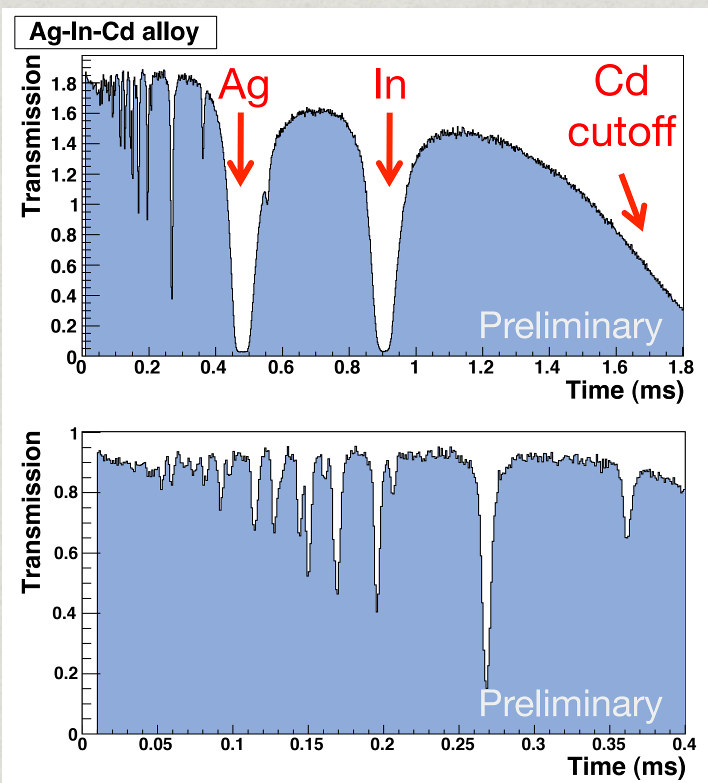
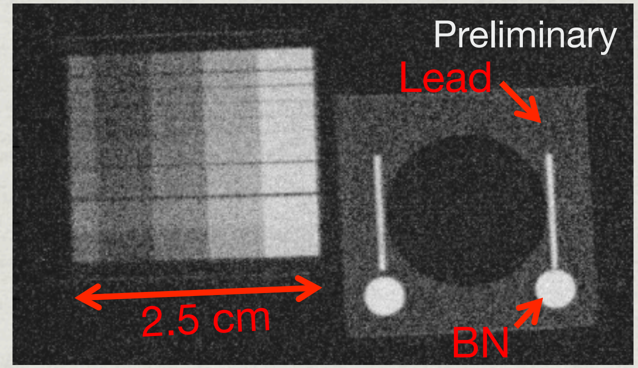


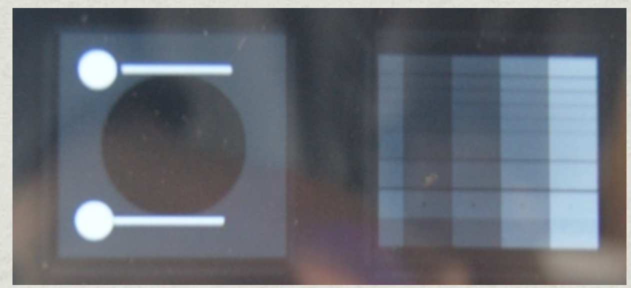
Image of ASTM indicator

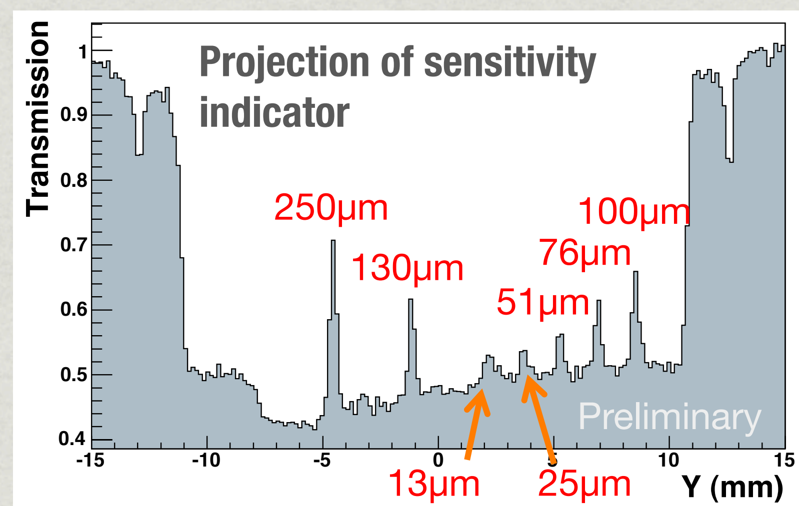
Image taken with μPIC (100 μm bins)



- Exposure: 3 hrs.
- No TOF gate.
- ~120 kcps.
- Live time: 14%.

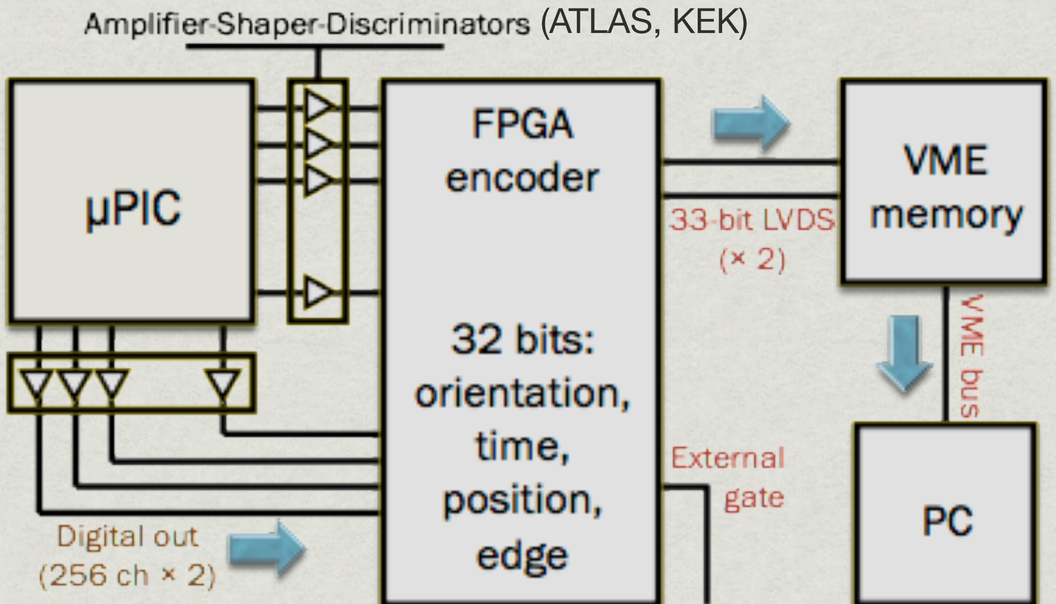
X-ray provided with sample





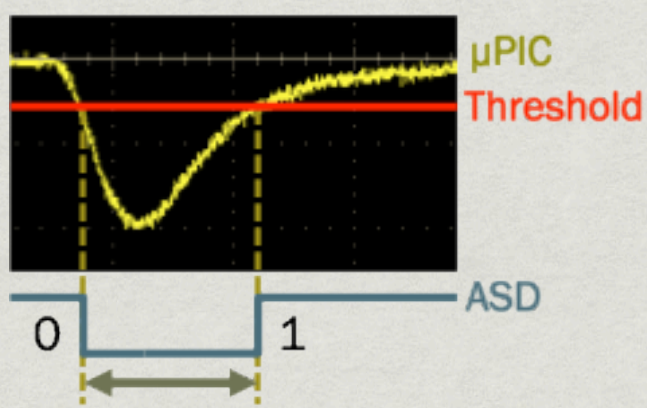
Data taken at NOBORU in March 2012.

DAQ and FPGA logic



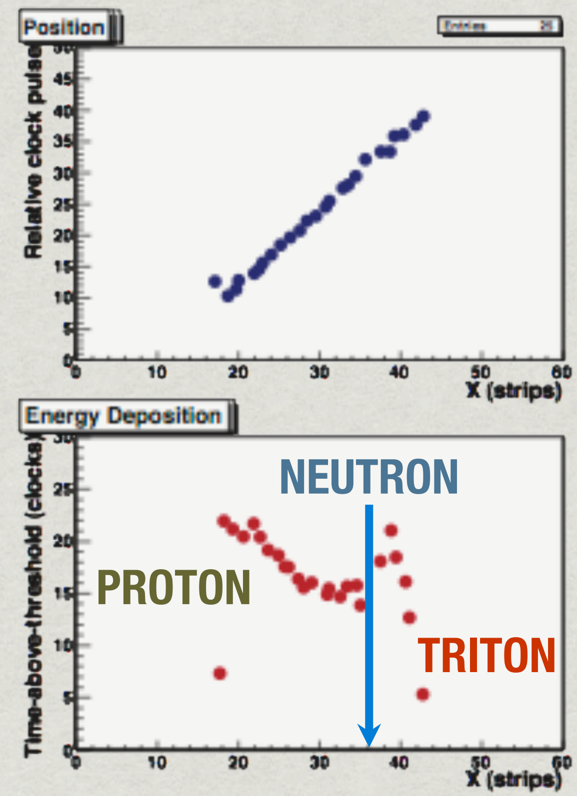
DATA ENCODING

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



Time-above-threshold
(∝ energy deposit)

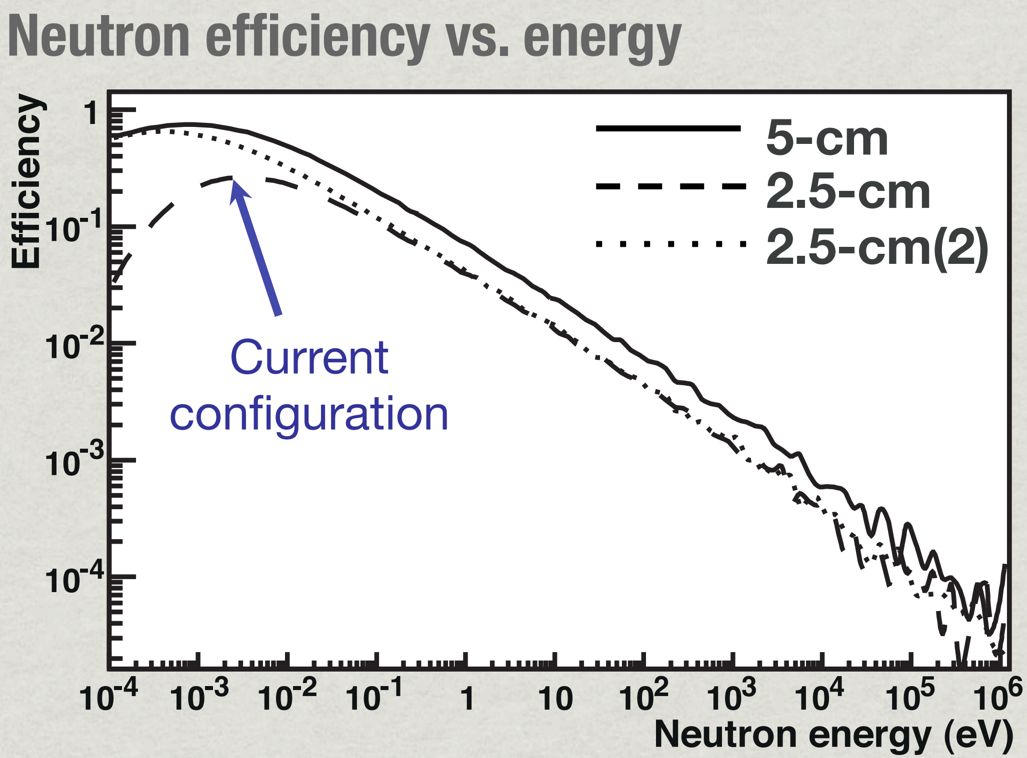
PROTON-TRITON TRACKS



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

Neutron efficiency

- Neutron efficiency as a function of neutron energy.
- Determined from GEANT4 simulation.
- Loss of peak efficiency due to large dead layer in current configuration (2.5-cm).



Drift cage configuration	Drift height	Dead layer	Efficiency at 25.3 meV	Peak efficiency
5-cm	5.0 cm	0.8 cm	0.35	0.75 (0.7meV)
2.5-cm	2.5 cm	3.3 cm	0.18	0.27 (3meV)
2.5-cm(2)	2.5 cm	0.8 cm	0.20	0.65 (0.35meV)

Optimize gas for improved position resolution

Strategies for improving position resolution

- Shorten proton-triton track lengths.
- Reduce diffusion of drift electrons.

Gas parameters determined by MAGBOLTZ.
Resolutions estimated with GEANT4.

	Pressure (atm)	Drift velocity (μm/ns)	Transverse diffusion (μm/cm$^{1/2}$)	p-t track length (mm)	Expected improvement in resolution
$Ar:C_2H_6:^3He$ (63:7:30)	2	23.1	273	7.9	(114 μm)
$Ar:C_2H_6:^3He$ (63:7:30)	3	23.4	231	5.3	~15%
$Xe:C_2H_6:^3He$ (50:20:30)	2	29.4	183	5.0	~15%
$Ar:CO_2:^3He$ (50:20:30)	2	22.5	107	7.4	~15%

Preliminary tests with $Ar:CO_2$ mixtures show relatively low gain.

Also considering other CO_2-based gas mixtures.

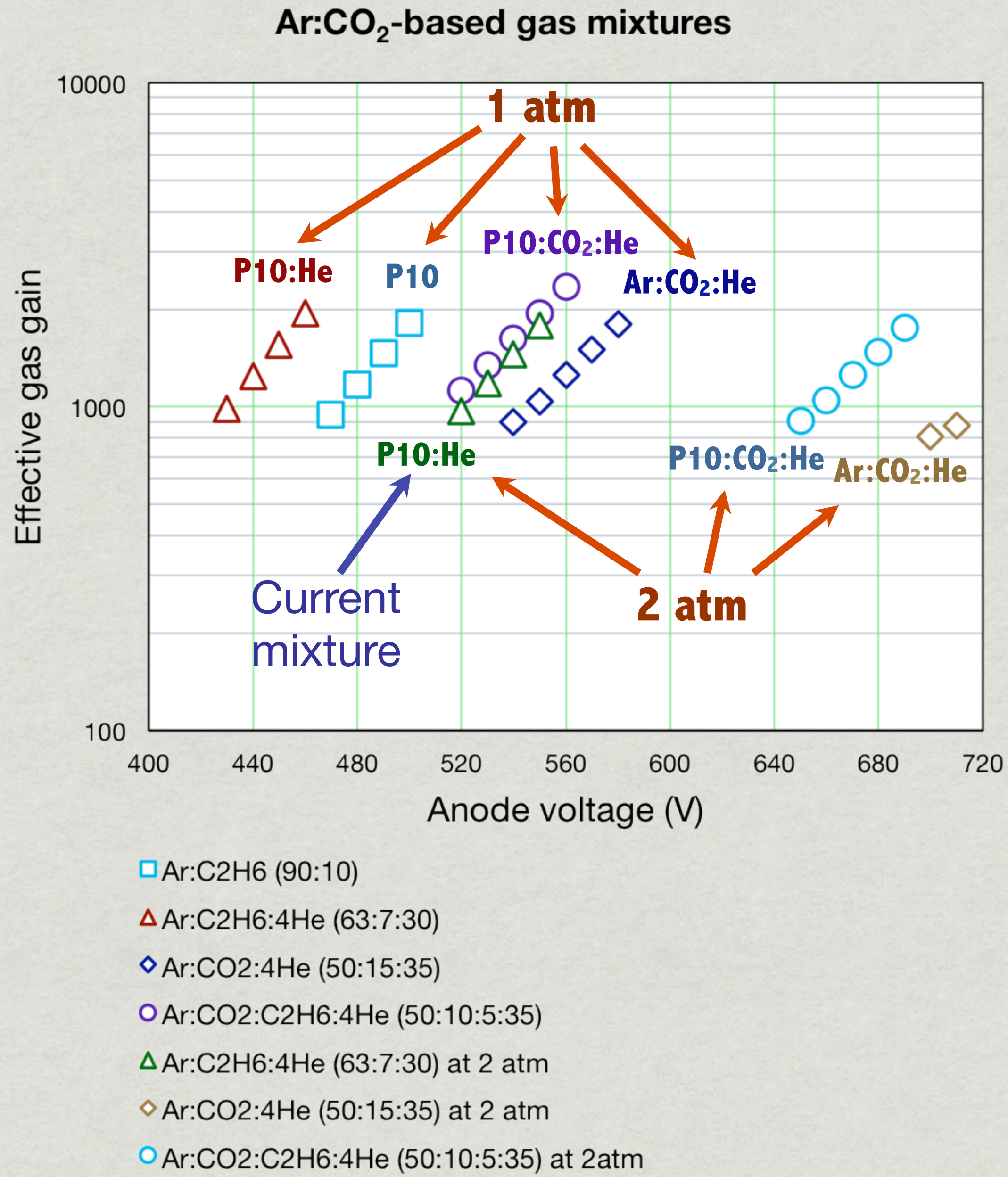
Gas study – Ar:CO_2-based mixtures

- Compared following mixtures at 1 and 2 atm:
  - Ar:C_2H_6:He (63:7:30)
  - Ar:CO_2:He (50:15:35)
  - Ar:CO_2:C_2H_6:He (50:10:5:35)
- C_2H_6 included to increase gain and stability.
- ^{4}He used in place of ^{3}He.

CO2-based mixtures require higher anode voltages.

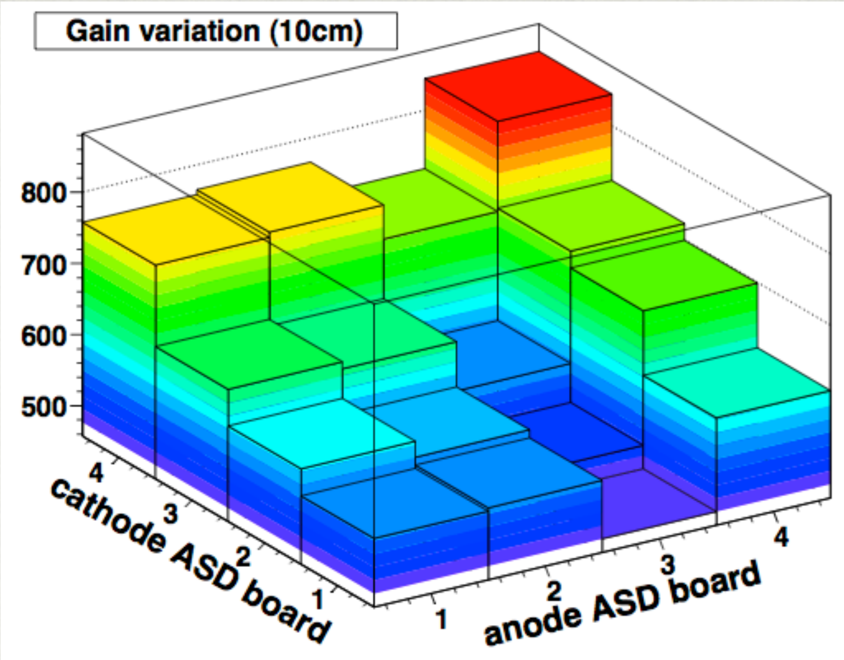
Next steps:

- Check gain variation.
- Add small amount of ^{3}He and measure proton-triton tracks.



Gain variation and pixel pitch

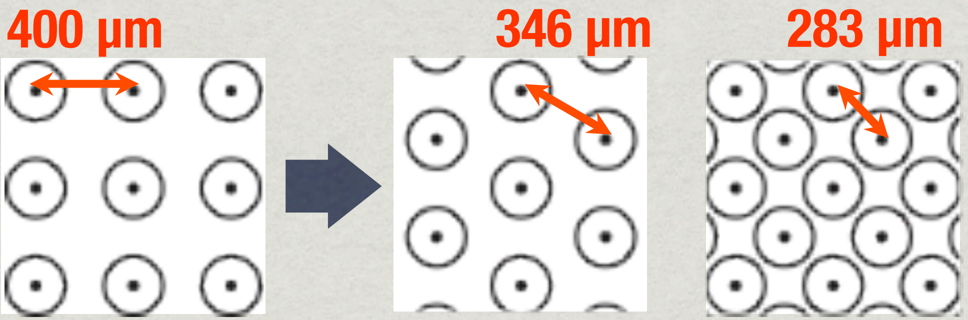
- Normal gain variation of μPIC: 4%(σ).
- Gain variation of prototype neutron detector: 16%(σ).
- Gain variation contributes 10~20% to resolution (GEANT4 simulation).
- Recent improvements in manufacturing procedure may reduce intrinsic gain variation of μPIC.



Gain variation of 10-cm neutron detector measured with ^{252}Cf source.

Denser packing of anode pixels

- Change arrangement of pixels (physical dimensions unchanged).
- Moderate reductions in pixel pitch produce corresponding reduction in position resolution (GEANT4).

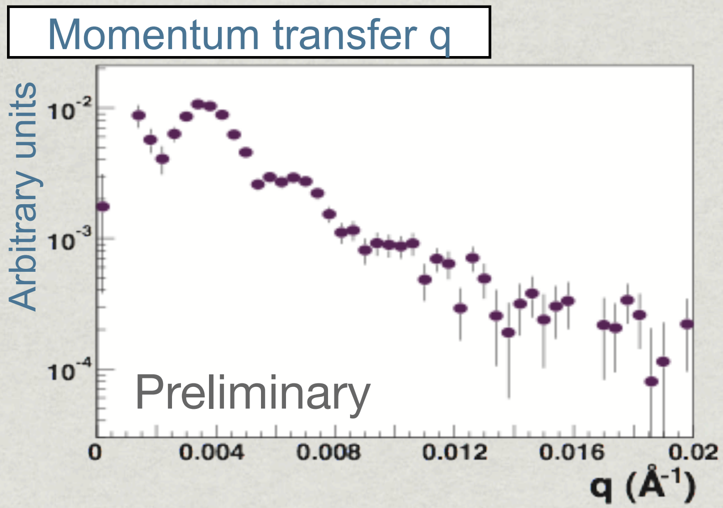


Cathode strips not shown.

Previous experiments

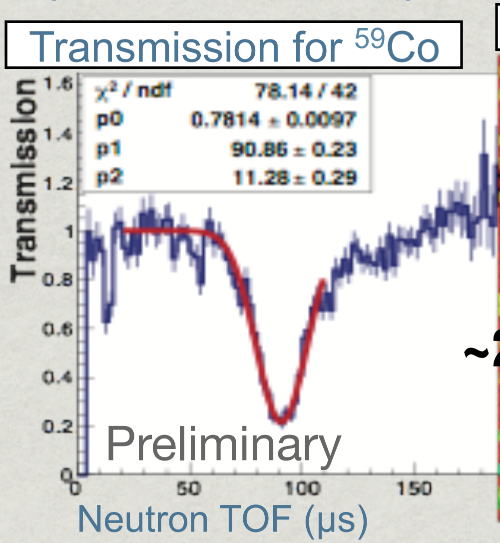
SMALL-ANGLE NEUTRON SCATTERING (2009)

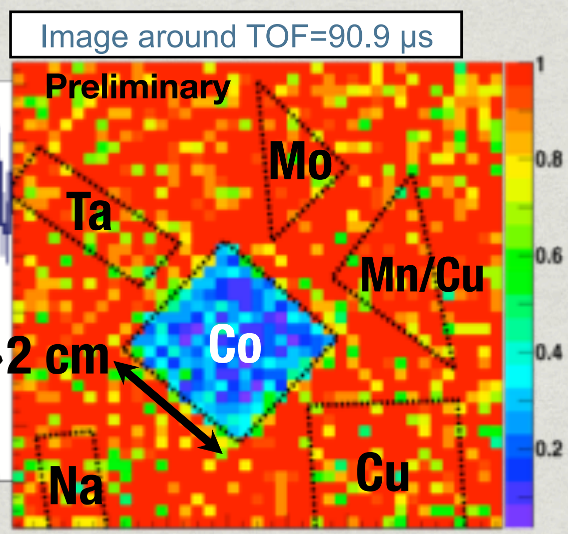
Spherical SiO_2 nanoparticles (ϕ 200μm).



RESONANCE IMAGING (2009)

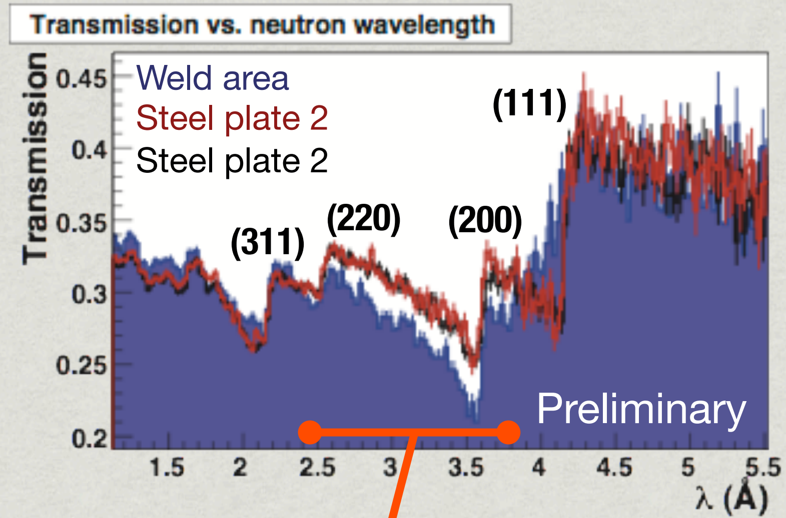
Square cobalt sample.

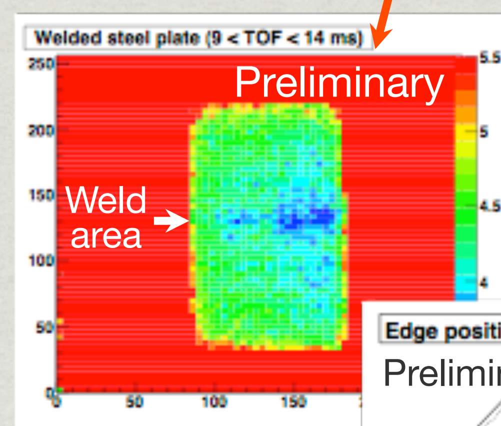




BRAGG-EDGE TRANSMISSION (2010)

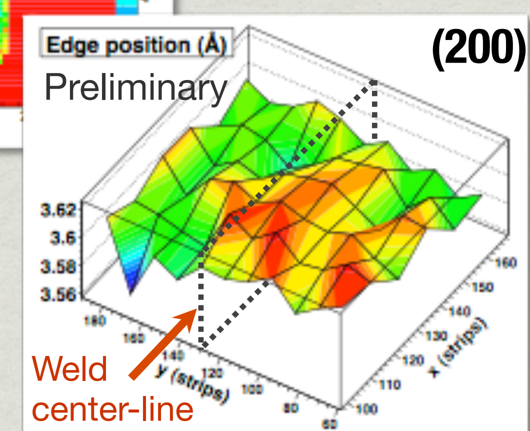
Welded steel plate.





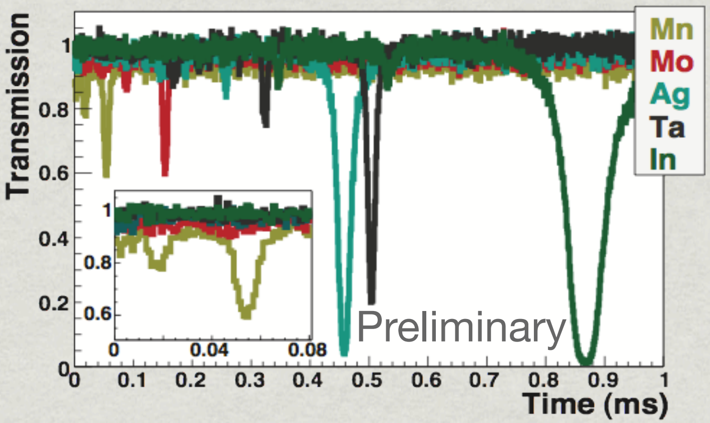
$$d = \frac{\lambda}{2}$$

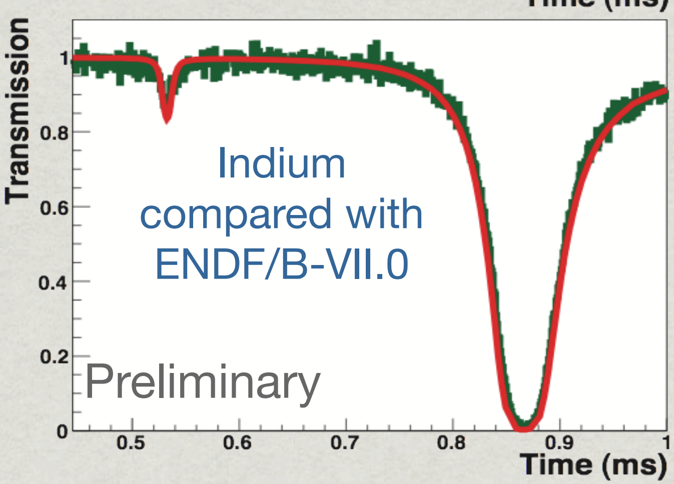
d-spacing from wavelength



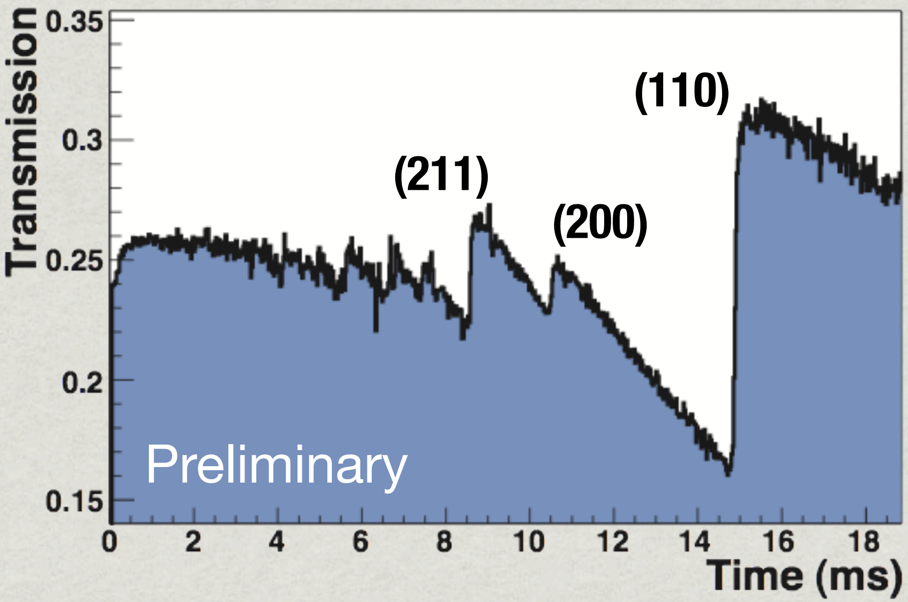
Resonance absorption

- Transmission for sheets of Mn, Mo, Ag, Ta, and In (thicknesses 10μm ~ 1mm).
- Time resolution of ~0.6 μs and good background rejection can distinguish peaks near beginning of pulse.





Bragg-edge transmission



- Transmission for Fe powder (>99% pure, grain size < 325 μm).
- Sample thickness of 1.6 cm.
- Bragg-edges are clearly visible.
- Edge spacing is consistent with expected BCC crystal structure.

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