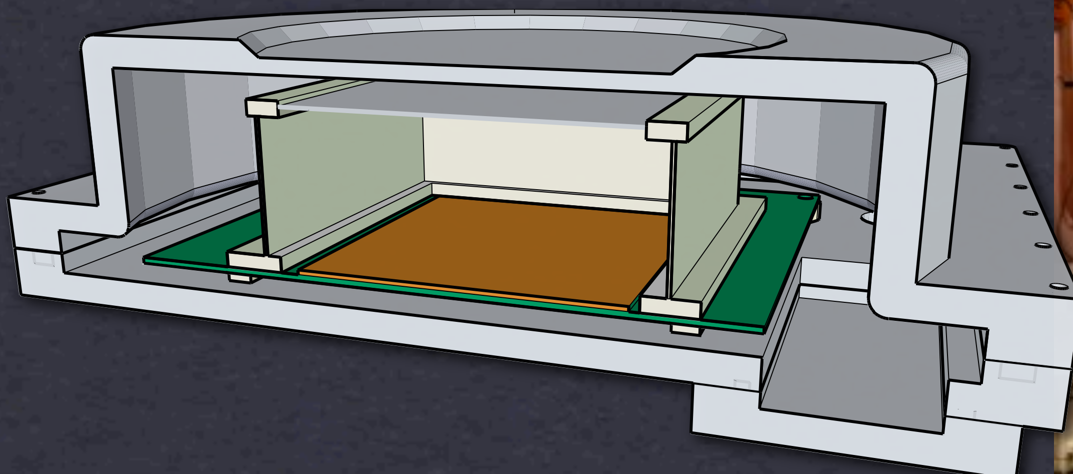
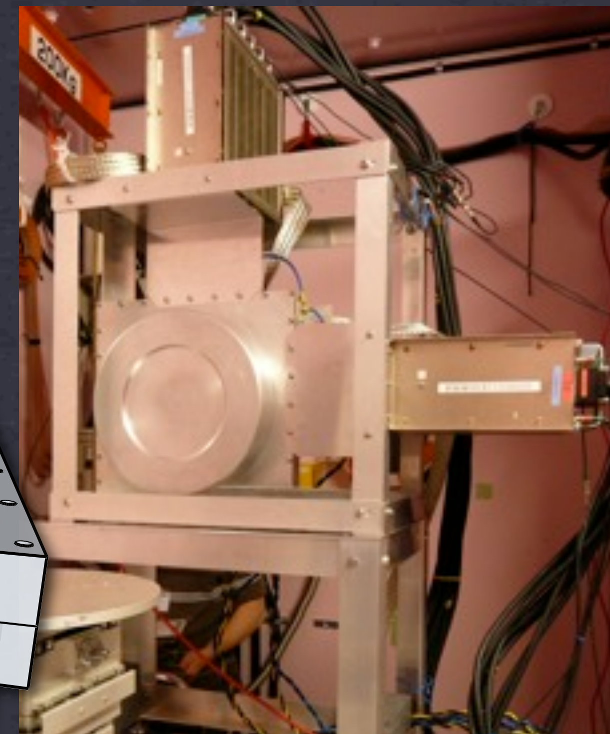
JPS Fall Meeting, Toyama University, 22 Sep 2011





Neutron Imaging Detector based on the μPIC

Joe Parker
Cosmic Ray Group, Kyoto University

JPS Fall Meeting, Toyama University, 22 Sep 2011

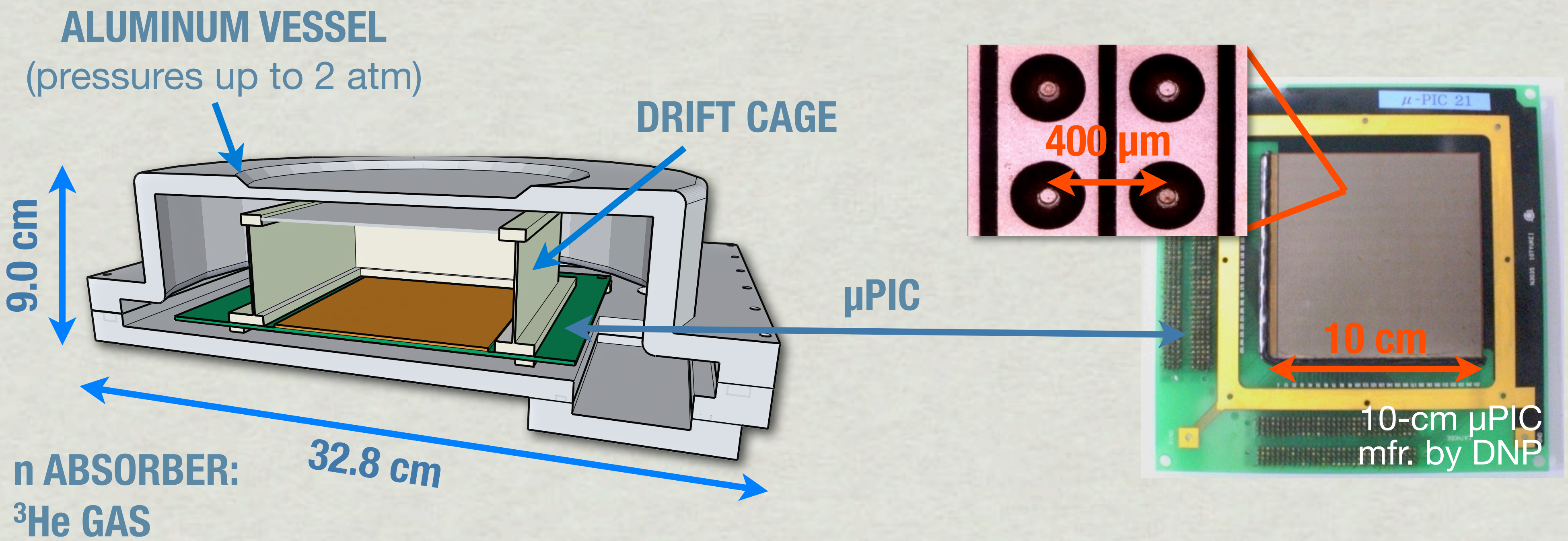
KYOTO UNIVERSITY, COSMIC RAY GROUP
J.D. Parker, K. Hattori, S. Iwaki, S. Kabuki, Y. Kishimoto, H. Kubo, S. Kurosawa, K. Miuchi, H. Nishimura, T. Sawano, T. Tanimori, K. Ueno

JAPAN ATOMIC ENERGY AGENCY, MATERIALS AND LIFE SCIENCE FACILITY DIVISION
M. Harada, T. Oku, T. Shinohara, J. Suzuki

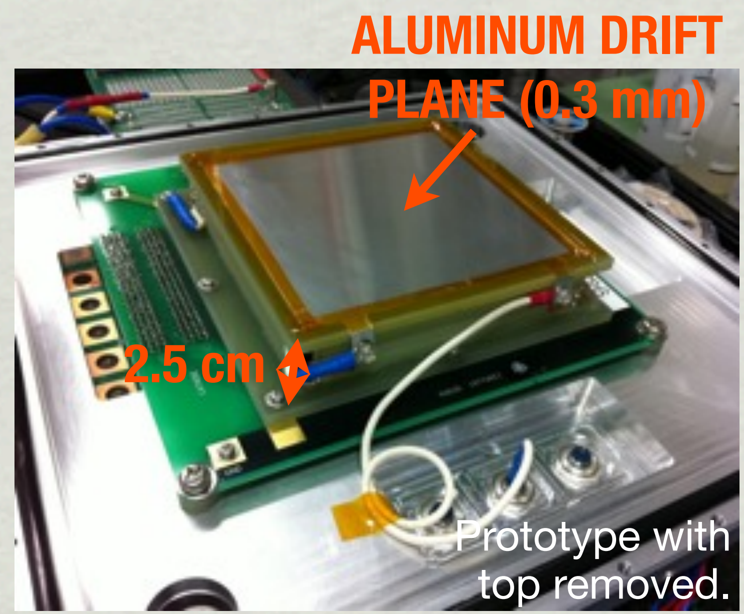
Neutron Imaging Detector based on the μPIC

- Prototype system and basic operation.
- Demonstration measurements.
- Future improvements.

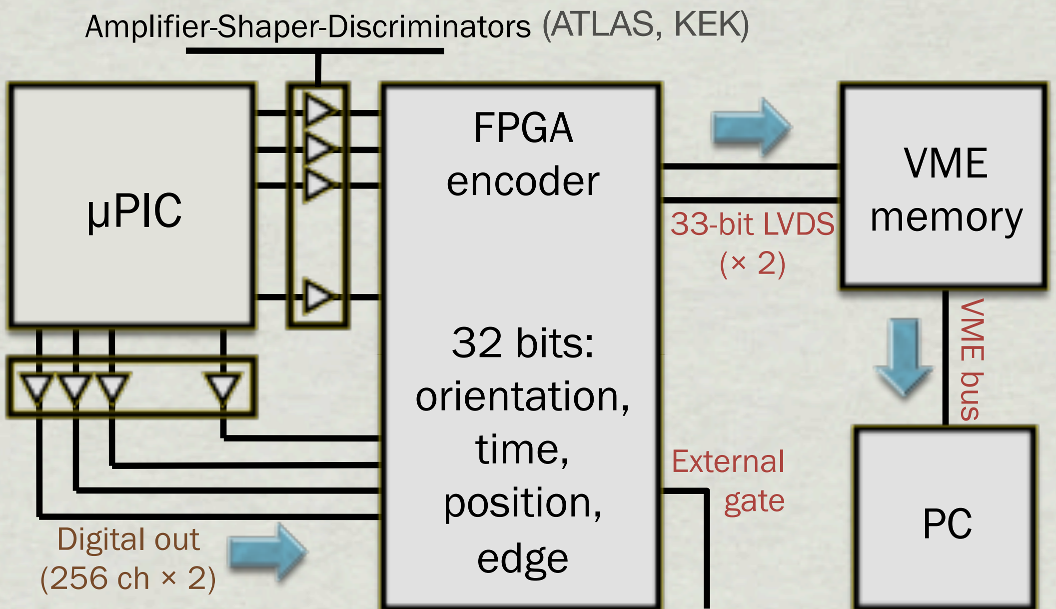
Neutron imaging detector prototype (μNID)



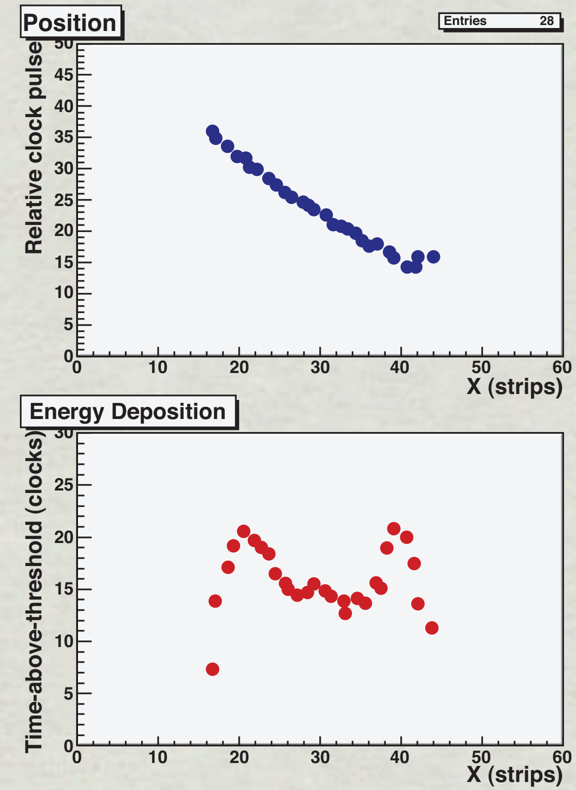
- High-rate FPGA-based DAQ.
- TPC measures 3D proton-triton tracks.
- Energy deposition estimated by time-above-threshold method.
- Gas gain < 1000 for neutron imaging.
- Efficiency up to ~30%, position res. of ~120 μm, time res. of ~1 μs.



DAQ and FPGA logic

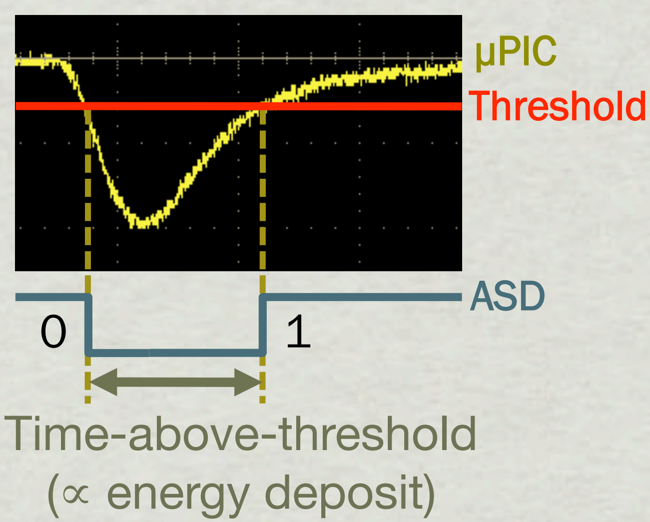


PROTON-TRITON TRACKS



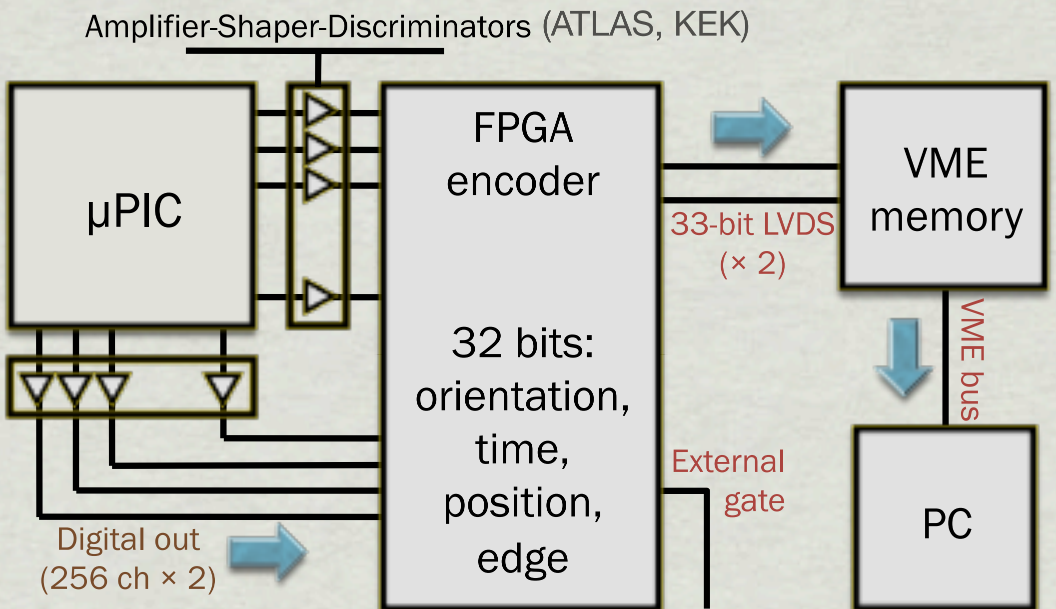
DATA ENCODING

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



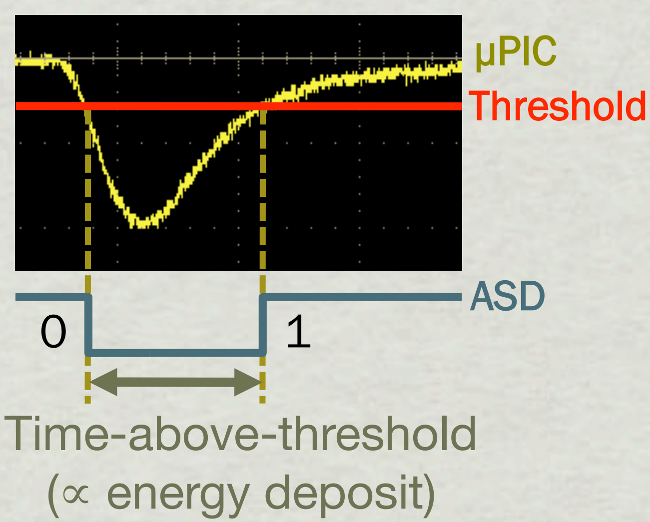
- Simultaneous measurement of position and 'energy deposit' at high rates.
- Excellent background rejection capability.

DAQ and FPGA logic

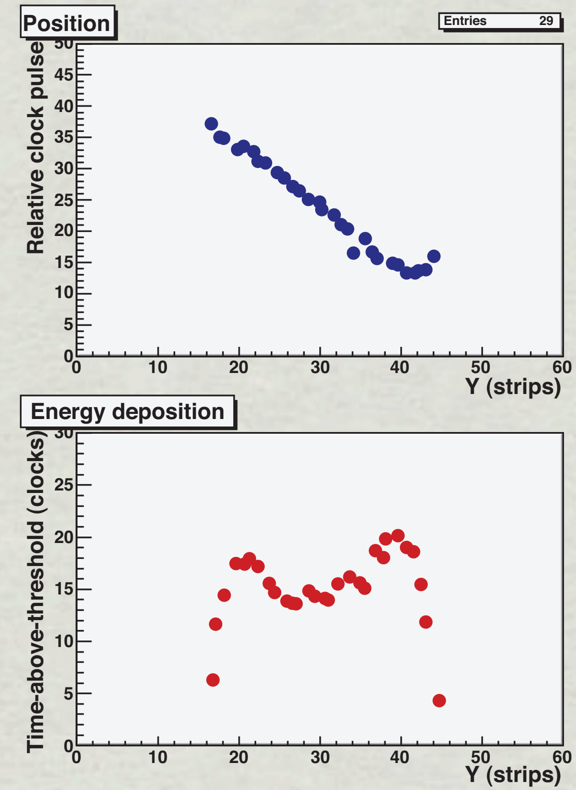


DATA ENCODING

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

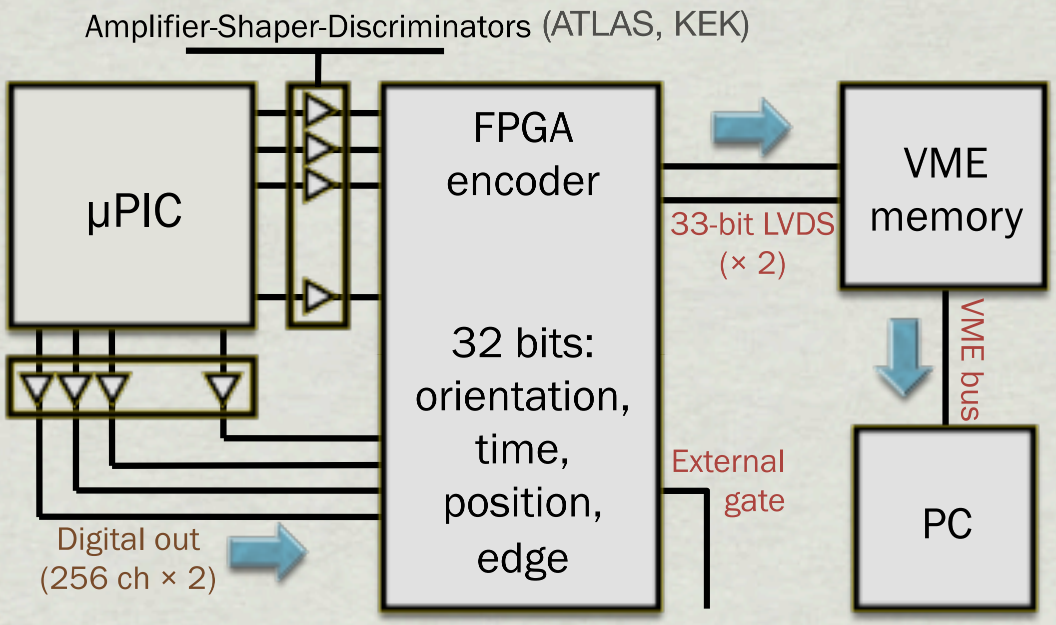


PROTON-TRITON TRACKS



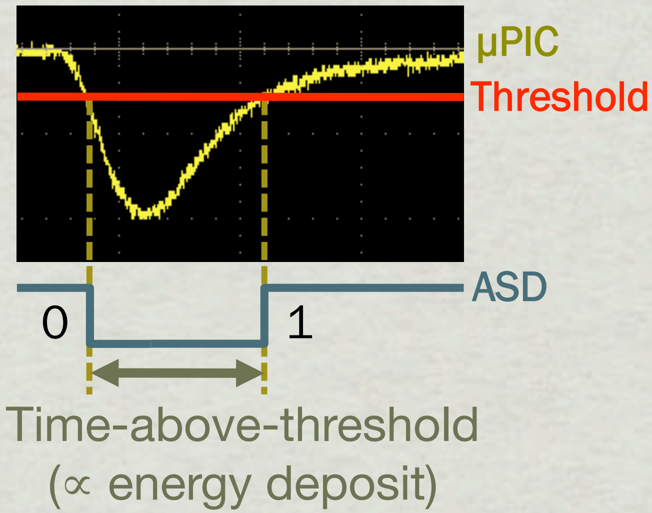
- Simultaneous measurement of position and ‘energy deposit’ at high rates.
- Excellent background rejection capability.

DAQ and FPGA logic

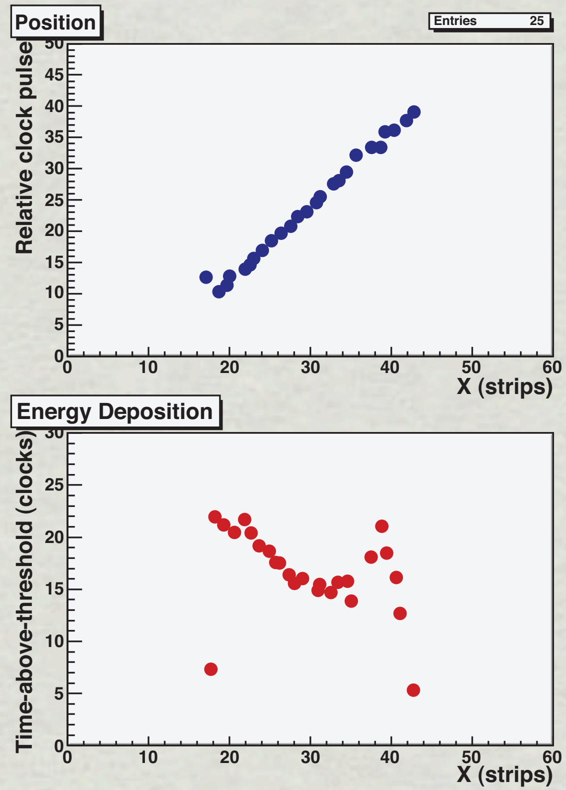


DATA ENCODING

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

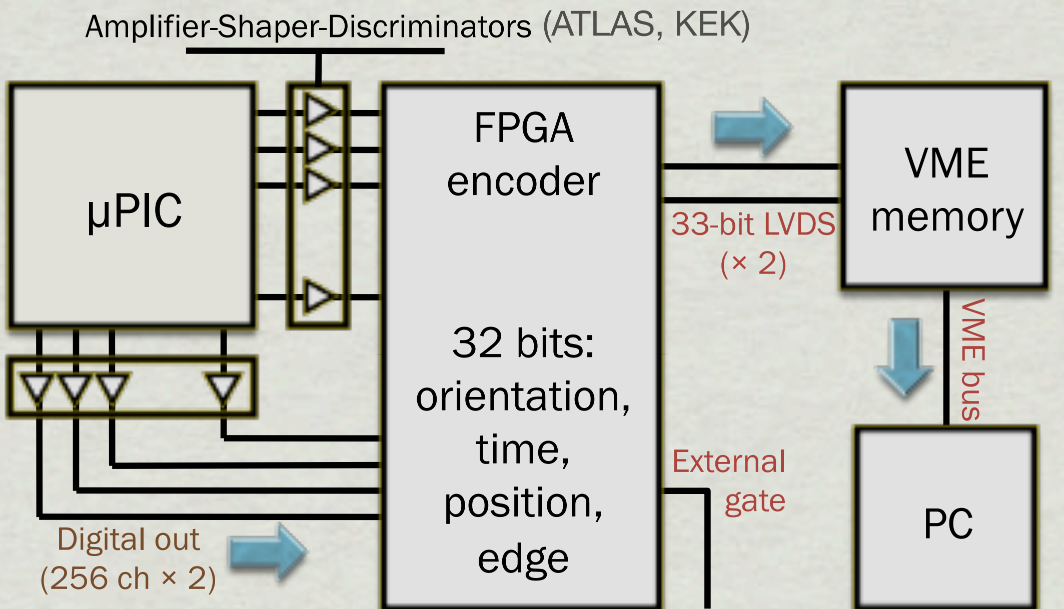


PROTON-TRITON TRACKS



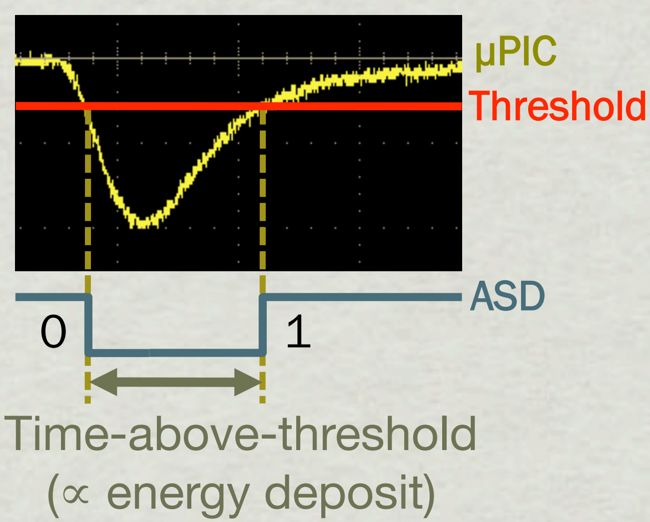
- Simultaneous measurement of position and ‘energy deposit’ at high rates.
- Excellent background rejection capability.

DAQ and FPGA logic

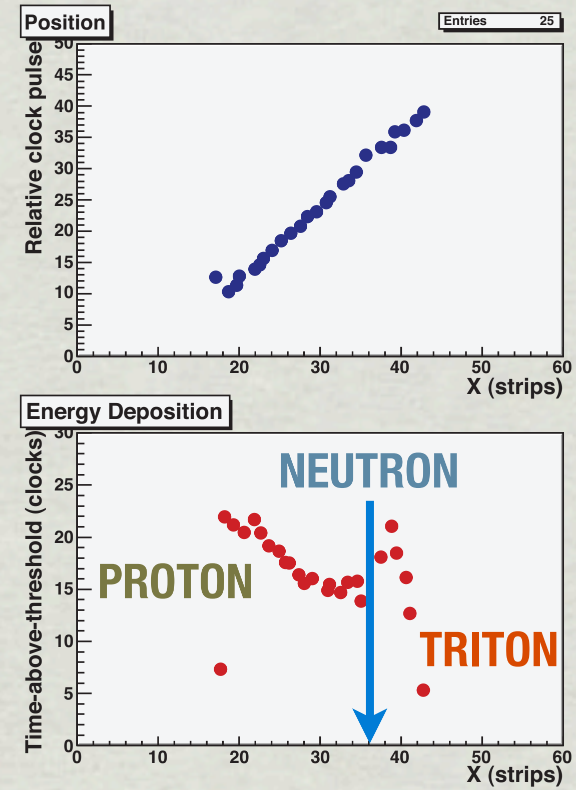


DATA ENCODING

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

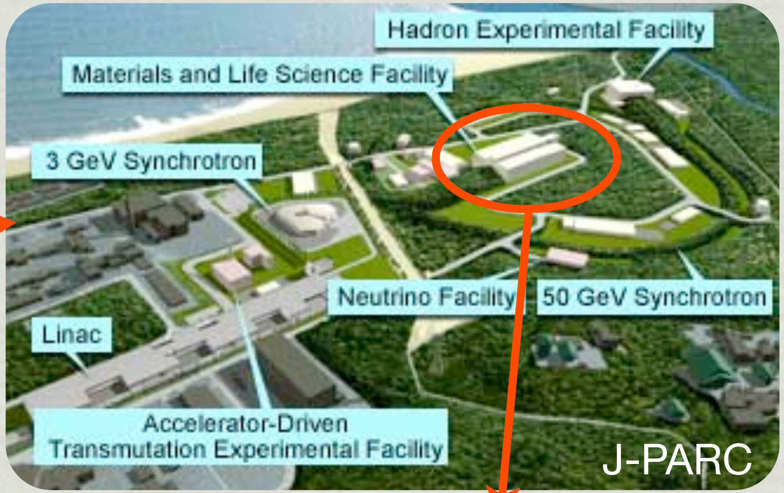


PROTON-TRITON TRACKS

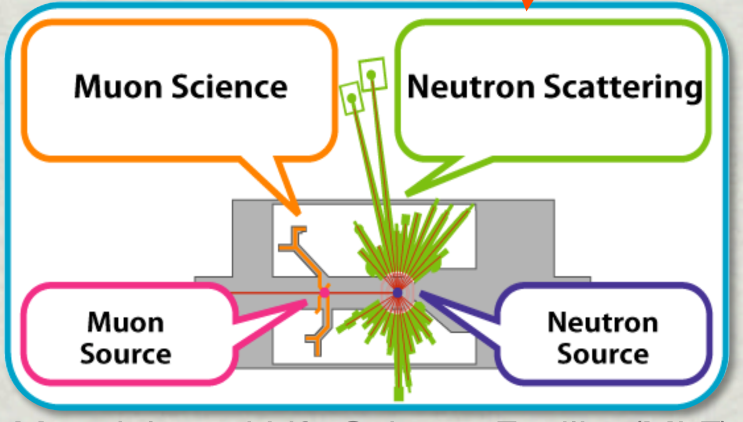


- Simultaneous measurement of position and ‘energy deposit’ at high rates.
- Excellent background rejection capability.

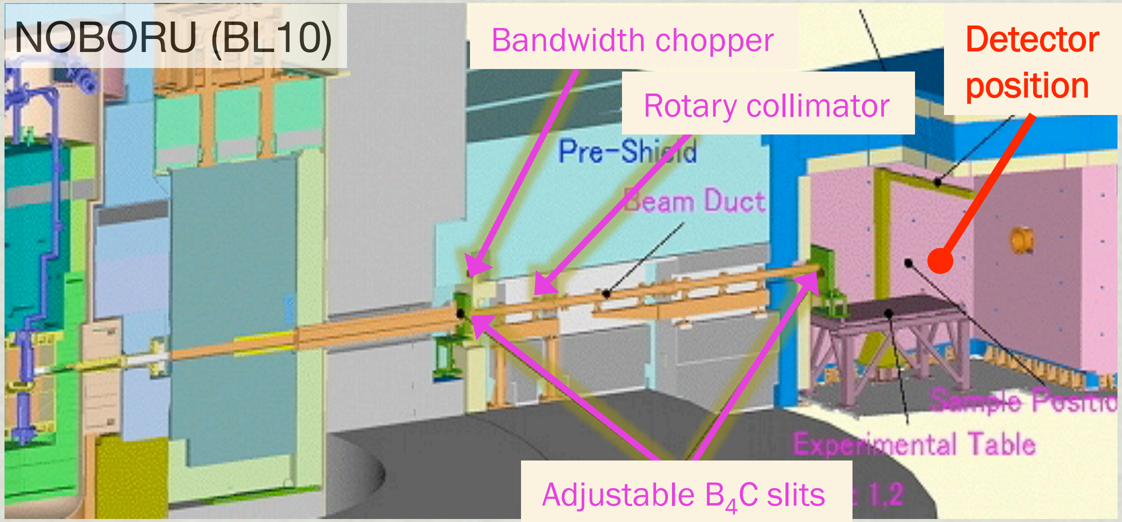
Test experiments at J-PARC



- Experiments in Nov. 2009, June 2010, and Feb. 2011.
- Beam power ~120 kW.
- Carried out at NOBORU beam line.
- Fill gas: Ar-C_2H_6-^3He (63:7:30) at 2 atm, efficiencies ~28%(5 cm), ~13%(2.5 cm).



Materials and Life Science Facility (MLF)

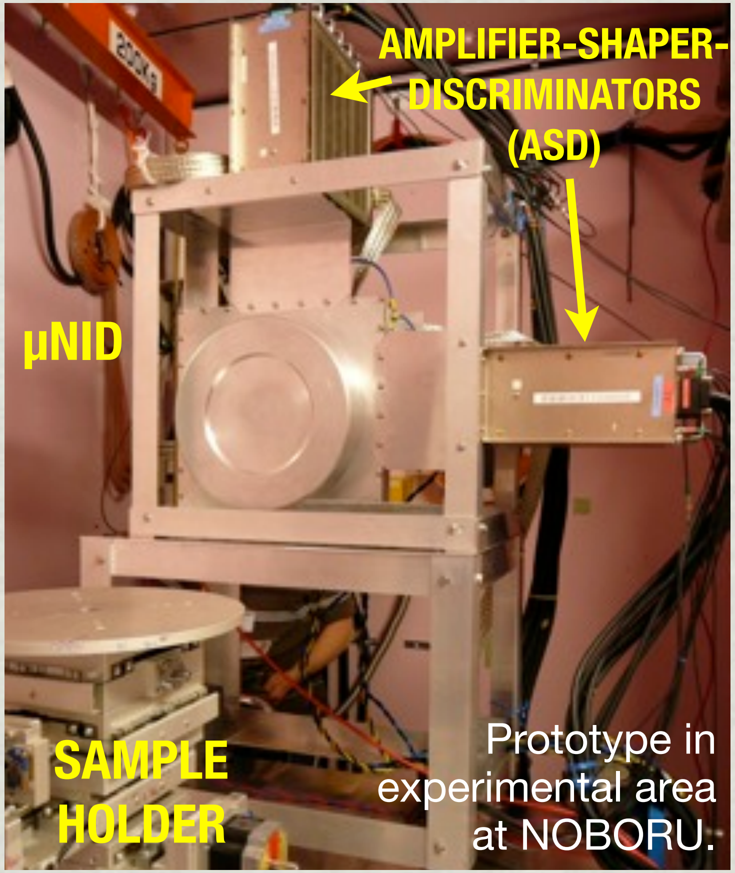


NOBORU BEAM LINE

- Moderator-to-detector distance of ~14.5 m.
- Max. beam size: 10 × 10 cm^2.
- 25 Hz pulse rate, 10 Å band-width.

Long term operability and ^{3}He usage

- Same gas filling used for first two experiments (separated by 8 months).
- No degradation in performance seen in June experiment.
- Gain recovered by increasing anode voltage.
- Detector remained operable after more than 1 year on single gas filling.



Prototype in experimental area at NOBORU.

	Time after filling	Gain (% of initial)
1st Exp (2009)	0 months	100
2nd Exp (2010)	8 months	67
Dec 2010	13 months	30

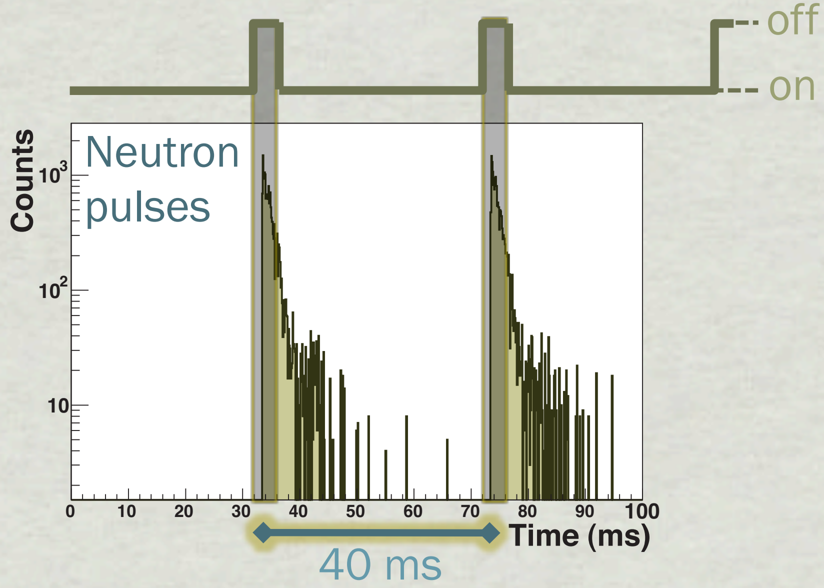
Strategies to extend operation

- Annealing of vessel and μPIC against outgassing.
- Careful selection of materials.
- Gas purification or ^{3}He reclamation system.

DAQ performance at NOBORU

- Time-averaged data rates from 200 kHz ~ 9.4 MHz (neutron rate of 80~100 kHz).
- Large dead time (40 ~ 85%).
- Encoder limits DAQ rate.
- VME-to-PC transfer creates dead time.
- Limitations can be reduced with further hardware development.

EXTERNAL TOF GATE



- Reduction in incoming data means fewer VME readouts.
- Effectiveness depends on details of TOF distribution and gate.
- Useful for Bragg transmission, resonance absorption.

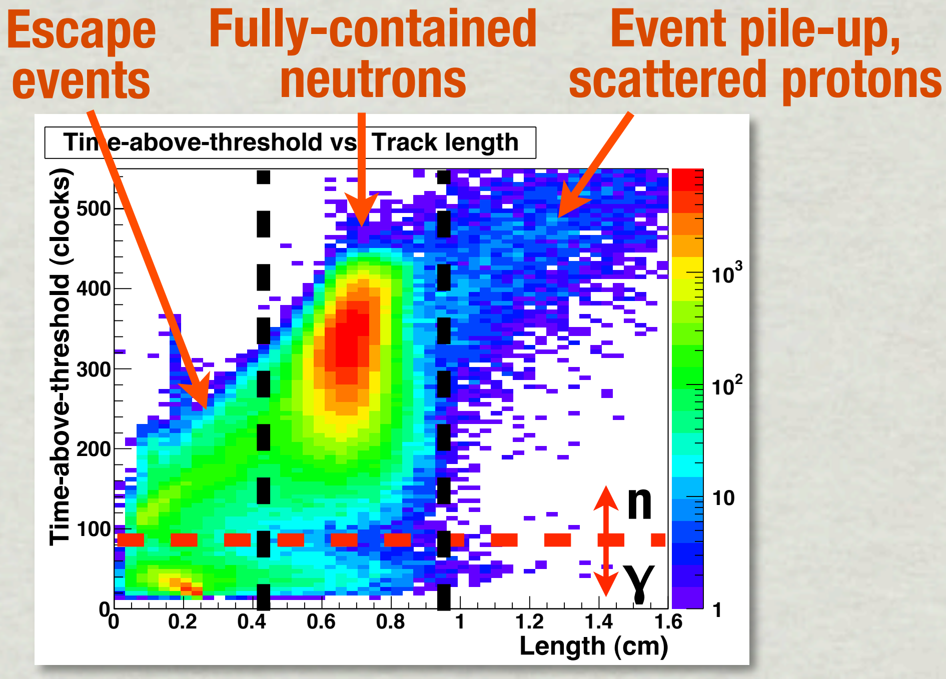
EXTERNAL TOF GATE

Ex: Bragg transmission measurement (2010).

	Ungated	TOF > 3 ms
No. of pulses	8948	191389
Total time (min)	34.5	226.2
Dead time (%)	82.7	43.6

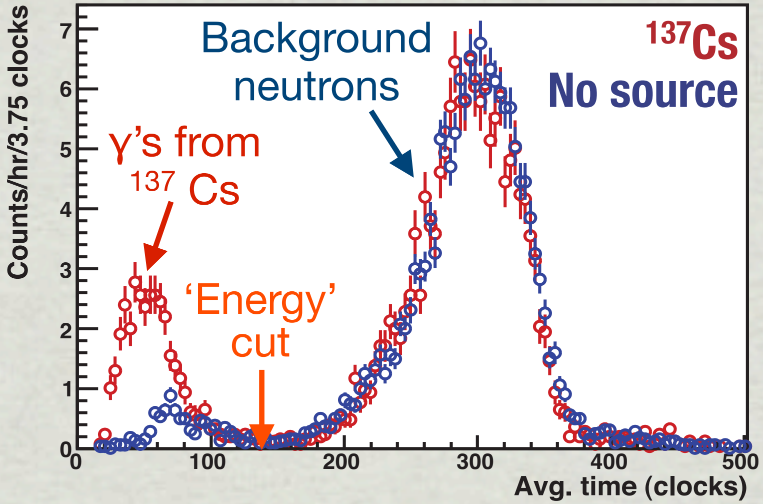
~70% decrease in measurement time.

Neutron-gamma separation



- Gamma rejection studied using RI sources.
- Data taken over 24 hours.

Pulse-width sum after track-length cut

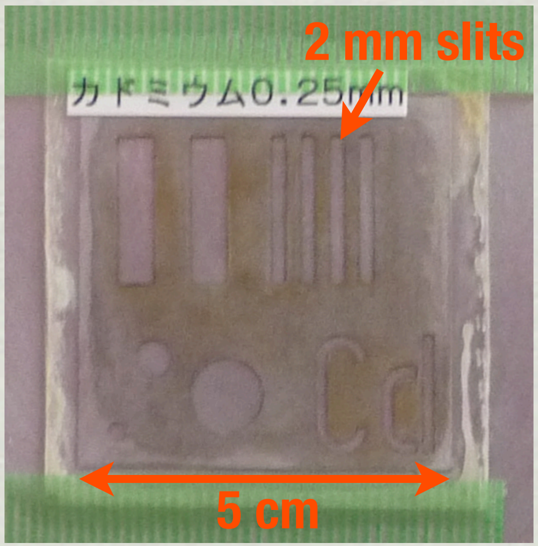


- Both neutrons and gammas are detected (γ efficiency ~10^{-3}).
- Neutrons selected by cuts in total time-above-threshold and 3D track length.
- Fraction of detected γ's surviving neutron cuts < 10^{-6} (effective gamma sensitivity of < 10^{-9}).

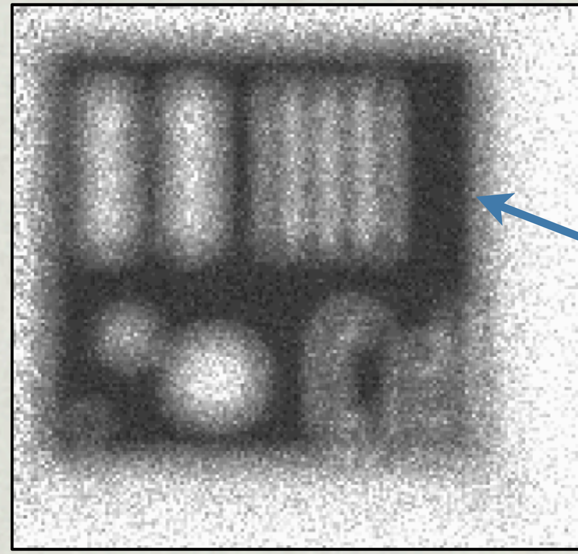
	Contamination fraction (95% CL)
Track length	< 5.5×10^{-6}
+ PID	< 2.9×10^{-6}

Position resolution with PID

Cd TEST CHART



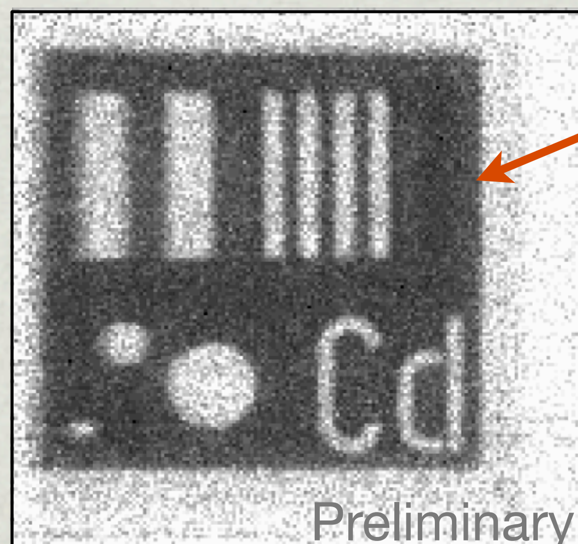
No PID



Position from mid-point of track.

Resolution: ~1 mm (σ)

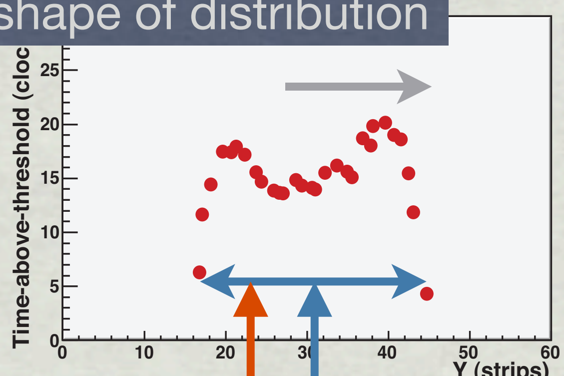
With PID



Resolution with PID: 349 ± 36 μm (σ)

(Includes beam dispersion.)

Proton direction from shape of distribution



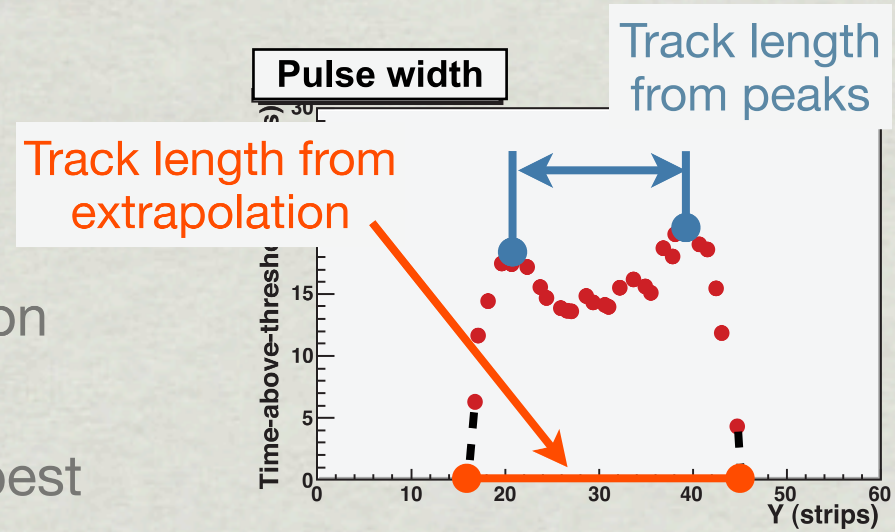
Corrected position

Mid-point

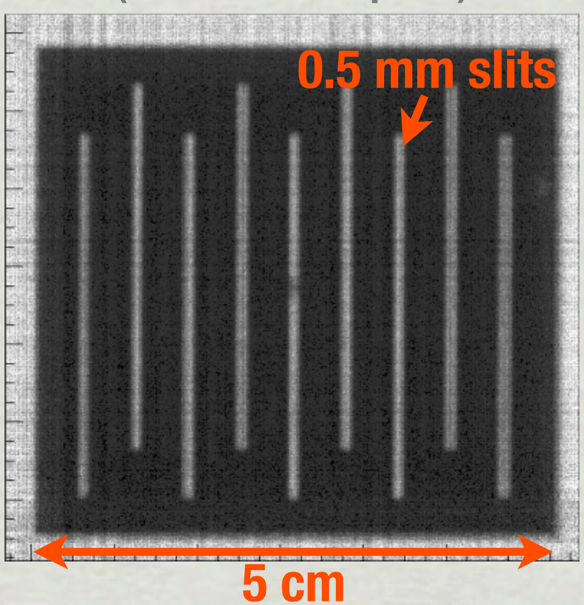
Data taken at NOBORU, J-PARC in Nov. 2009.

Refining position resolution

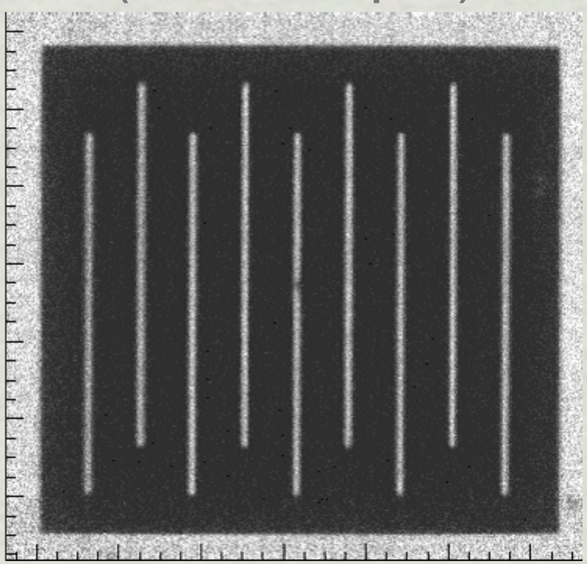
- Two methods: End-Point Extrapolation (EPE) and Peak Interpolation (PI).
- Combining both methods produces best result of σ = 118.4 ± 0.2 μm.



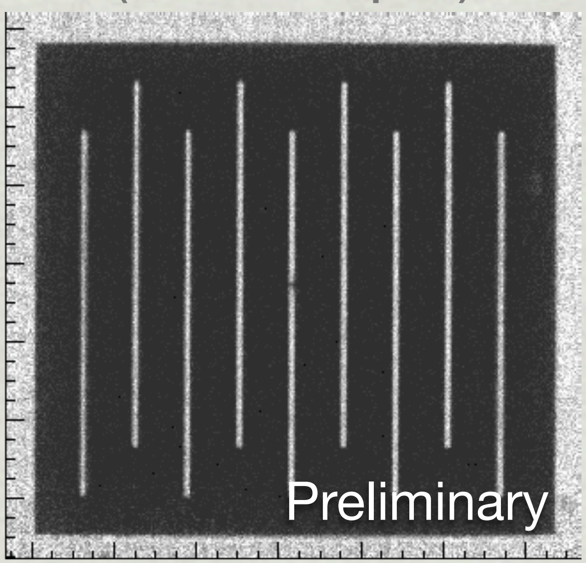
NO REFINEMENT
(σ = 315 μm)



EPE ONLY
(σ = 182 μm)



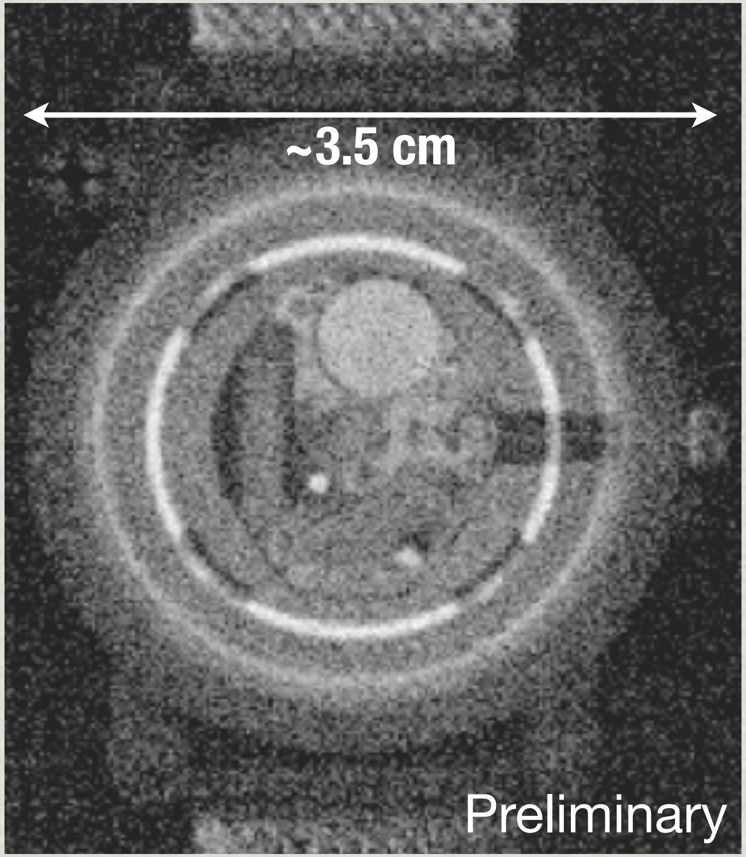
EPE + PI
(σ = 118 μm)



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

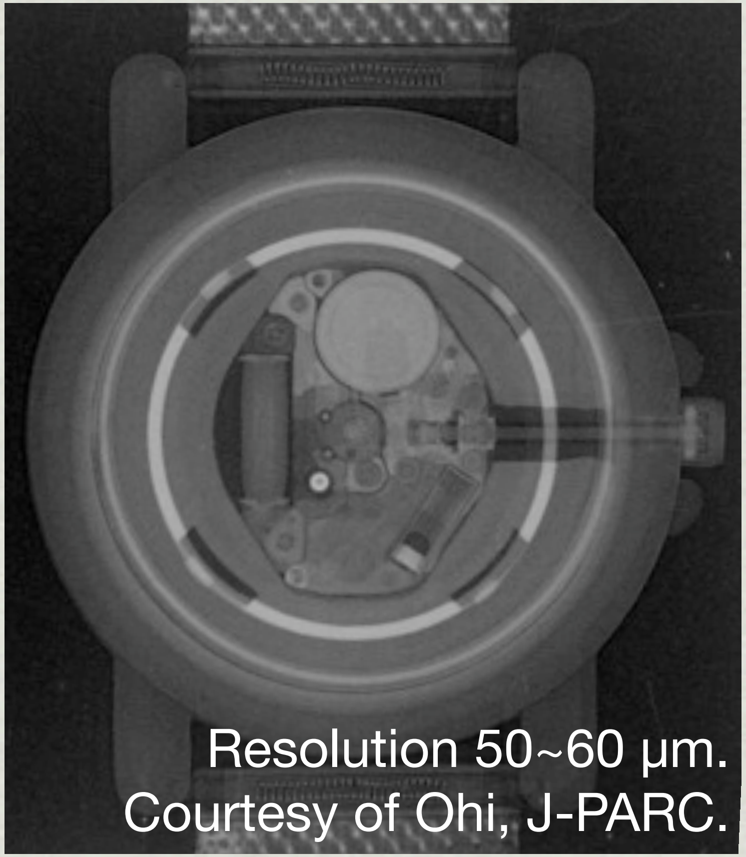
Image of a wristwatch

μPIC (29 MIN.)



Bin size: 200 μm × 200 μm.

IMAGING PLATE (200 MIN.)

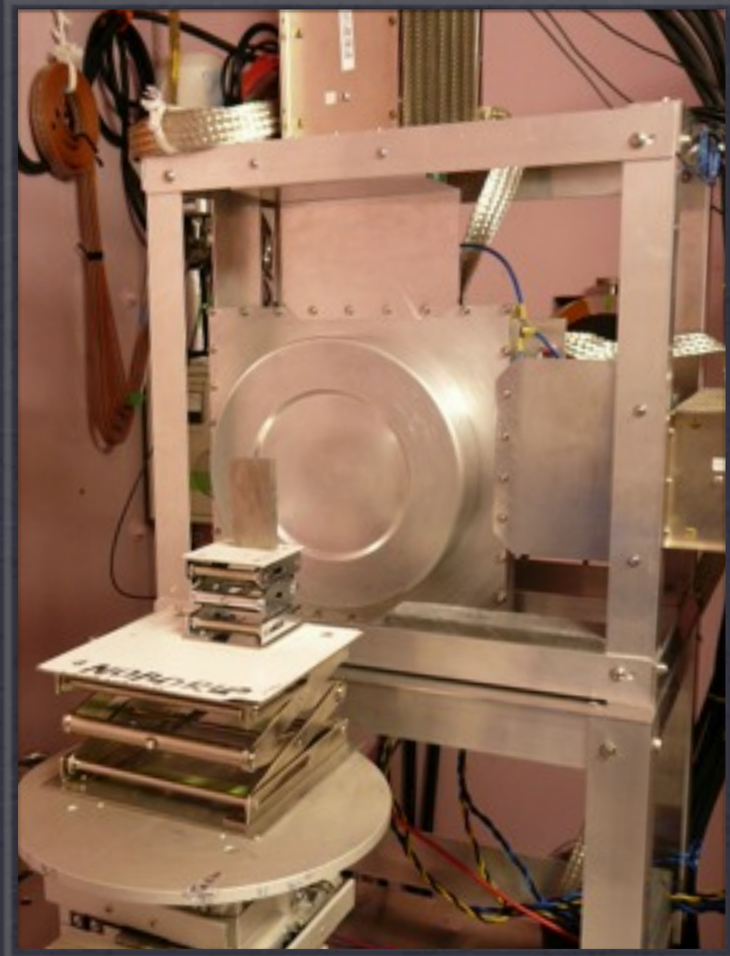


- Bin size can be decreased with higher statistics.
- Image processing techniques could improve image.

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

Demonstration measurements

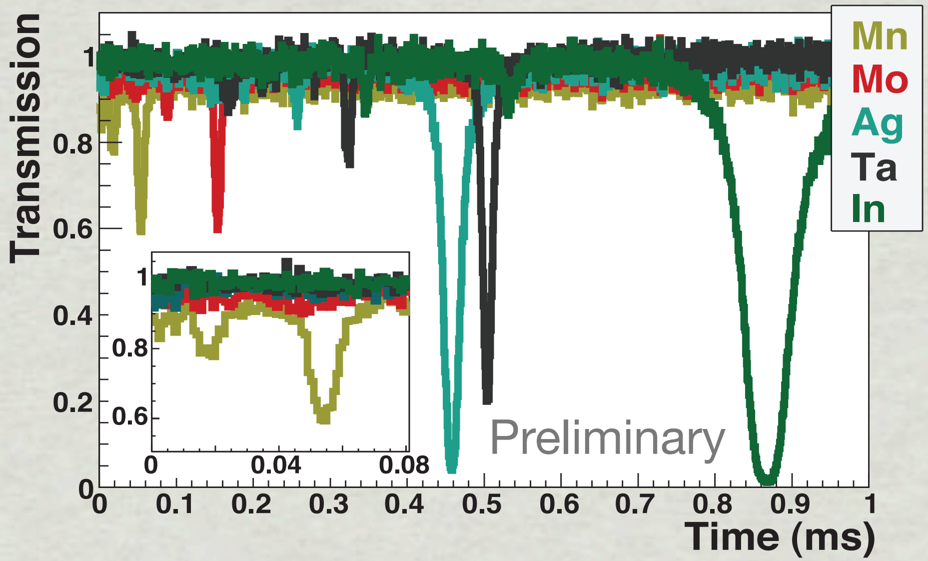
- Resonance absorption.
- Bragg-edge transmission.

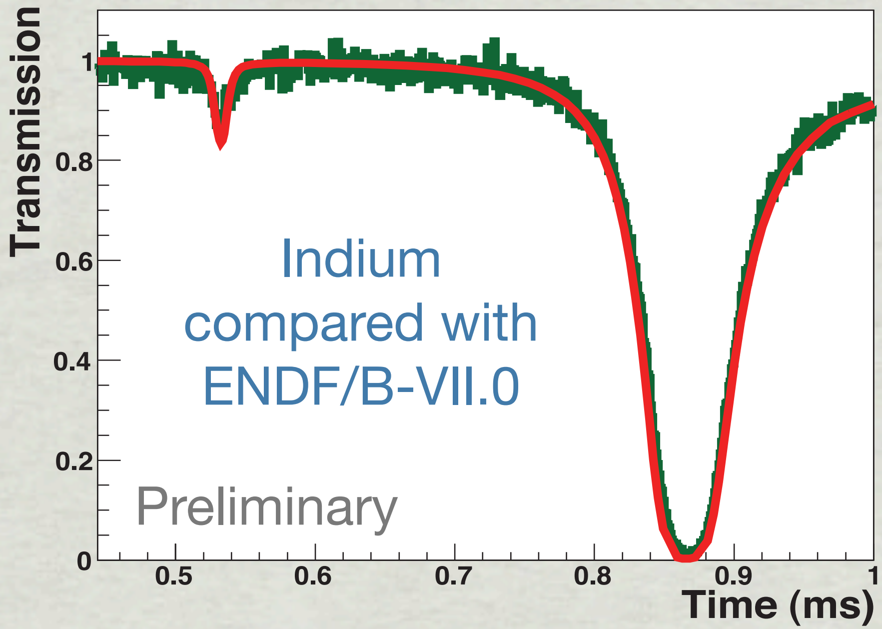


Resonance absorption

- Sheets of In, Ta, Ag, Mo, and Mn.
- Typical area of 10 cm × 10 cm.
- Thicknesses from 10 μm to 1 mm.

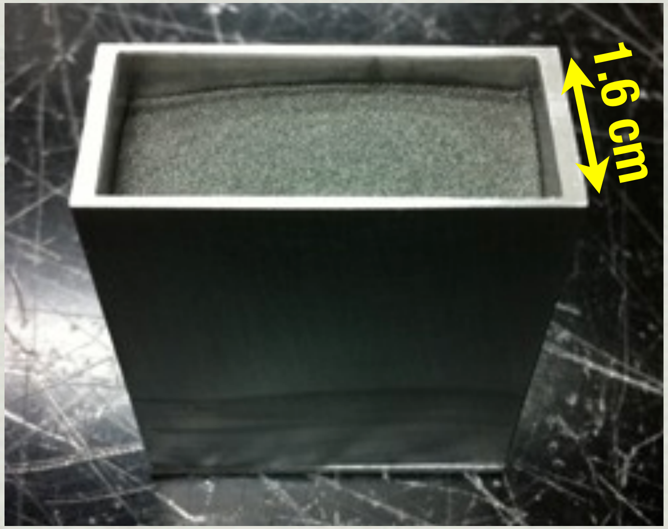
- Resonance absorption occurs when neutrons of a particular energy are absorbed preferentially by a target nucleus.
- Large samples to accumulate statistics quickly (~16 min/sample).
- Good time resolution and background rejection allows us to see resonances near beginning of pulse.





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

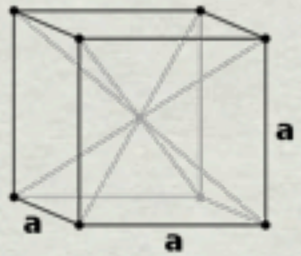
Bragg-edge transmission



Fe powder (> 99% purity, grain size < 325 μm).

Fe CRYSTAL STRUCTURE

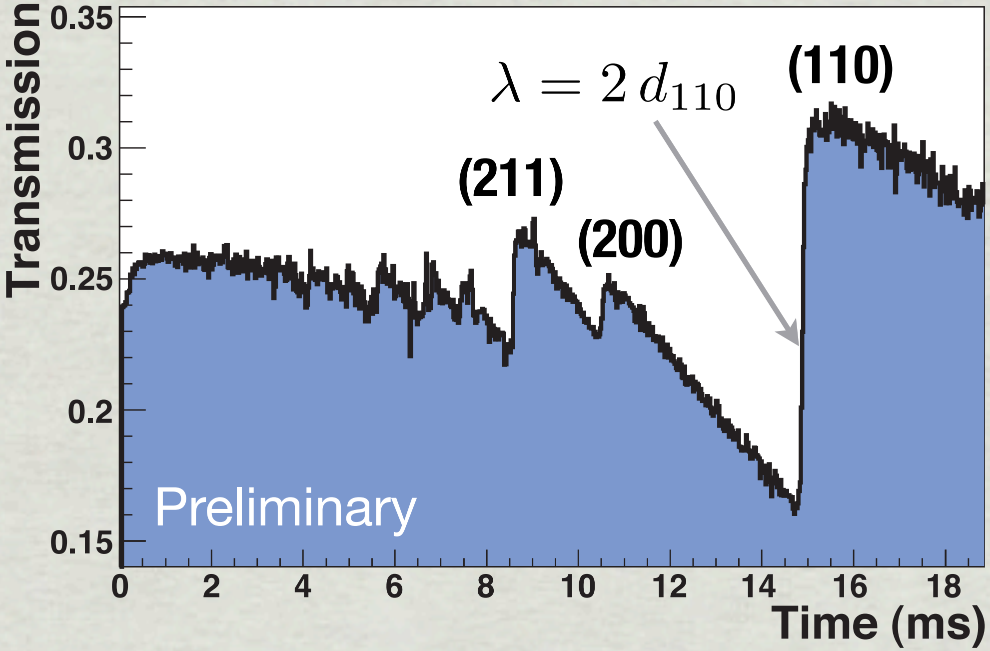
Body-centered cubic (BCC)



a is referred to as the lattice parameter.

$$a = d_{lmn}\sqrt{l^2 + m^2 + n^2}$$

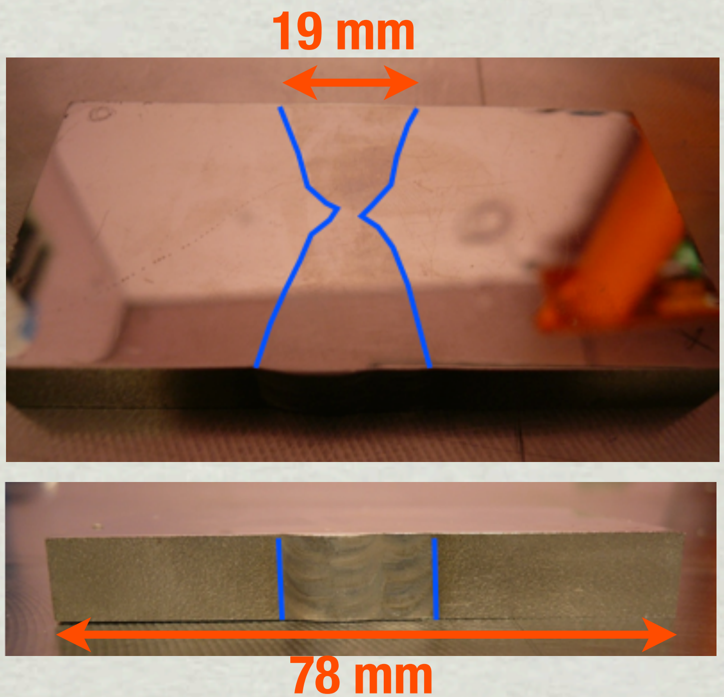
- Edges appear when neutron wavelength is twice crystal plane spacing (Bragg's law at 2θ = 180º).
- Edge spacing is consistent with expected BCC crystal structure.
- Precise measurement of edge positions determines lattice parameter.

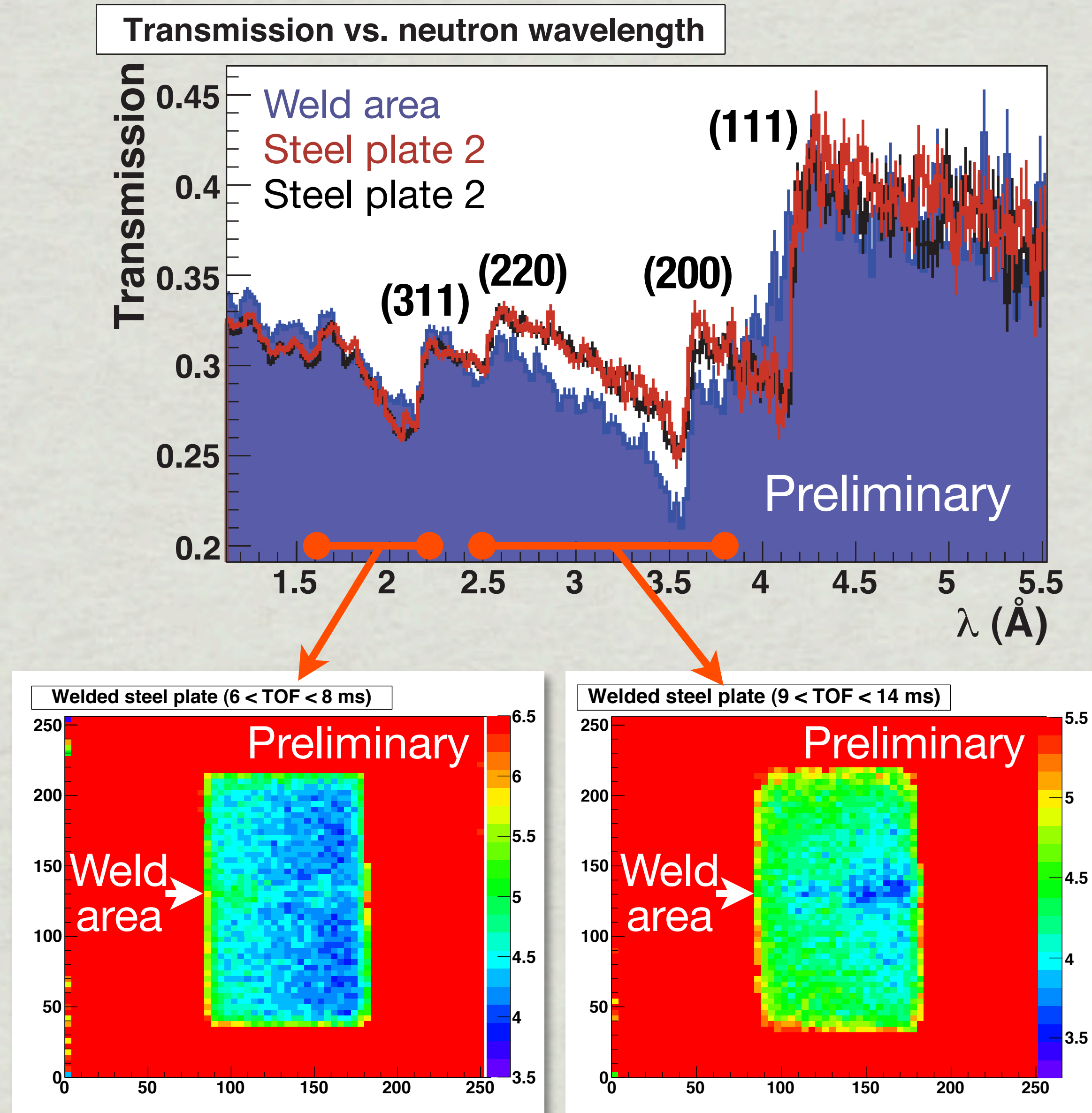


Data taken at NOBORU, J-PARC in Feb. 2011.

Bragg-edge transmission

78 × 40.5 × 10 mm³ TIG-WELDED 316L STAINLESS STEEL PLATE

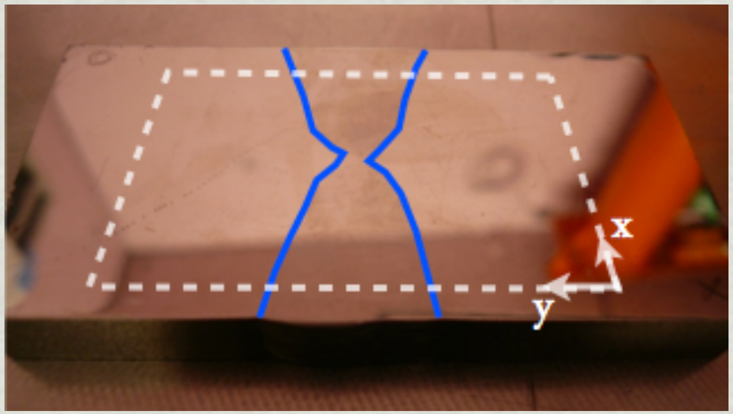




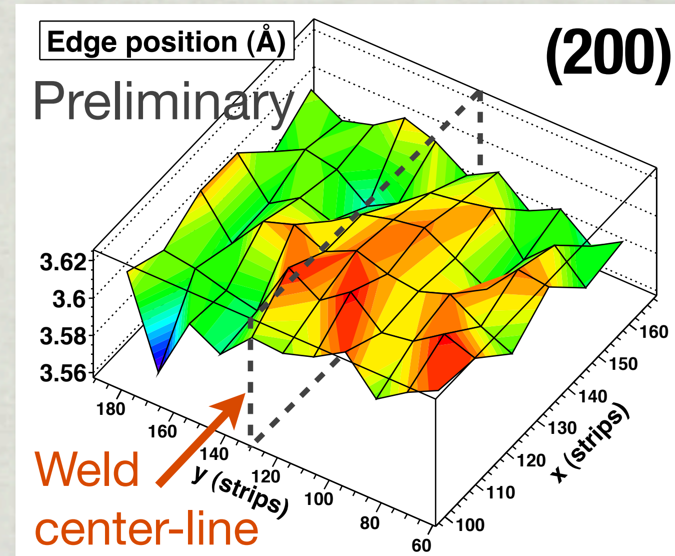
Edge spacing is consistent with FCC crystal structure.

Data taken at NOBORU, J-PARC in June 2010.

Bragg-edge transmission



Divide image into 4.8 × 4.8 mm^2 ‘pixels’ and fit edge positions*.



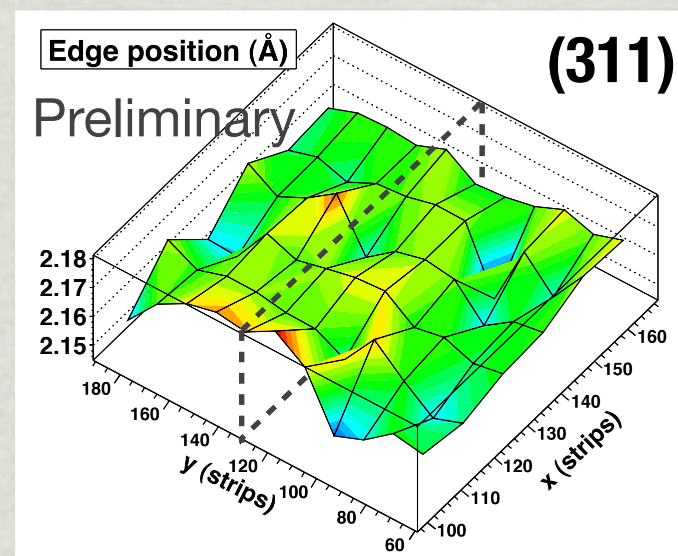
- Variation in edge positions may be related to internal strain.
- Full strain tensor requires measurements from at least six independent directions.
- Only one direction observed in this measurement.

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

d-spacing from wavelength

$$\varepsilon = \frac{d - d_0}{d_0}$$

strain component in beam direction

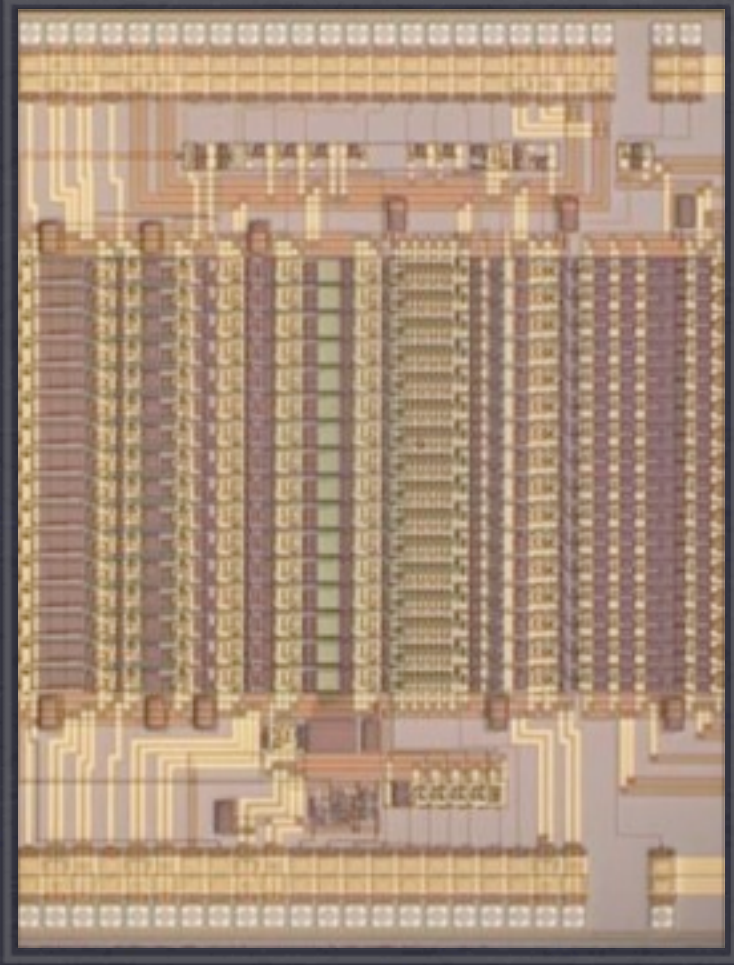


* Fit procedure based on Santisteban, et al. (2001)

Data taken at NOBORU, J-PARC in June 2010.

Future improvements

- Optimization of gas mixture.
- Smaller pitch μPIC.
- New ASICs and encoder for more compact DAQ.



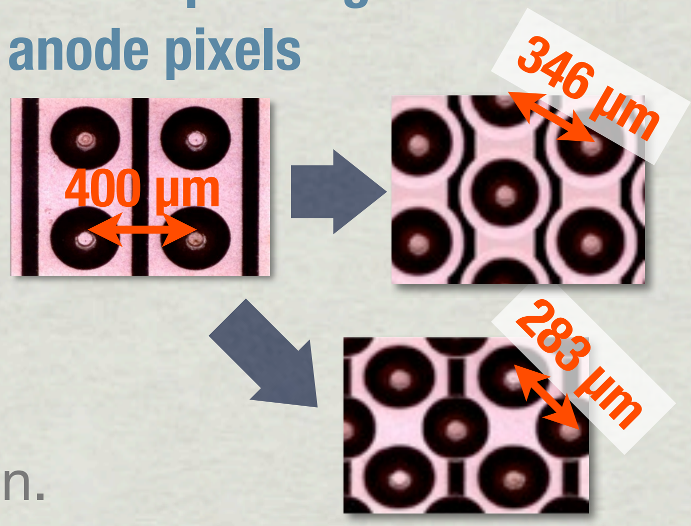
Gas optimization and pixel pitch

	Pressure (atm)	Drift velocity (μm/ns)	Transverse diffusion (μm/cm$^{1/2}$)	Longitudinal diffusion (μm/cm$^{1/2}$)	Expected improvement in resolution
$Ar:C_2H_6:{}^3He$ (63:7:30)	2	23.1	273	169	(118 μm)
$Ar:C_2H_6:{}^3He$ (63:7:30)	3	23.4	231	126	~15%
$Xe:C_2H_6:{}^3He$ (50:20:30)	2	29.4	183	125	~15%
$Ar:CO_2:{}^3He$ (50:20:30)	2	22.5	107	114	~15%

Gas parameters determined by MAGBOLTZ.
Resolutions estimated with GEANT4.

- Shorten p-t track lengths by increasing pressure or changing to gas with higher stopping power.
- Reduce diffusion of drift electrons.
- Moderate reductions in pixel pitch produce corresponding reduction in position resolution.

Denser packing of anode pixels



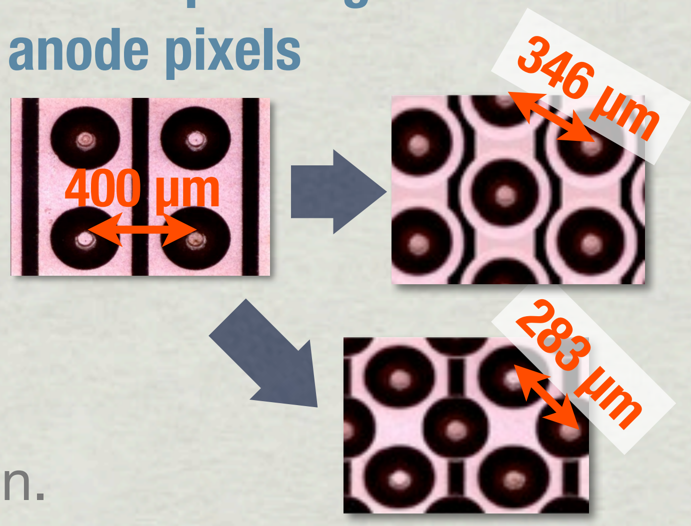
Gas optimization and pixel pitch

	Pressure (atm)	Drift velocity (μm/ns)	Transverse diffusion (μm/cm$^{1/2}$)	Longitudinal diffusion (μm/cm$^{1/2}$)	Expected improvement in resolution
$Ar:C_2H_6:{}^3He$ (63:7:30)	2	23.1	273	169	(118 μm)
$Ar:C_2H_6:{}^3He$ (63:7:30)	3	23.4	231	126	~15%
$Xe:C_2H_6:{}^3He$ (50:20:30)	2	29.4	183	125	~15%
$Ar:CO_2:{}^3He$ (50:20:30)	2	22.5	107	114	~15%

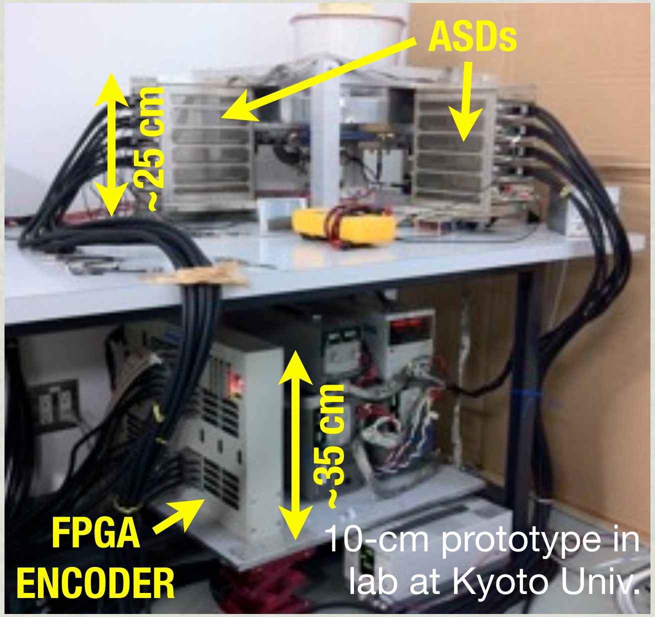
Gas parameters determined by MAGBOLTZ.
Resolutions estimated with GEANT4.

- Shorten p-t track lengths by increasing pressure or changing to gas with higher stopping power.
- Reduce diffusion of drift electrons.
- Moderate reductions in pixel pitch produce corresponding reduction in position resolution.

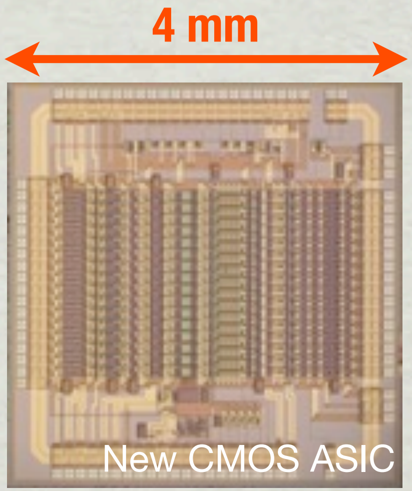
Denser packing of anode pixels



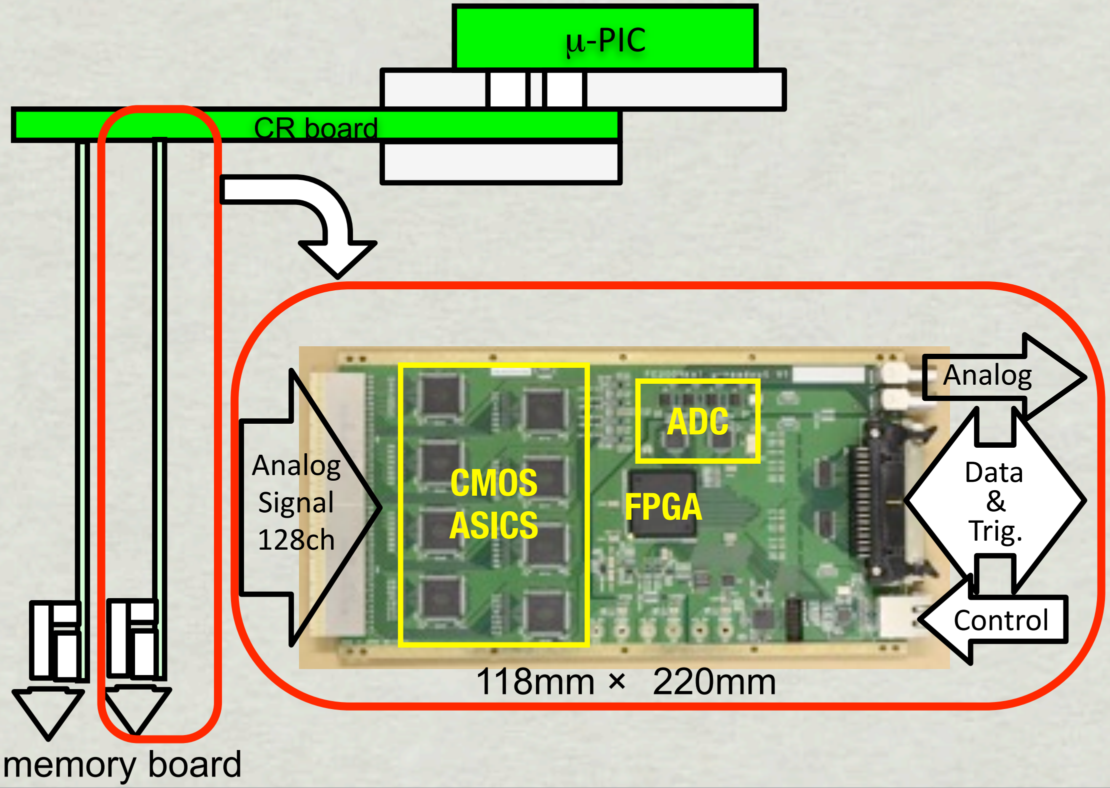
DAQ improvements



- Replace ASDs with CMOS chips (developed with KEK for SMILE project).
- 16 channels/chip (increased from 4).
- Power per channel reduced by factor of more than 3.



- Combine CMOS chips with FPGA on single board.
- Four boards replace ASD racks, encoder, cables.
- Each board writes to memory, increasing max. data rate.
- New boards now under testing.



Summary

- TPC based on micro-pattern gaseous detector and FPGA DAQ system.
  - Position resolution of 118 μm; time resolution of ~1 μs.
  - FPGA-based DAQ with high data rates.
  - Strong rejection of gammas and fast neutrons.
- Detector remains operable over long time.
  - Annealing to reduce outgassing for increased long-term stability.
  - Gas filtration system could extend operation considerably.
- Development of compact DAQ and optimization of gas mixture are ongoing.
- μPIC manufactured using standard, inexpensive PC board manufacturing processes.
  - μPIC sizes up to 30 × 30 cm^2 are currently available.
  - Tiling of detectors to cover large area.