Fast Neutron Multiplicity Counter: Development of an active-mode counter

UM-INL Collaboration

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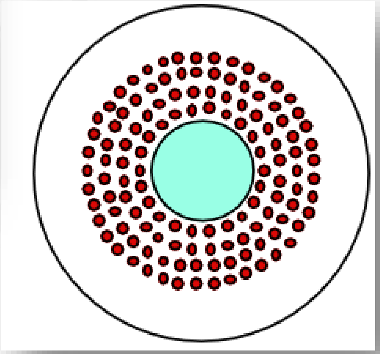
Introduction

- Need technological advances for the verification and monitoring of special nuclear material (SNM)
- Neutron multiplicity counting (NMC) used for non-destructive assay
- Traditional NMC systems utilize capture-based thermal neutron detectors
  - Typically a well-type geometry
  - Relies heavily on ^{3}He-based detectors/systems
  - Increasing cost of ^{3}He gas
- Investigate ^{3}He alternatives

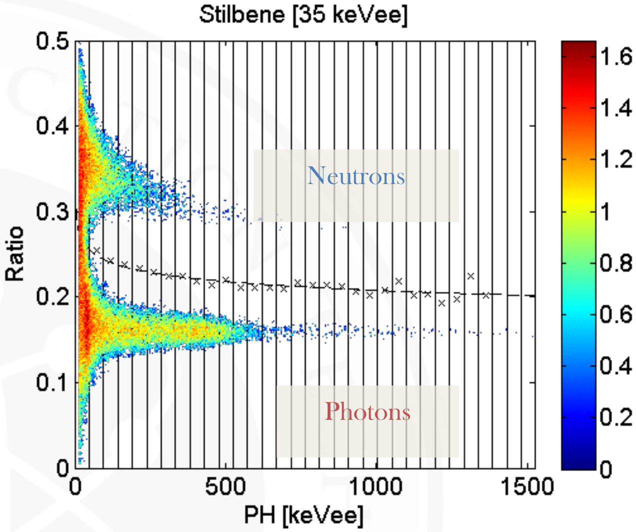
^{3}He tubes with moderator

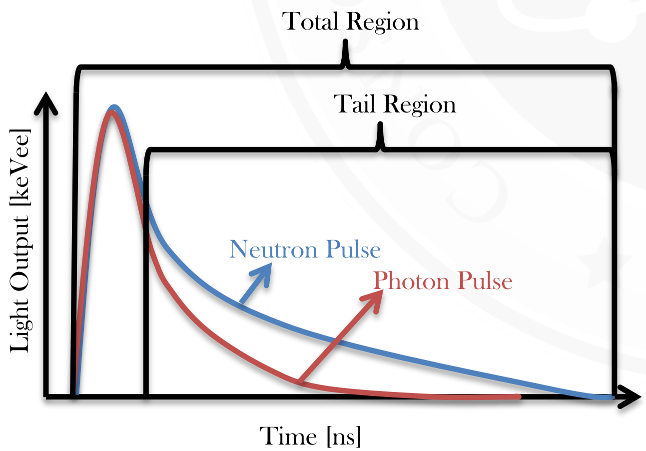
Canberra© JCC-13
Coincidence Counter

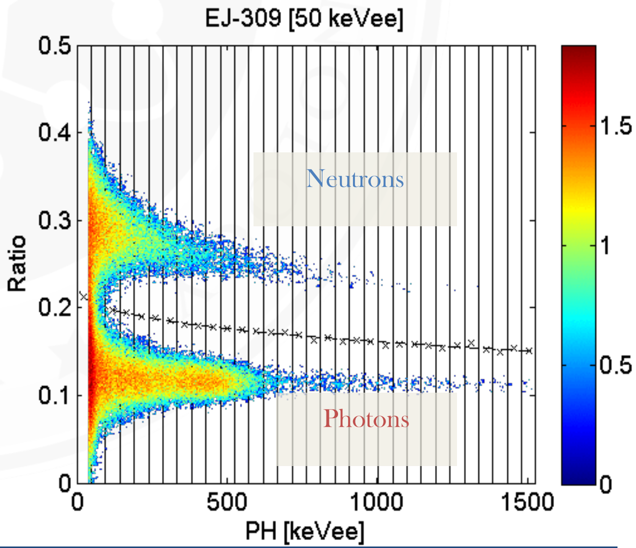


Design schematic of a typical multiplicity counter[1]

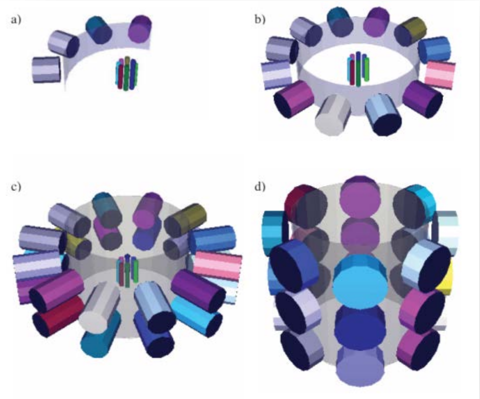
UM-INL Collaboration: Organic Scintillators



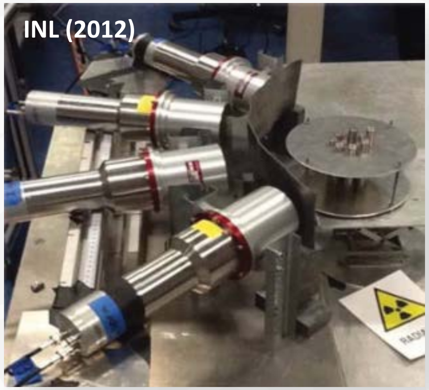




UM-INL Collaboration: Fast Neutron Multiplicity Counters

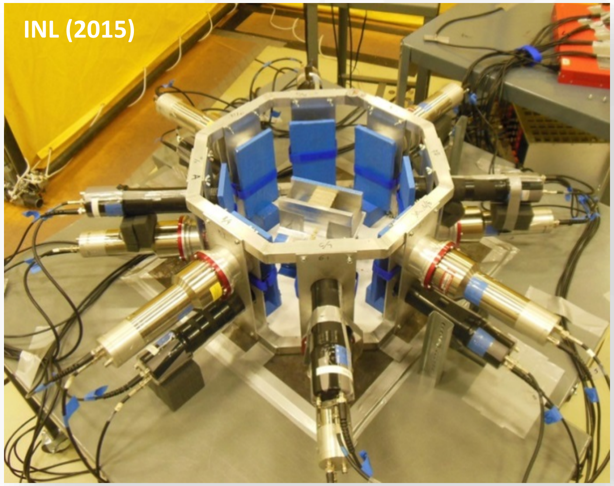


Design concepts in MCNPX-PoliMi (2012)

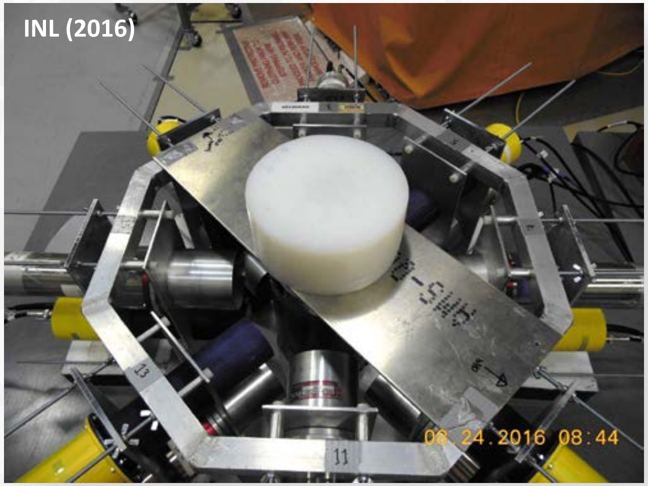


Passive measurements: 4 EJ-309 (2012)

Passive measurements: 16 EJ-309 (2013)



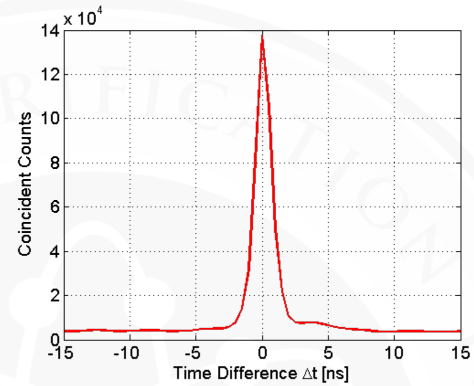
Passive measurements: 8 EJ-309 and 8 Stilbene (2015)

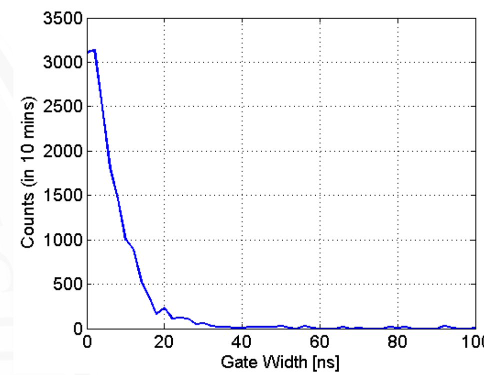


Active measurements: 8 EJ-309 and 8 Stilbene (2016)

Advantages of Fast Neutron Multiplicity Counters

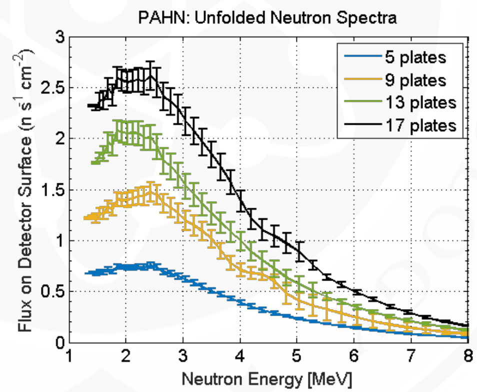
1) Much faster timing properties relative to thermal systems
   → improved timing resolution



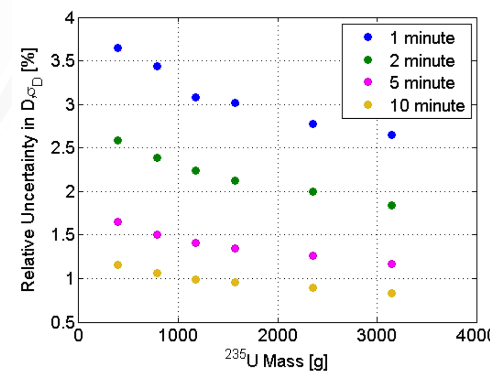


2) No moderating material required
   → short die-away times

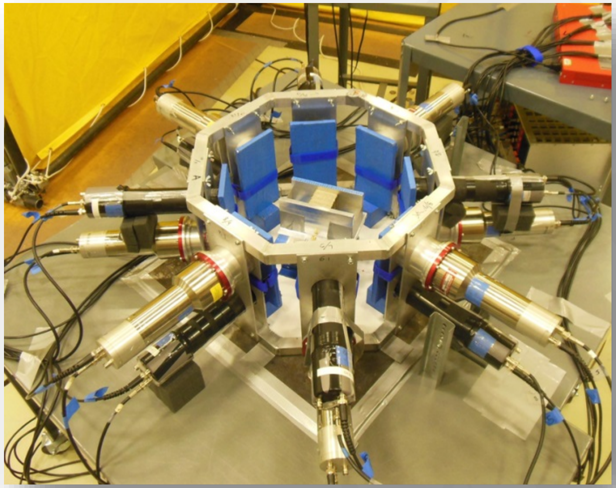
3) Portion of initial neutron energy information retained
   → spectrum unfolding capabilities



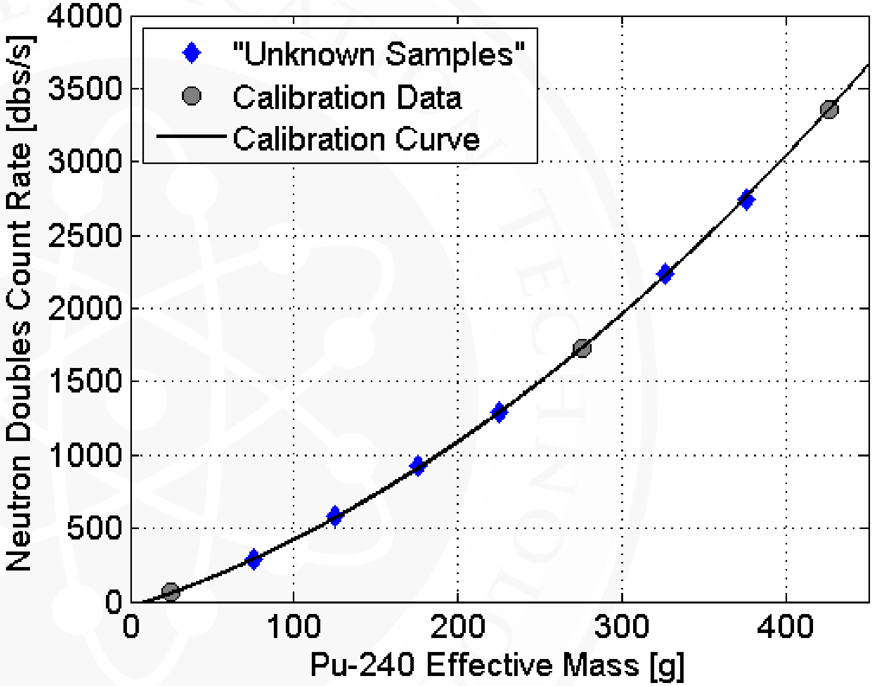
4) Low rate of accidental correlated counts
   → lower uncertainty



UM-INL Collaboration: Passive Measurements (2015)



FNMC System at INL 2015

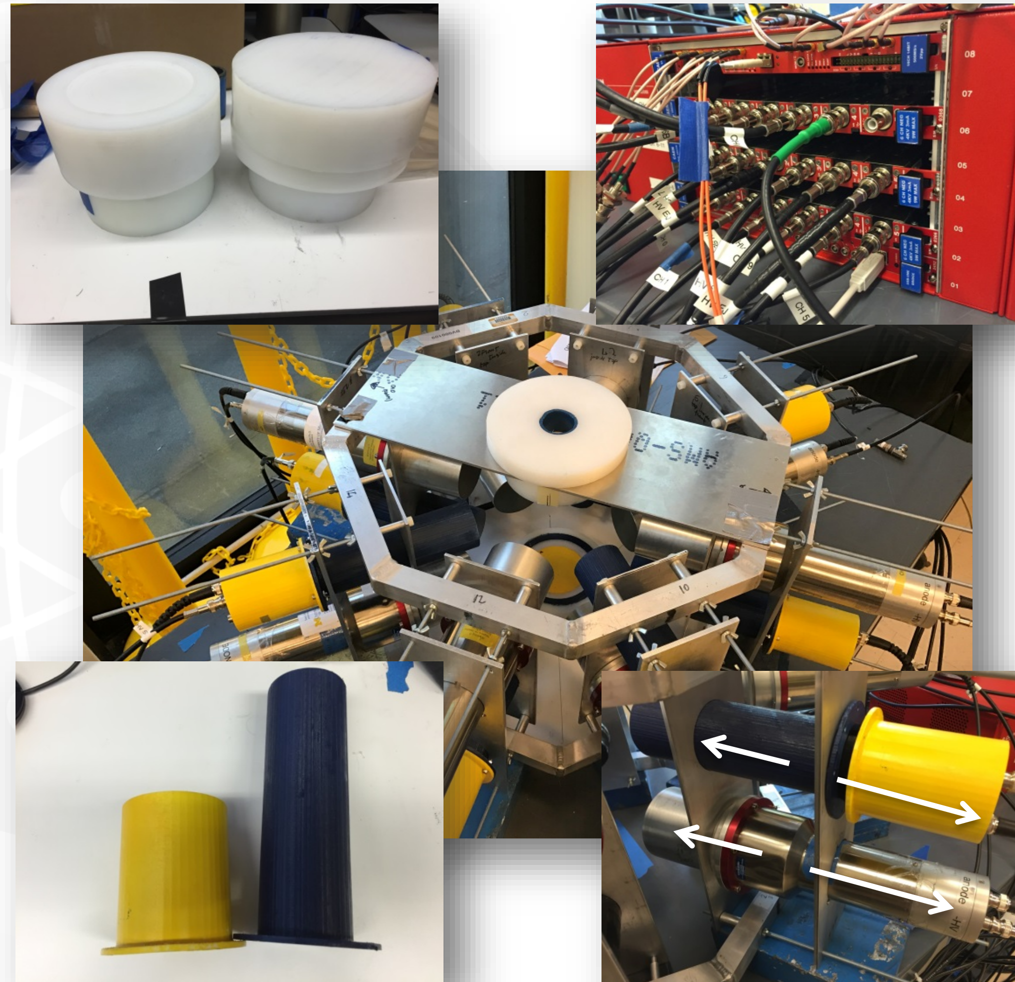


Number of Plates	3	5	7	9	13	15
Actual Mass [g]	75.15	125.25	175.35	225.45	325.65	375.75
Estimated Mass [g]	75.80 ± 0.18	126.03± 0.13	177.74 ±0.20	225.75 ± 0.21	327.20 ± 0.17	374.39 ± 0.18
Percent Difference	**-0.87 %**	**-0.62%**	**-1.36%**	**-0.13%**	**-0.48%**	**0.36%**

From Passive to Active-Mode: System Design

- Interrogative source: AmLi
  - Two AmLi neutron sources (~50,000 n/s)

- New components/features for active FNMC system
  1) Polyethylene moderator/reflector for AmLi sources
  2) Compact electronics
  3) 3-D printed Stilbene detector casing
  4) New detector holder structure
  5) Special acquisition techniques (on-board photon rejection)



Experimental Campaign UM-INL 2016

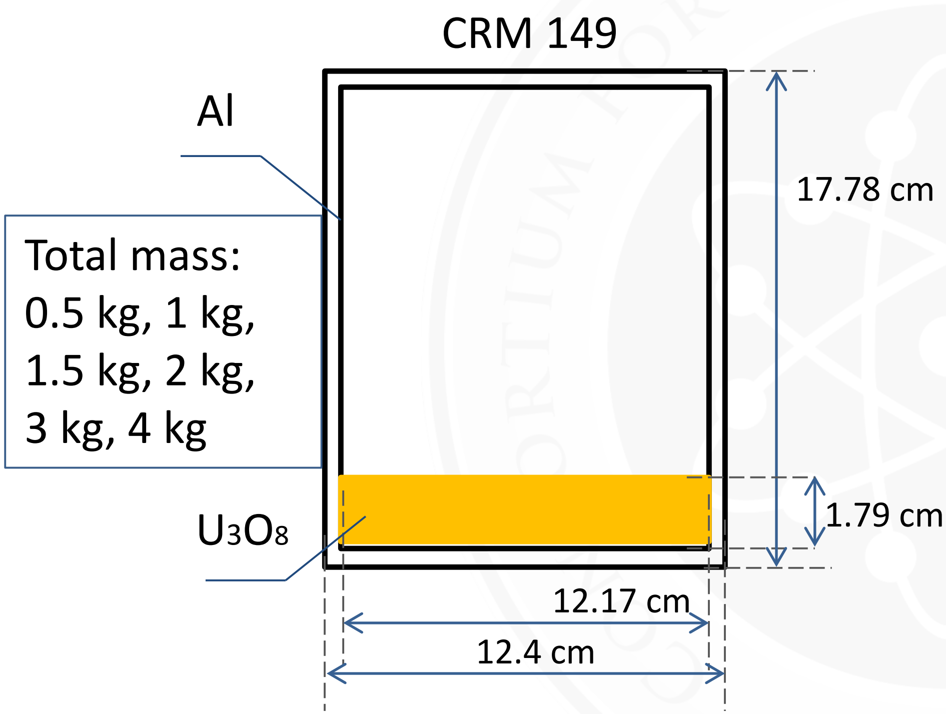
Objectives:

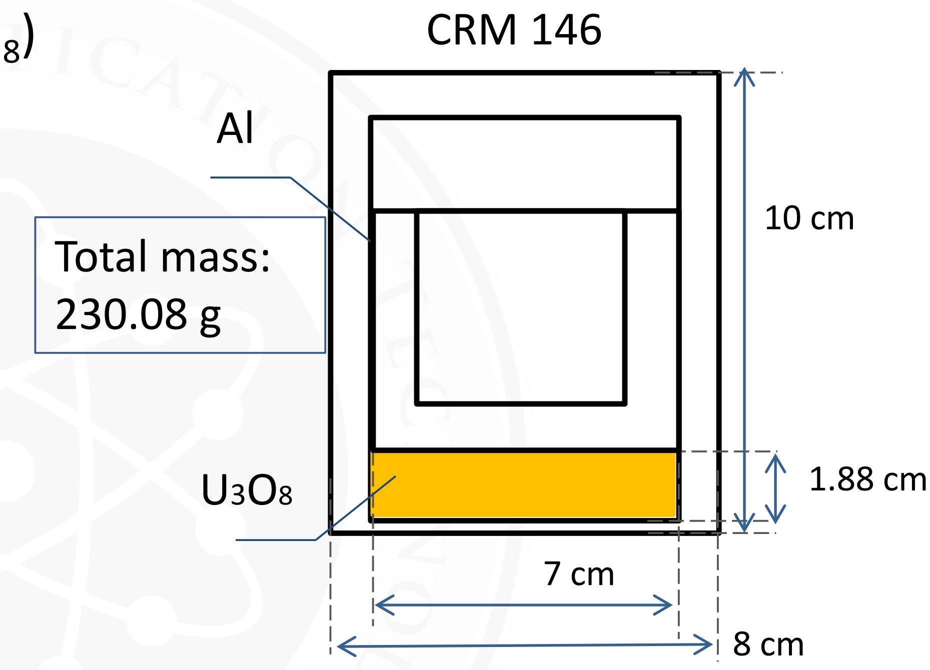
1. Measure multiplicity counts from induced fissions in Uranium samples of various mass content / enrichment
2. Produce mass calibration curve for fissile mass estimation
3. Investigate FNMC system sensitivity to diversion scenarios

Three sets of measurements: CRM-146, **CRM-149**, and **uranium pins**

Experimental Campaign UM-INL 2016

- **CRM 149** and CRM 146 details (U_3O_8)



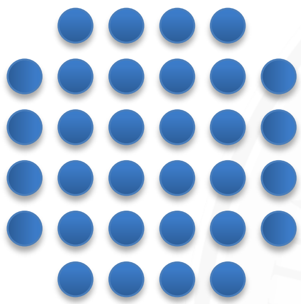


CRM-149 (For all)	^{234}U	^{235}U	^{236}U	^{238}U
Iso. Comp. (wt%)	1.018	**93.257**	0.395	5.329

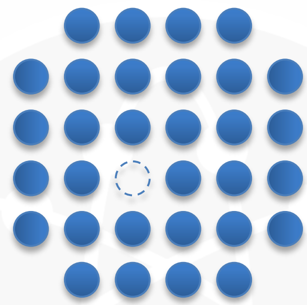
CRM-146 Iso. Comp. (wt%)	^{234}U	^{235}U	^{236}U	^{238}U
CRM146-69	0.148	**20.107**	0.197	79.547
CRM146-70	0.375	**52.800**	0.264	46.560
CRM146-71	0.980	**93.170**	0.293	5.555

Experimental Campaign UM-INL 2016

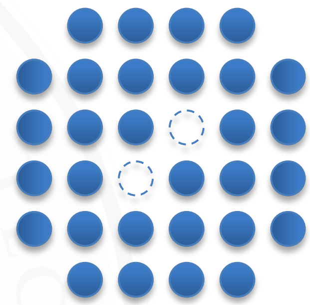
- **Uranium pins** (75.52 g per pin, enrichment = 16.37%, U_3O_8)



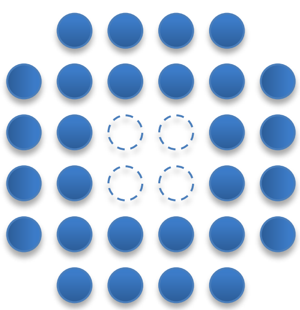
32 pins
Mass = 2416.64 g



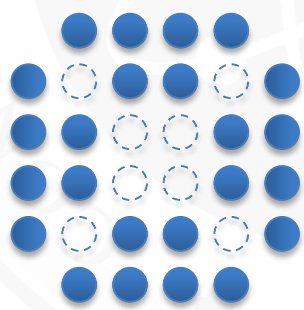
31 pins
Mass = 2341.12 g



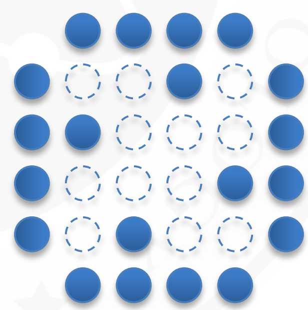
30 pins
Mass = 2265.60 g



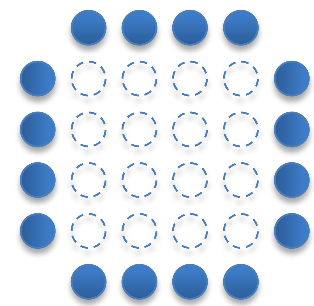
28 pins
Mass = 2114.56 g



24 pins
Mass = 1812.48 g



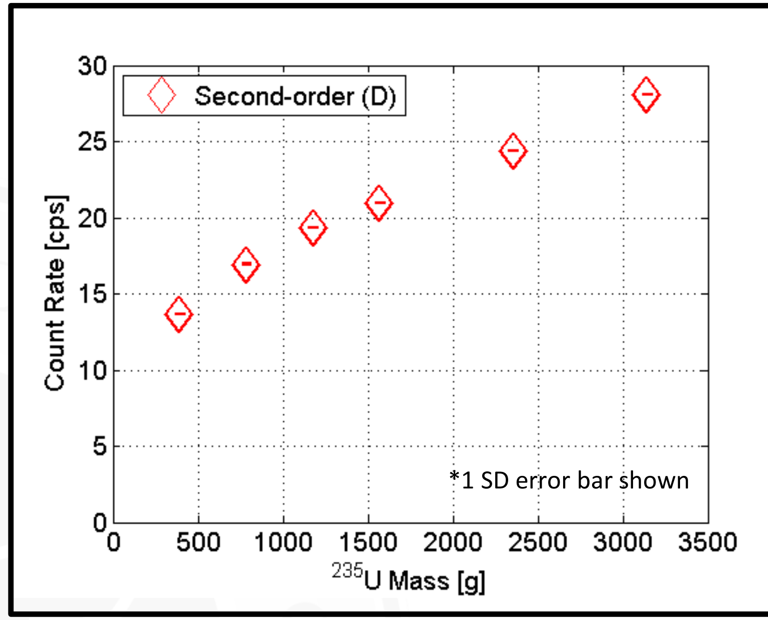
20 pins
Mass = 1510.4 g



16 pins
Mass = 1208.32 g

Results: CRM-149

- 10 min measurement
- 60 keVee applied threshold (≈ 0.5 MeV neutron energy)

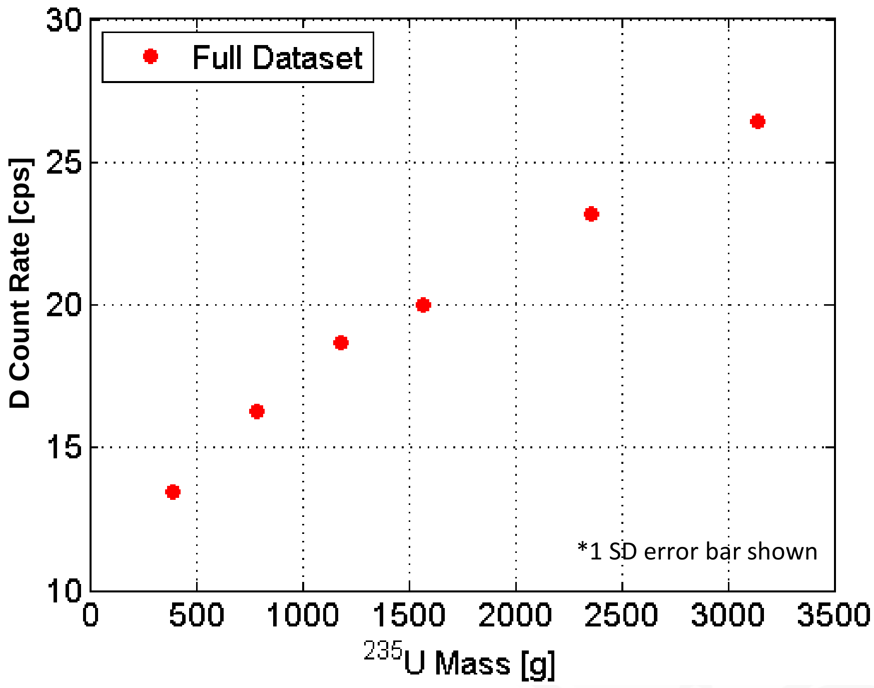


CRM-149	66	67	68	69	70	71
^{235}U Mass [g]	393.1	786.2	1179.4	1572.2	2358.1	3144.3

Results: Mass Estimation

- 10 min measurement
- 60 keVee applied threshold (≈ 0.5 MeV neutron energy)

Proof of concept:



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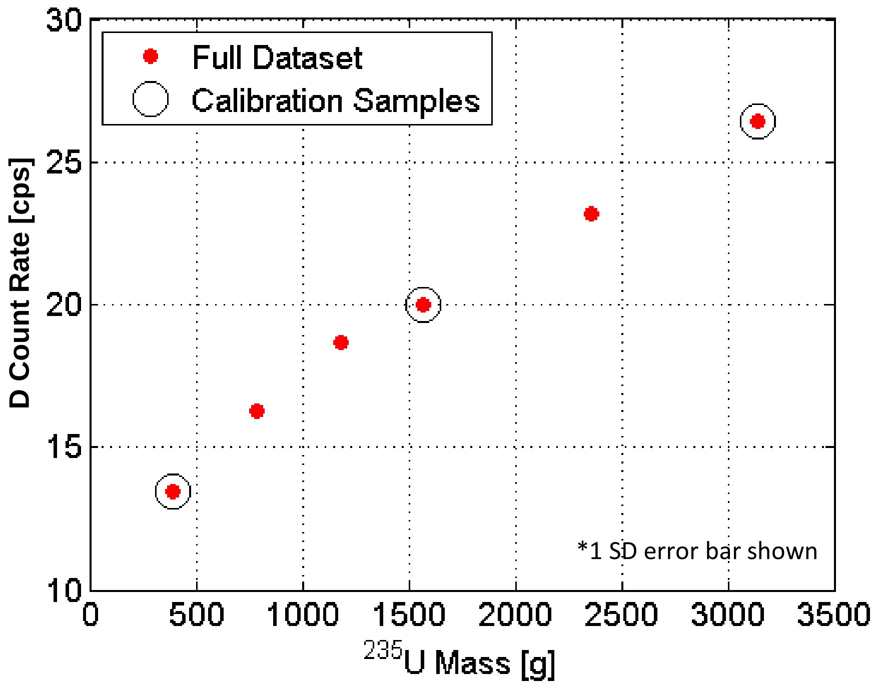

Proof of concept:

1) Take subset of data as calibration samples

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Results: Mass Estimation

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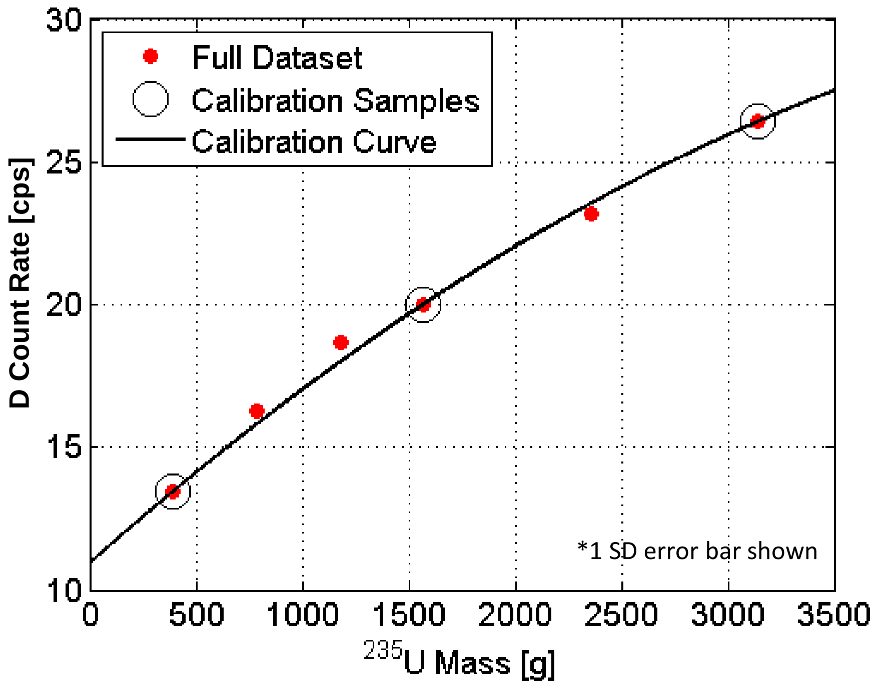
Proof of concept:

1) Take subset of data as calibration samples
2) Fit calibration curve (second-order polynomial)



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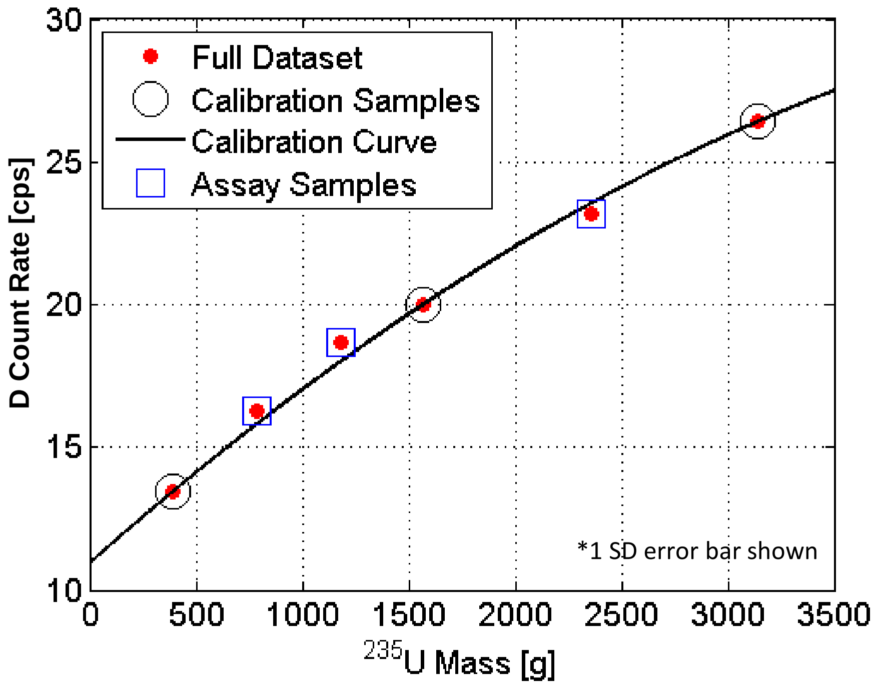

Proof of concept:

1) Take subset of data as calibration samples
2) Fit calibration curve (second-order polynomial)
3) Take remainder of data as assay samples

CRM-149	66	67	68	69	70	71
^{235}U Mass [g]	393.1	786.2	1179.4	1572.2	2358.1	3144.3

Results: Mass Estimation

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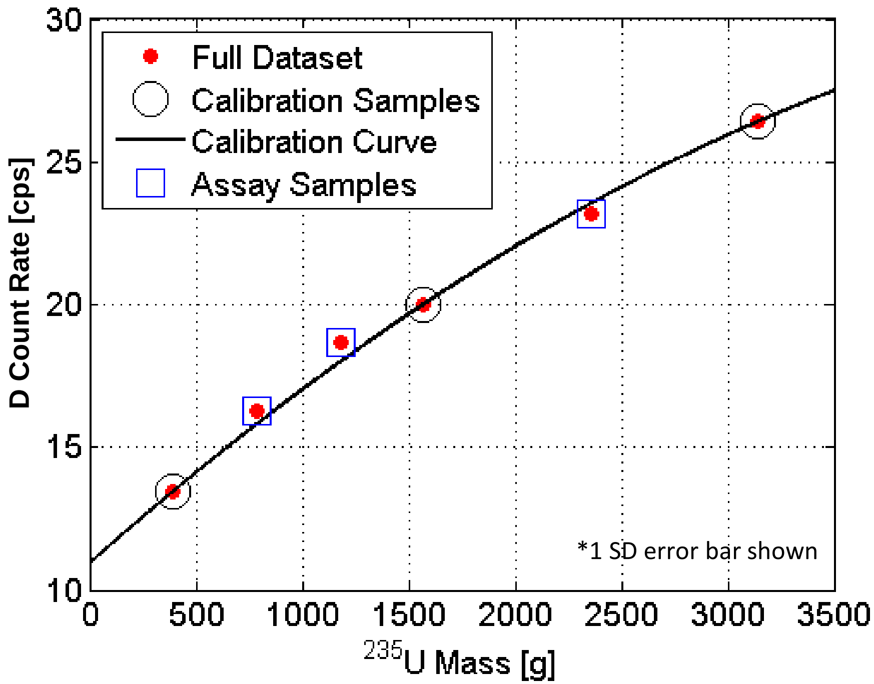


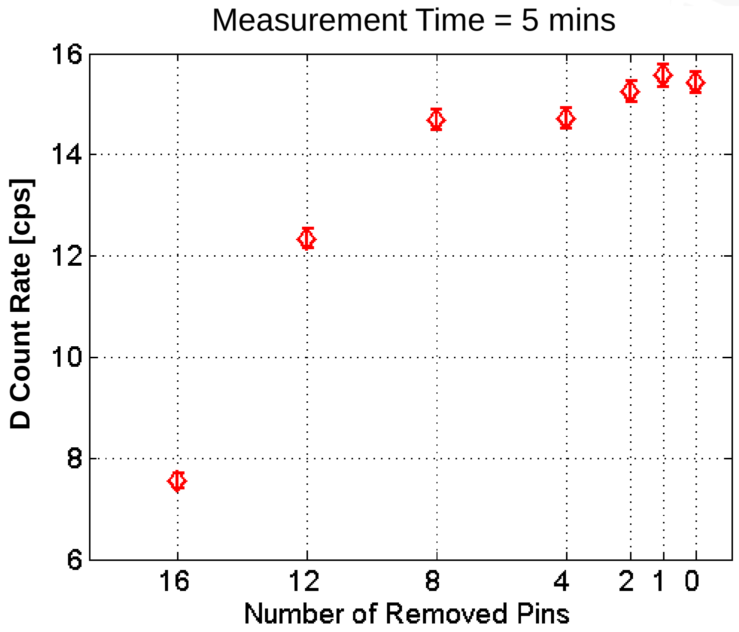
Proof of concept:
1) Take subset of data as calibration samples
2) Fit calibration curve (second-order polynomial)
3) Take remainder of data as assay samples
4) Estimate mass of assay samples with calibration curve

CRM-149	67	68	70
Actual Mass [g]	806.5	1244.7	2203.6
Estimated Mass [g]	786.19 ± 3.96	1179.4 ± 4.64	2358.1 ±6.49
Percent Difference	-2.58 %	-5.54%	6.43%

CRM-149	66	67	68	69	70	71
^{235}U Mass [g]	393.1	786.2	1179.4	1572.2	2358.1	3144.3

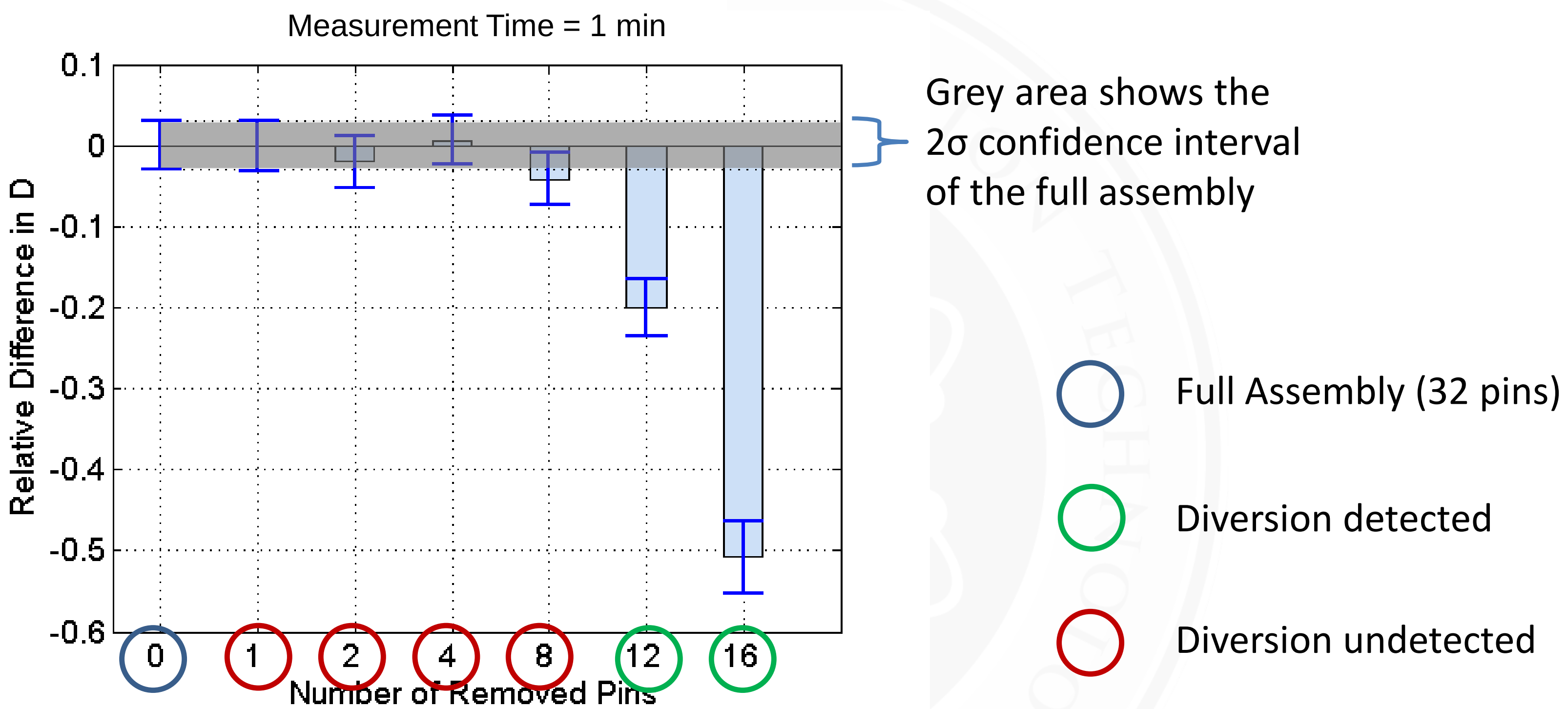
Results: Pin Diversion Sensitivity

- What is the sensitivity of the FNMC system to detect a diversion scenario with > 95% confidence for a fixed measurement time?
  1) How many pins must be removed such that the relative difference in D > $2\sigma_D$ of full assembly?
  2) How does sensitivity change for various measurement times?



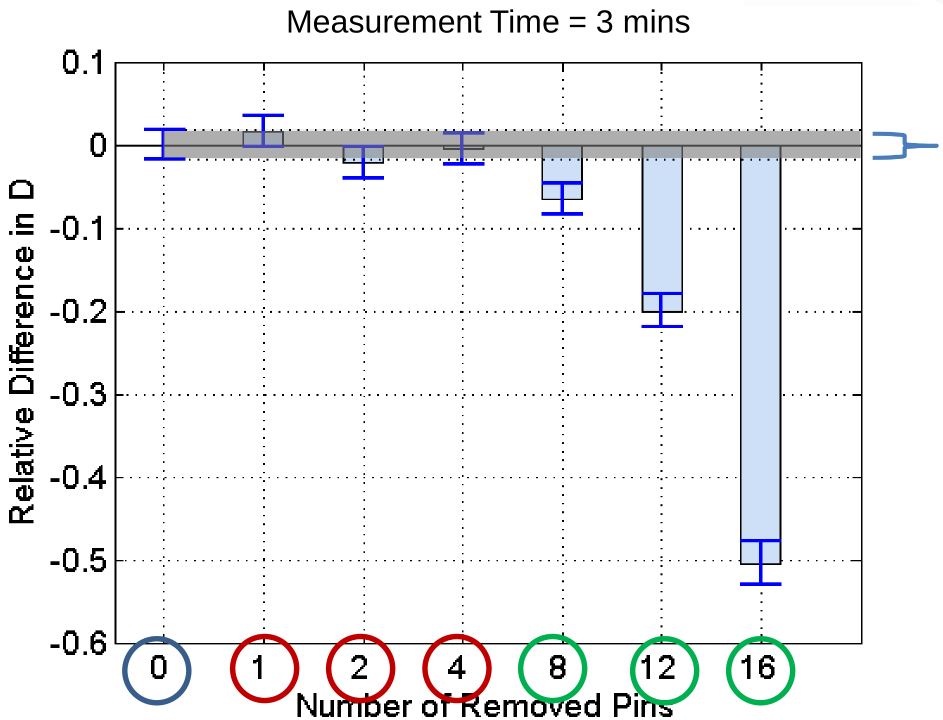
Pins / Removed pins	^{235}U Mass [g]	D [cps]	σ_D
32 / 0	**2416.64**	**15.42**	**0.214**
31 / 1	2341.12	15.56	0.218
30 / 2	2265.60	15.25	0.214
28 / 4	2114.56	14.72	0.211
24 / 8	1812.48	14.70	0.210
20 / 12	1510.40	12.33	0.192
16 / 16	1208.32	7.55	0.154

Results: Pin Diversion Sensitivity



For a *1 minute measurement time*, FNMC system can detect a
<u>12 pin diversion scenario (approx. 900 g removal) with > 95% confidence</u>

Results: Pin Diversion Sensitivity



Grey area shows the 2σ confidence interval of the full assembly

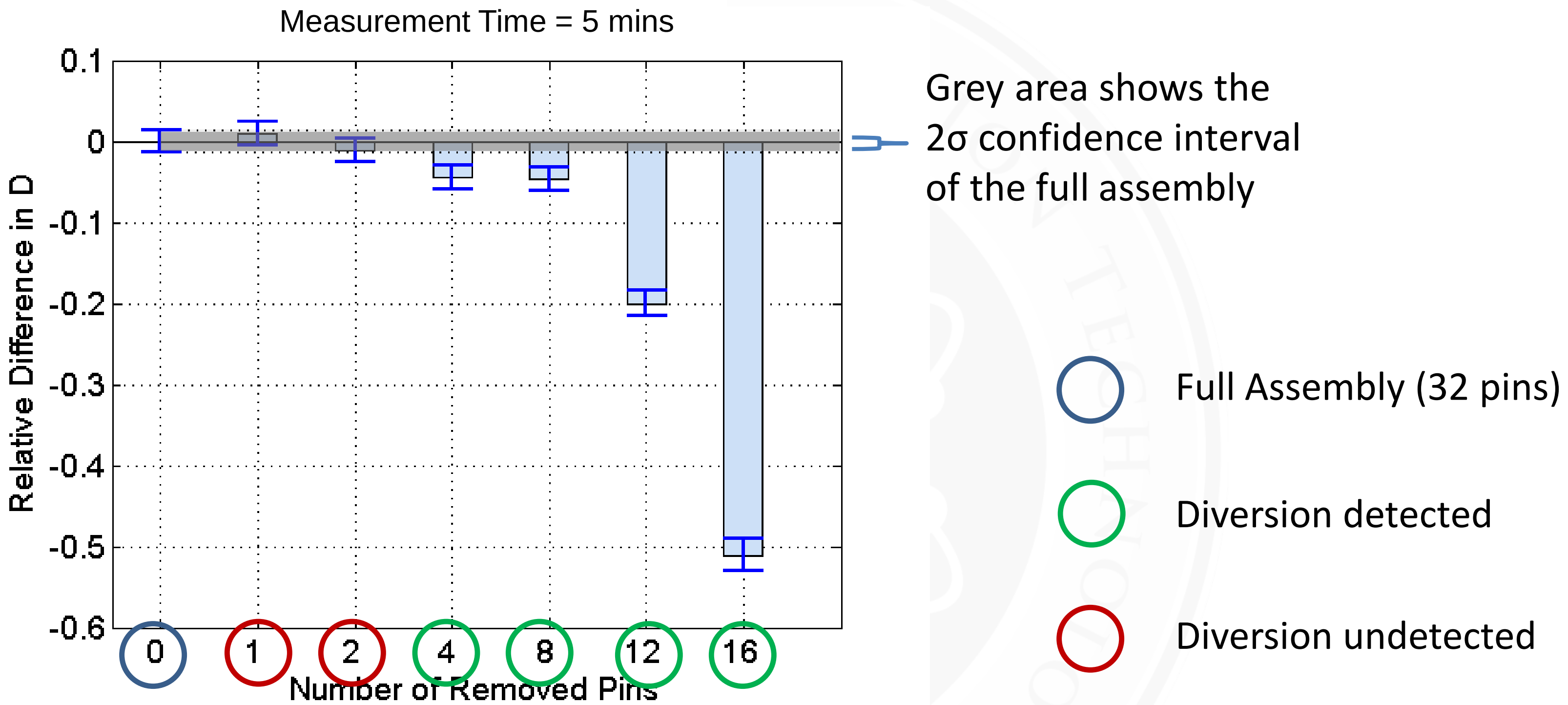
Full Assembly (32 pins)

Diversion detected

Diversion undetected

For a *3 minute measurement time*, FNMC system can detect a
<u>8 pin diversion scenario (approx. 600 g removal) with > 95% confidence</u>

Results: Pin Diversion Sensitivity



For a *5 minute measurement time*, FNMC system can detect a
<u>4 pin diversion scenario (approx. 300 g removal) with > 95% confidence</u>

Conclusions

- Successfully measured neutron multiplets from induced fissions in active-mode (AmLi)
  - U_3O_8 samples of various mass content and enrichment levels
  - Uranium pin assemblies of various configurations
- Produced mass calibration curve and estimated fissile mass within ± 7% of actual mass for a 10 min measurement time
- Investigated FNMC system sensitivity of pin diversion scenarios
  - Sensitive to 4 diverted pins with > 95% confidence in 5 mins

Acknowledgment

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Thank you for your time!

Special thanks to C. Sosa and S. Watson for their help during the experiment!

Demonstration: Michigan Room

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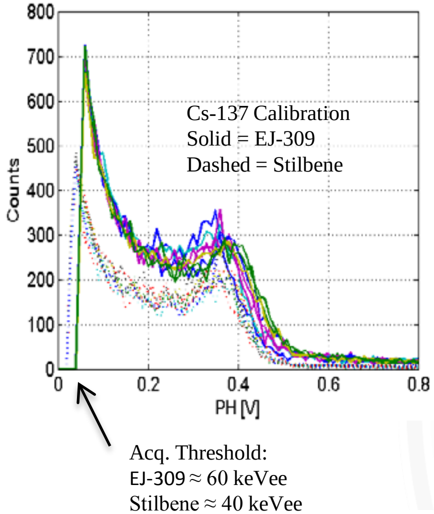
References

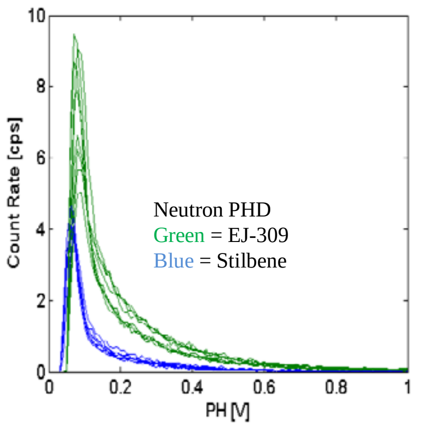
1) N.Ensslin, W.C. Harker, M.S. Krick, D.G. Langner, M.M. Pickrell, J.E. Stewart, Application guide to neutron multiplicity counting, LA-13422-M, Los Alamos National Laboratory (1998)
2) T.H. Shin, A. Di Fulvio, T. Jordan, D.L. Chichester, S.D. Clarke, S.A. Pozzi. "Fast Neutron Multiplicity Counter based on Stilbene and EJ-309 Scintillators for Nuclear Non-Destructive Assay" INMM 57th Annual Meeting, Atlanta GA. (2016)
3) D.L. Chichester, S.A. Pozzi, J.L. Dolan, M.T. Kinlaw, A.C. Kaplan, M. Flaska, A. Enqvist, J.T. Johnson, S.M. Watson, MPACT Fast Neutron Multiplicity System Design Concepts, INL/EXT-12-27619, Idaho National Laboratory (2012)
4) J.L. Dolan, M. Flaska, A. Poitrasson-Riviere, A. Enqvist, P. Peerani, D.L. Chichester, S.A. Pozzi. "Plutonium measurements with a fast-neutron multiplicity counter for nuclear safeguards applications" Nuclear Instuments and Methods in Physics Research A, Vol 763, pgs. 565-574 (2014)
5) W. Hage, D.M. Cifarelli. "Models for a three-parameter analysis of neutron signal correlation measurements for fissile material assay" Nuclear Instruments and Methods in Phys. Research A, Vol 251, pgs. 550-563 (1986)

Extra Slides

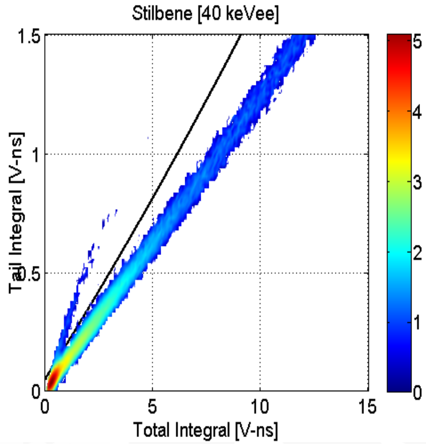
System Characterization

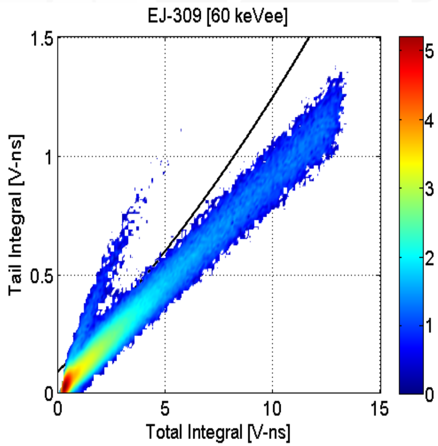
1) Gain matching



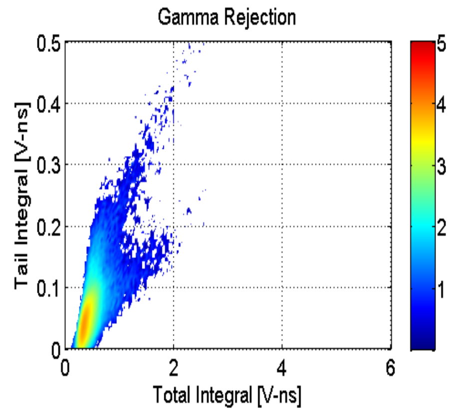


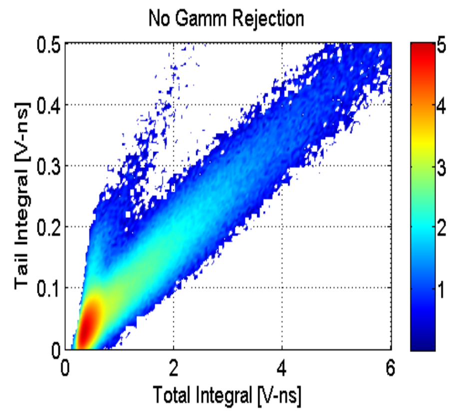
2) PSD performance



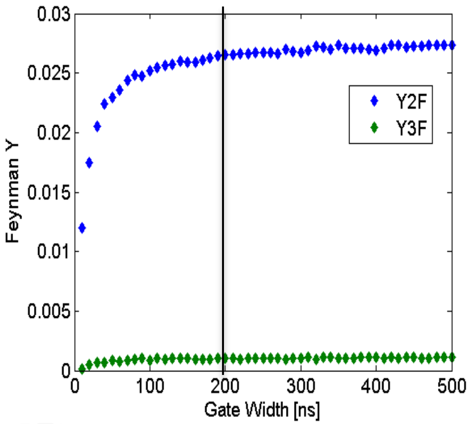


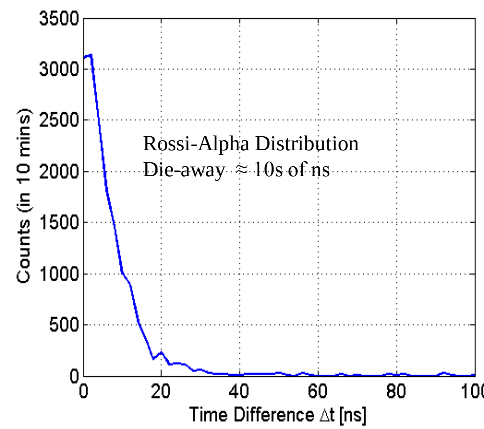
3) Gamma rejection





4) Timing properties





Counting Method

- Feynman counting method (constant window, random triggers)
  - Gate width = 200 ns
  - Gives number of single detections (n=1), two-event coincidences (n=2), and three-event coincidences(n=3) within gate width → Det(n)
  - First- (S), second- (D), and third-order (T) factorial moments from combinatorial expansion of Det(1), Det(2), and Det(3).

$$S = \sum_{n=1}^{\infty} nDet(n)$$

$$D = \sum_{n=2}^{\infty} n(n-1)Det(n)$$

$$T = \sum_{n=3}^{\infty} n(n-1)(n-2)Det(n)$$

*Det(n) = $B_x^+(\tau)$ and S, D, and T are $m_{b(\mu=1)}$, $m_{b(\mu=2)}$, $m_{b(\mu=3)}$, respectively according to Hages-Cifarelli notations

$$m_{b(\mu)} = \sum_{x=\mu}^{\infty} \binom{x}{\mu} B_x^+(\tau) \text{ , [5]}$$

Doubles vs. Energy Threshold

- Neutron cross-talk decreases as energy threshold increases
- Comparison of D for various energy threshold (marginal differences in shape)
- Higher energy threshold = more sensitive to changes in D