

Towards developing Compact HFIR Anti-neutrino Monitoring Platform (CHAMP)

TEAM:

Irakli Garishvili (ARDIDSA) – PI

James Matta (CARDE5) – Monte Carlo, DAQ and HFIR

Maureen Searles (HFIR) – HFIR lead and coordinator

Brandon Longmire (ARDIDSA) – Lead Engineer/Detector Platform Design

Jake Carter (ORNL/UT) – Simulations, project management

Lorenzo Fabris (ARDIDSA) – Detector Electronics Advisory and Assembly

Michael Willis (ARDIDSA) – Jack of all trades

Entire ARDIDSA group and Newby

- 190K awarded through ORNL LDRD SEED funding: 151K (FY 20) + 39K (FY21)

Strategic Goal

- Laying groundwork for developing new program/platform at HFIR for testing compact neutrino detectors exclusively for nuclear non-proliferation applications
- Compact and portable neutrino detectors for nuclear reactor monitoring in near-field or cooperative regime major area of interest for NNSA(DOE) and IAEA

Project Outline: Achieving this goal

- Comprehensive new measurements of directional gamma and neutron backgrounds at 2 select locations at HFIR Experimental hall (5-7 meter radial distance from core)
- Extensive Monte Carlo simulations to explore multiple shielding geometries given size constraints
- Final viability study. Tentative design of background rejection system for future platform

Project schedule planned vs actual

Feb 2: Submitted proposal

May 6/13: defense/cond. approval

June 8: Money deposited

Aug 6/7: Finished detector array assembly
& moved to HFIR

Aug 18: HFIR cycle-489 **START**

Sep 12: HFIR cycle-489 **END**

Oct 10*: HFIR cycle-490 **START**

Nov 8*: HFIR cycle-490 **END**

Analysis, Simulations, publication(s)
by end of FY21



Cycle-489
Aug 17-Sep9, 2020

**HFIR shut down due to
unforeseen issues**

Cycle-490
Feb/Mar, 2021

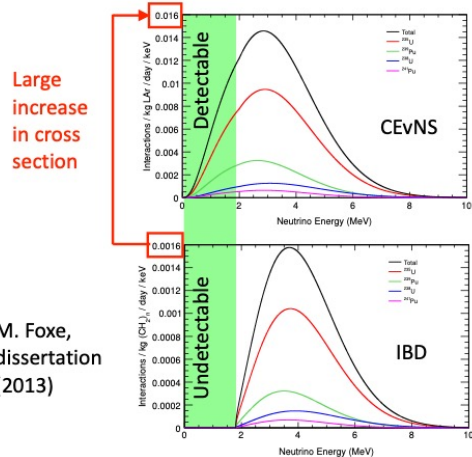
Cycle-491
April 14-May8, 2021

Will discuss below *

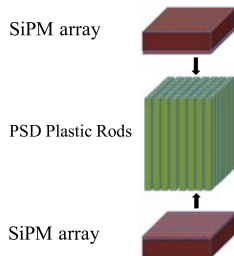
Reactor neutrino detection approaches and HFIR

- Typical detectors utilize “inverse beta decay” (IBD) reaction for detecting incoming neutrinos: distinct experimental signal feature
- CEvNS detectors can extend energy reach below IBD detection threshold of 2MeV in energy
- IBD detectors with large detector volume and shielding for improved signal to background used in reactor monitoring (far-field regime)
- PROSPECT large IBD detector made first high statistics measurement of neutrino spectrum from U-235 at HFIR
- Nuclear non-proliferation funding agencies shifting their focus to compact-size portable detectors for monitoring
- MTV consortium with multi million \$ funding from NA-22 developing new highly segmented compact IBD detector with “directionality” capability ready for testing: Crucial monitoring tool for nuclear facilities with multiple reactors
- They also developing CEvNS detectors
- Given our local expertise in CEvNS and plastic detectors we are also well positioned to make a play for this specific R&D

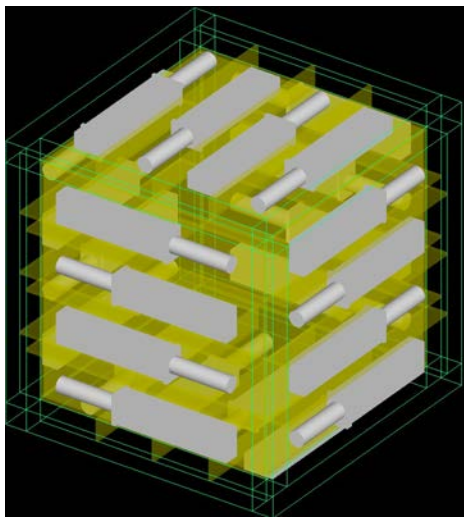
Detection and monitoring of plutonium production



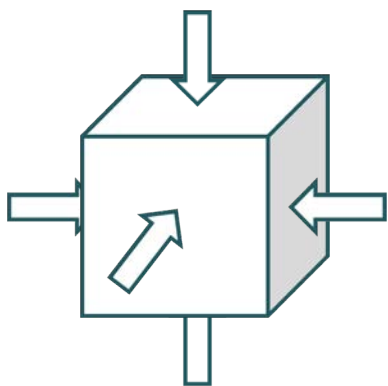
M. Foxe, dissertation (2013)



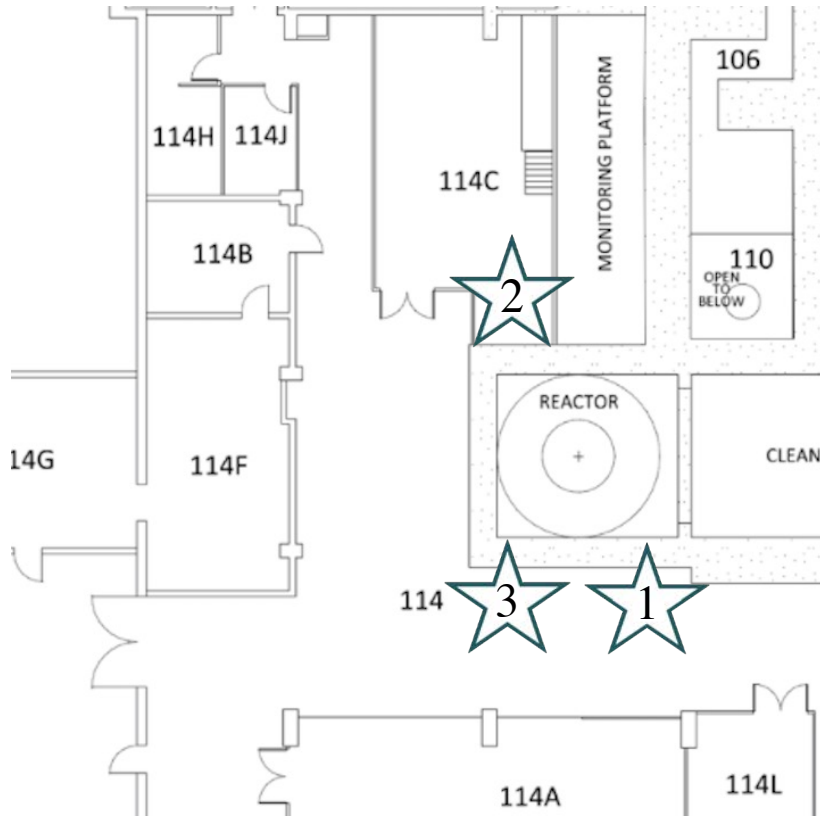
Project activities for developing platform



- Build detector array frame ($V \sim 1\text{m}^3$) for γ/n directional background measurements
- Leveraged existing γ/n detectors and data acquisition system (DAQ) from within RDI group
- Worked HFIR folks on the safety approvals for potential list of test locations close to reactor core
- Measuring directional γ/n backgrounds entering 1m^3 virtual box (testbed proxy) from all six sides at each location
- Background measurement will enter as input into extensive GEANT4 based Monte Carlo simulations exploring multiple shielding configuration geometries for background reduction
- Analyze results for optimal configuration and determine:
 - Is proposed platform viable given compact size limitations ?
 - Will need feedback from neutrino community on this*



Testbed/Measurement locations at HFIR



2 locations at the HFIR experimental floor were approved for the background measurements activities, including former PROSPECT (large antineutrino) experiment location

Initial measurements revealed 2nd location to have 5-10 higher background rates plus other issues



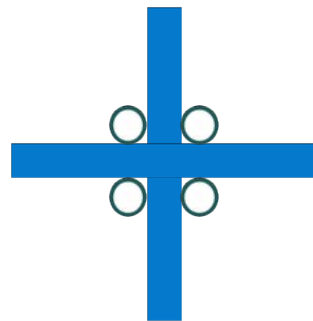
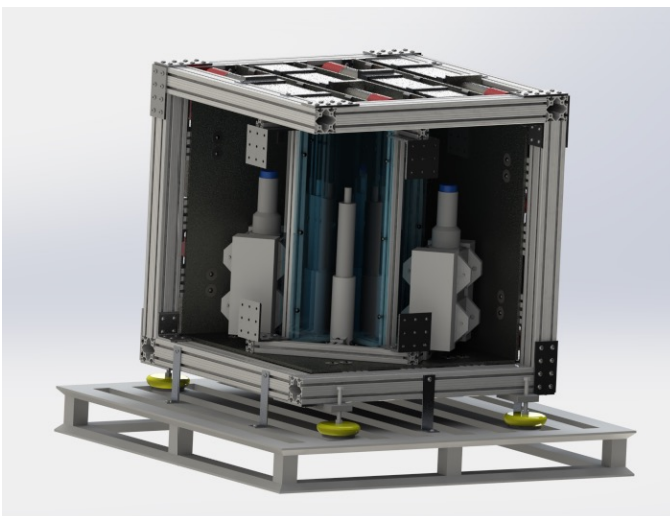
Worked with HFIR and got permission for the third “bonus” location

HFIR folks are great!

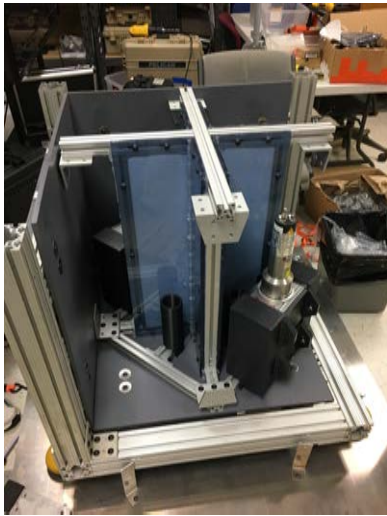
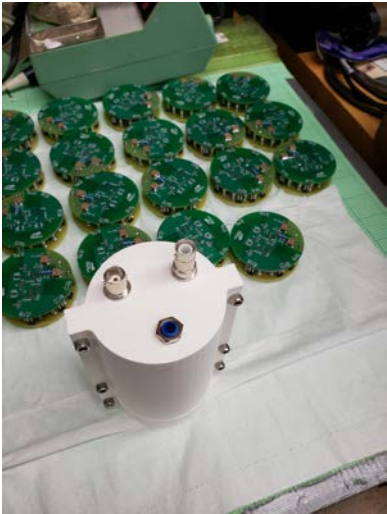
Platform for directional background detection



- 80cm x 80cm x 80cm cube frame w/ sides covered by large quadratic 1 cm thick lead
- 24 NaI detectors - **directional gamma**
- 4 cylindrical He-3 detectors – **directional* thermal neutrons**
- 2 large EJ309 liquid scintillators – **fast neutrons from cosmics**
- 6 large and 18 small 1cm thick Pb sheets shielding NaI detectors from each other.
- He-3 14 inch cylindrical tubes shielded by boric acid filled plexiglass in “cross” formation



detector construction: Little innovation here and there

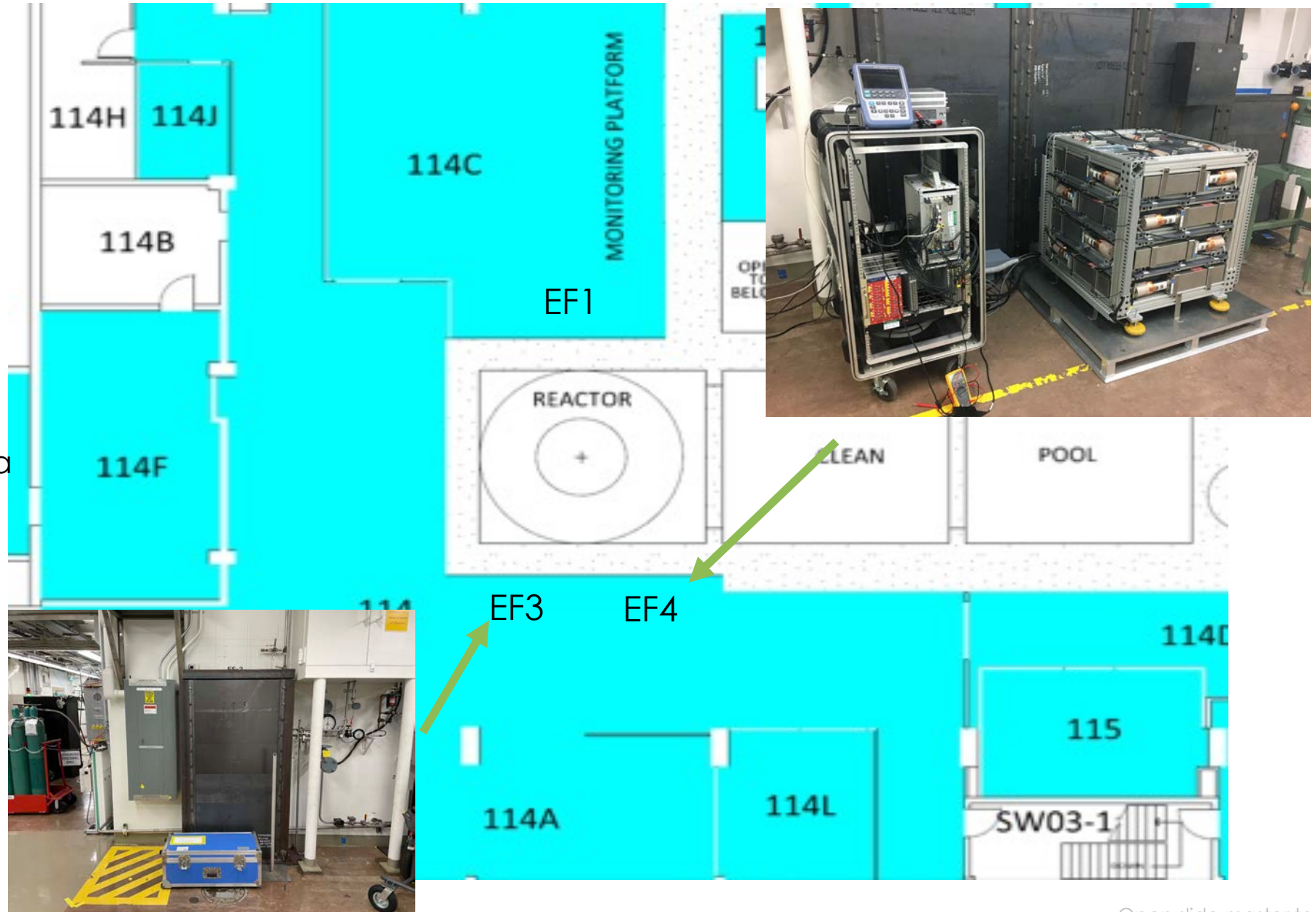


Measurement Locations and Cycles

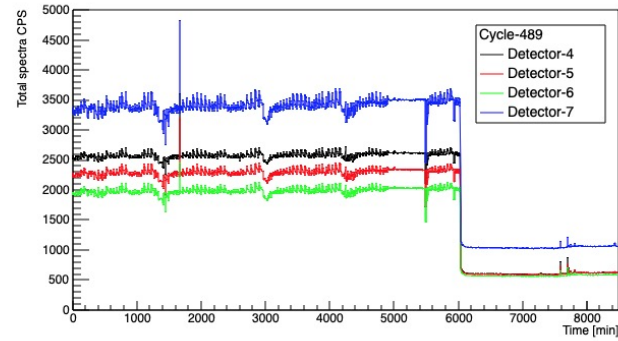
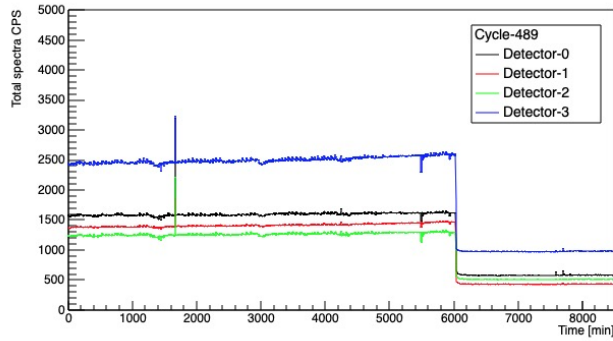
Cycles 489/491 processed
Calibrated*

EF1 (Cycle 490) showed
Order of magnitude higher
backgrounds

Cycle 490 65-70% of all data
Very high backgrounds

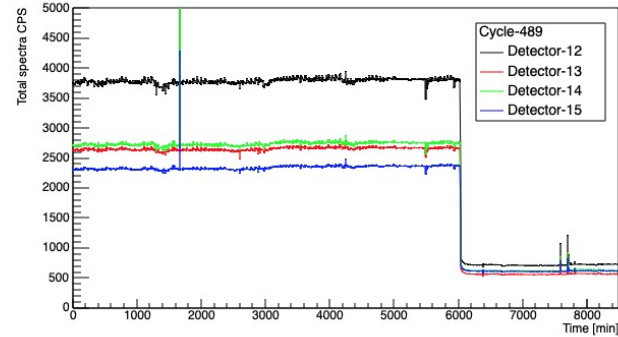
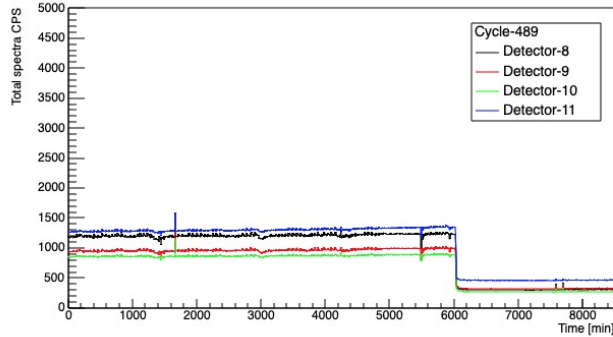


Cycle-489 Raw rates



Reactor core

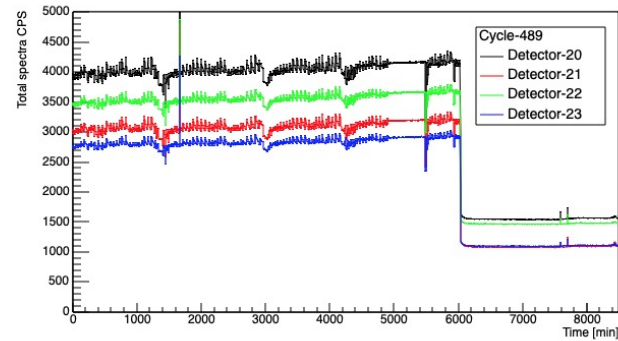
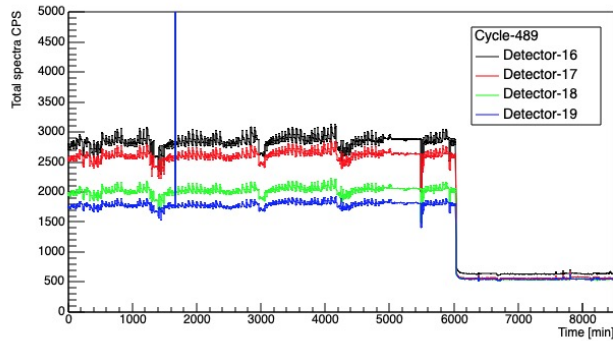
8-11



20-23

4-7

12-15

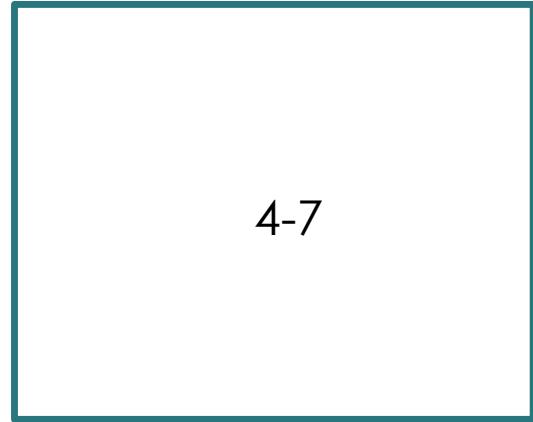
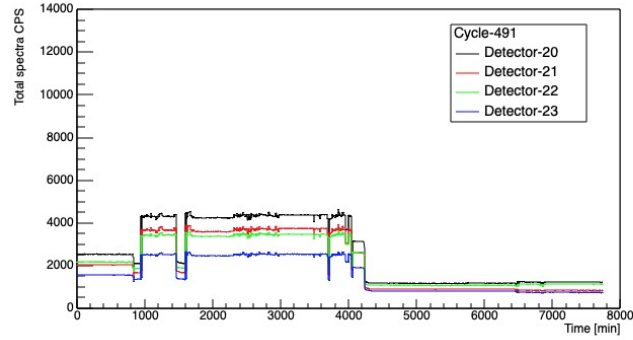
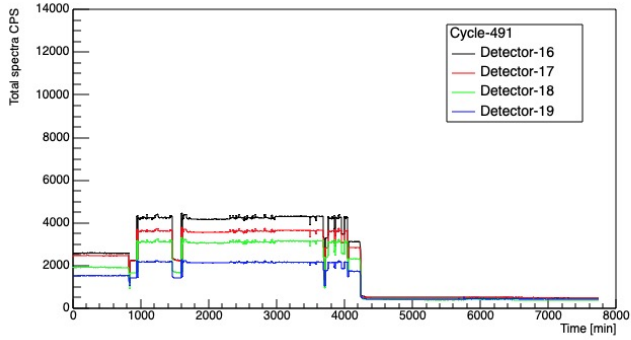
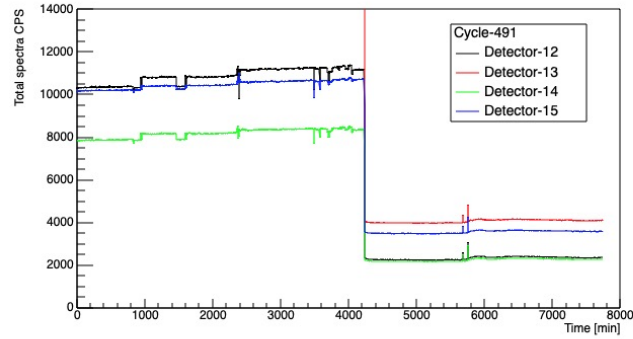
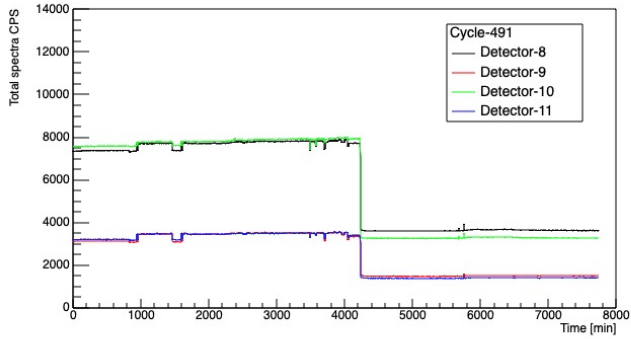
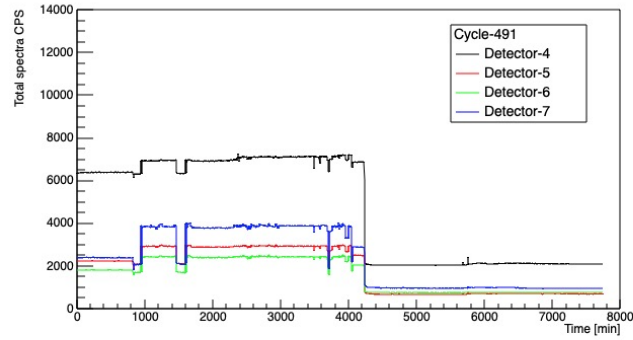
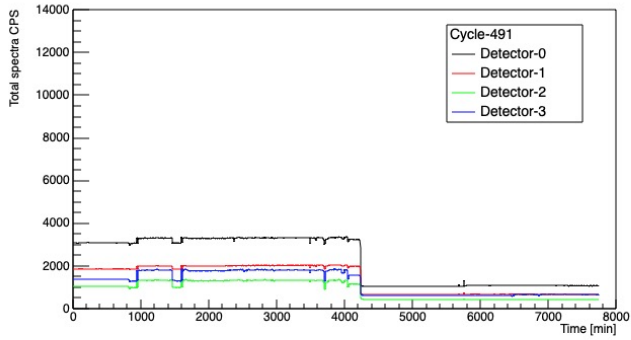


16-19



Cycle-491 Raw rates

Reactor core



8-11

20-23

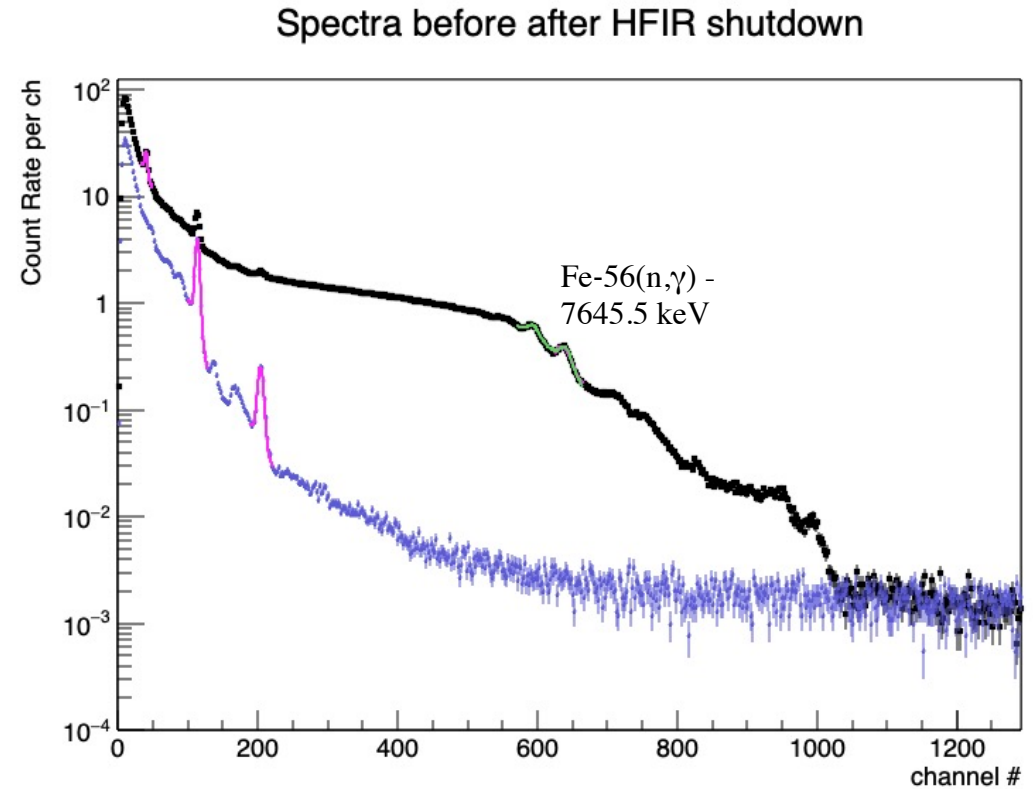
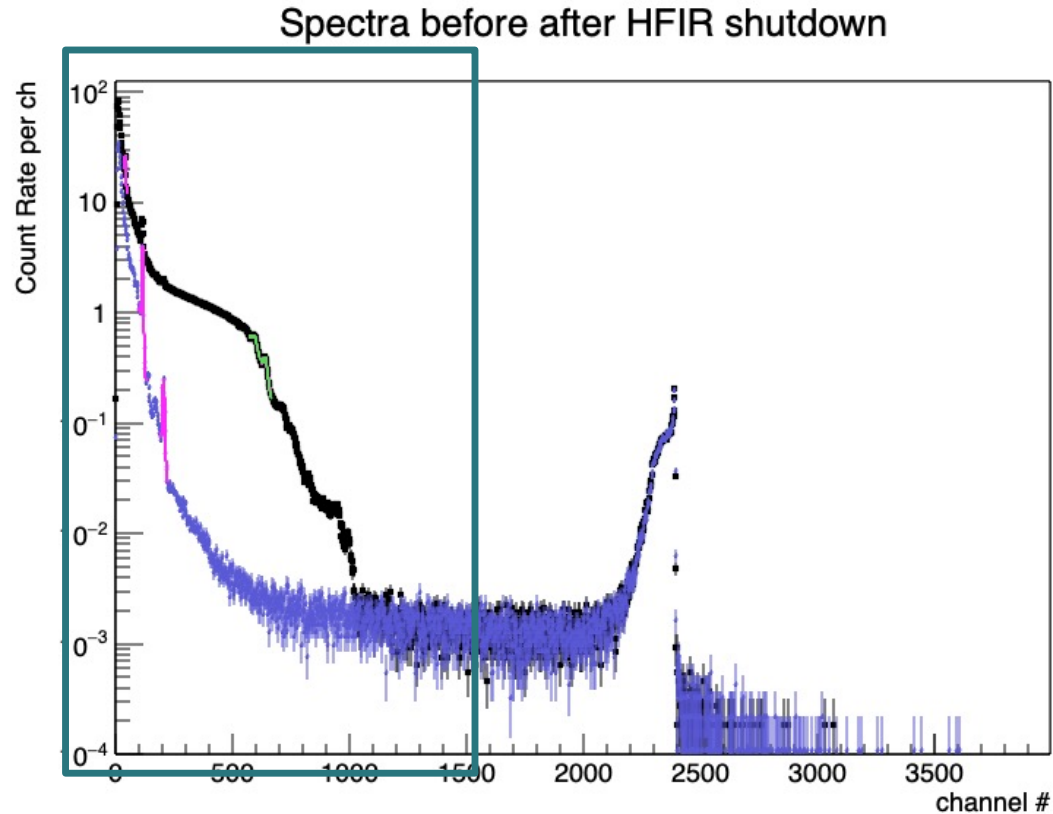
4-7

12-15

16-19



Calibration step1 identify existing peaks (Cycle-489, Det-1)

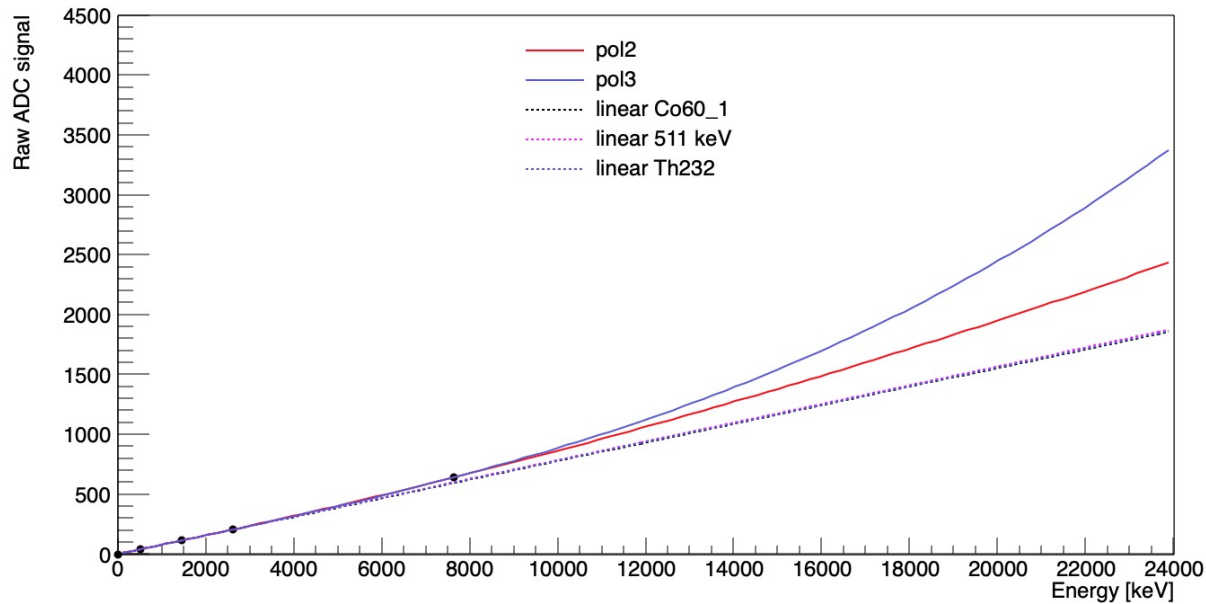


- Every detector calibrated separately
- Each cycle was different (change in calibration)
- Identify existing peaks

- HFIR OFF: K-40 (1461keV), Co-60*(1132keV, 1332.5), Th232 (2614keV)
- HFIR ON: 511keV, Fe-56 (7645 keV), Ar-41(1294 keV)

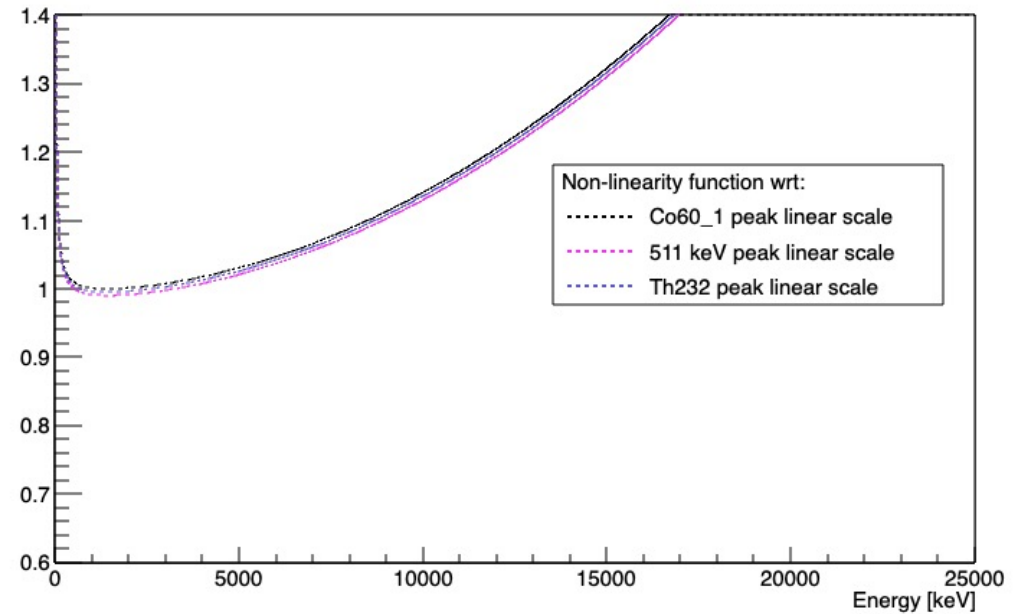
Calibration step-2: non-linearity

Calibration Curves



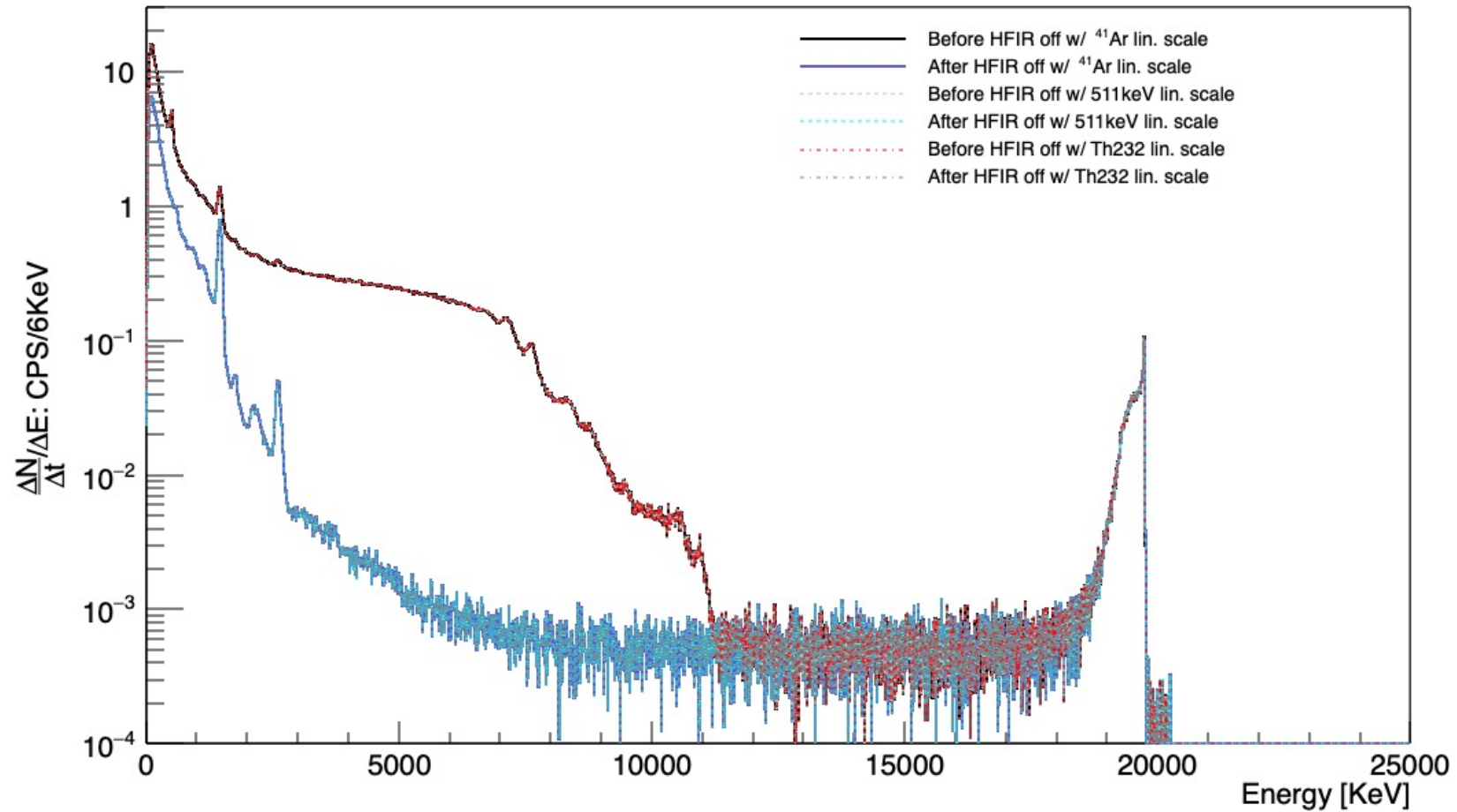
- Every detector calibrated separately
- Each cycle was different (change in calibration)
- Identify existing peaks

Non-linearity function histogram



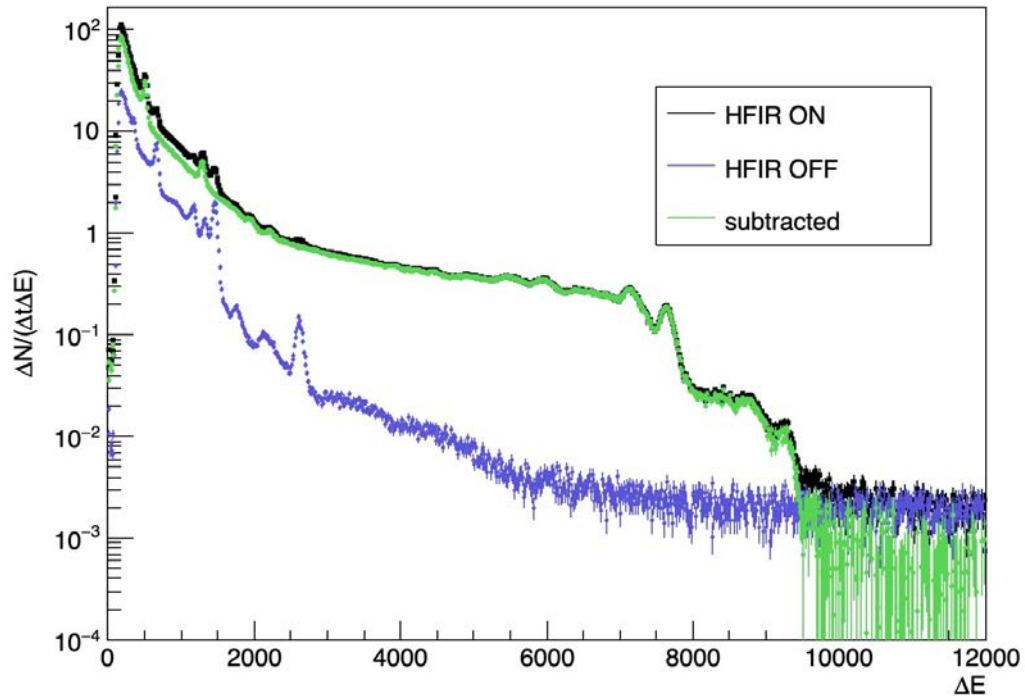
Cycle-489 Det-1: Rebin Calibrated Rebinned Spectra

Calibrated and corrected spectra

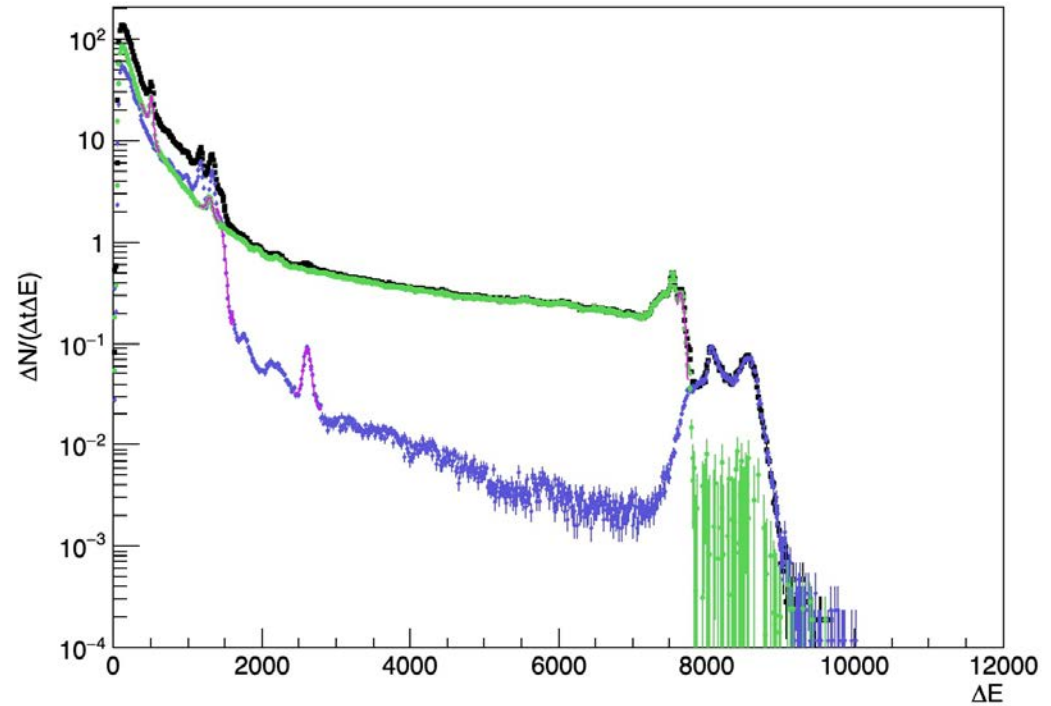


Preparing input for GEANT4

Calibrated Spectra: HFIR ON/OFF/Subtracted - NaI Det-16

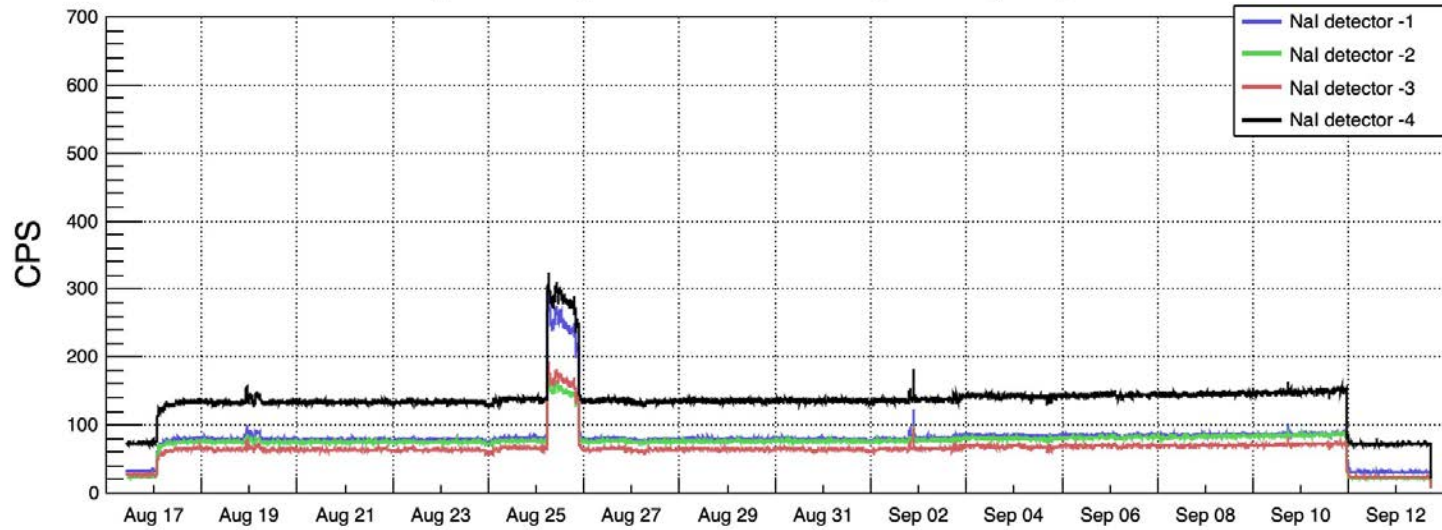


Calibrated Spectra: HFIR ON/OFF/Subtracted - NaI Det-22

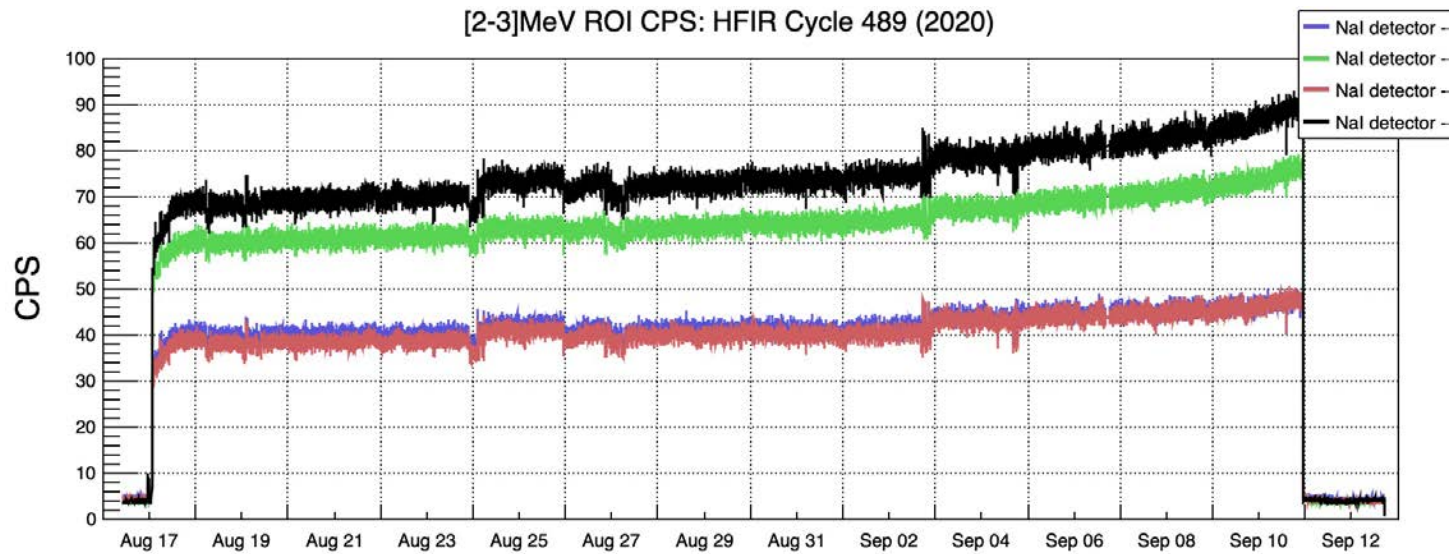


Need to to subtract spectrae for a couple of detectors to remove “pathology” due cosmic High energy depositions

[1000-1400]keV ROI CPS: HFIR Cycle 489 (2020)

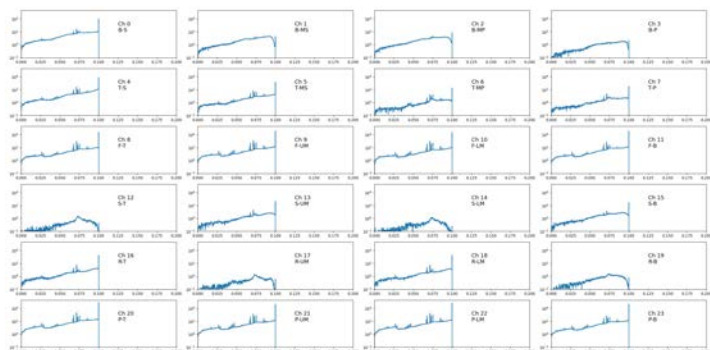


[2-3]MeV ROI CPS: HFIR Cycle 489 (2020)

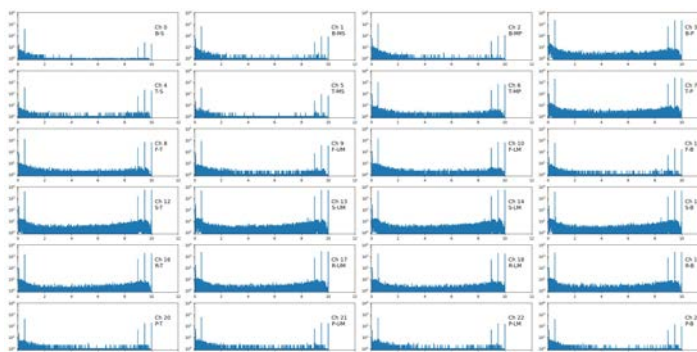
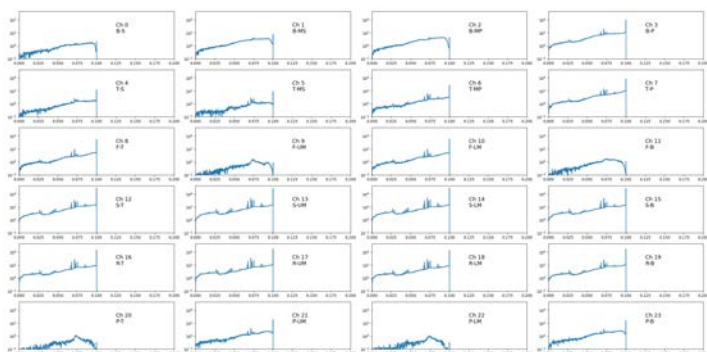
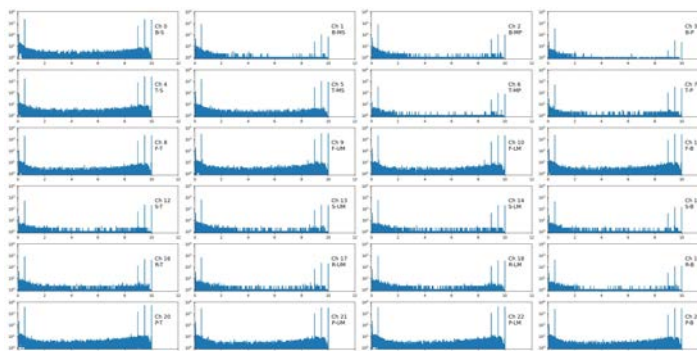


Simulation of Response Functions

100 keV



10 MeV



Pos₀

- Position Sensitivity
 - Icosahedron Triangle = Sources
- Convolve with Det Widths
- Concatenate Responses
- Position + Energy gives a single row (column) of the response matrix.

Pos₁₇

- Row₀ = Pos₀ + En₀
- Row₁ = Pos₀ + En₁
- ...
- Row₁₂₀₀ = Pos₁ + En₀
- Row₁₂₀₁ = Pos₁ + En₁
- ...

Decomposition Mathematics – Maximum Likelihood Expectation Maximization (MLEM)

MLEM – Iteration Formula

$$I_{\mu}^{s+1} = \frac{1}{\sum_j R_{\mu j}} \sum_i \frac{I_{\mu}^s R_{\mu i} O_i}{\sum_{\alpha} R_{\alpha i} I_{\alpha}^s}$$

$$\Sigma \vec{f} = \mathbf{J} \Sigma \vec{x} \mathbf{J}^T$$

Generic Error Prop

Jacobian For MLEM Last Iteration

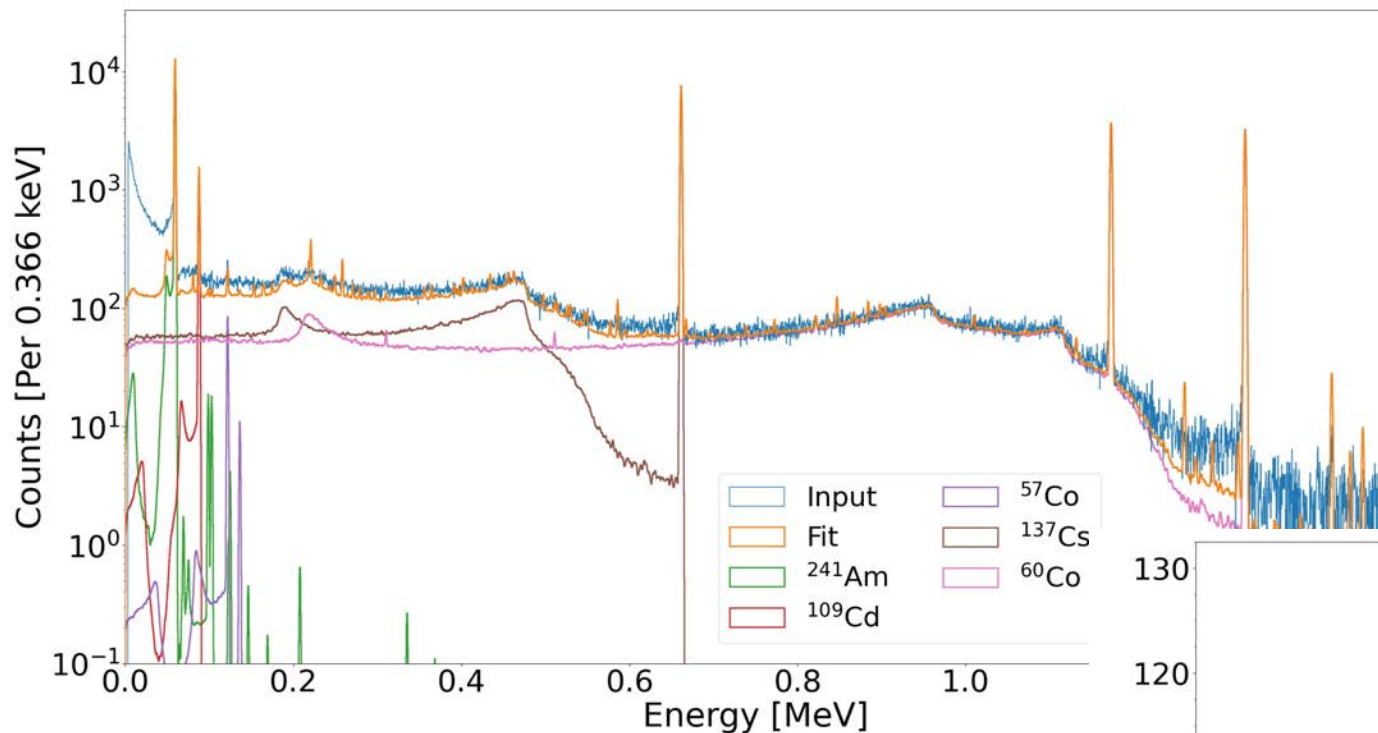
$$J_{\mu,j}^{s+1} = \frac{\partial I_{\mu}^{s+1}}{\partial x_j} = \frac{1}{\sum_l R_{\mu,l}} \times \begin{cases} -\delta_{\mu,[j/m]} I_{\mu}^{s+1} + \frac{I_{\mu}^s O_{j\%m}}{\sum_{\alpha} R_{\alpha,j\%m} I_{\alpha}^s} \left(\delta_{\mu,[j/m]} - \frac{R_{\mu,j\%m} I_{[j/m]}^s}{\sum_{\alpha} R_{\alpha,j\%m} I_{\alpha}^s} \right) & 0 \leq j < p \\ \frac{I_{\mu}^s R_{\mu,j-p}}{\sum_{\alpha} R_{\alpha,j-p} I_{\alpha}^s} & p \leq j < p+m \end{cases}$$

$$\Sigma_{a,b}^{\vec{x}} = \delta_{a,b} \times \begin{cases} \Delta R_{[a/m],a\%m}^2 & 0 \leq a < p \\ \Delta O_{a-p}^2 & p \leq a < p+m \end{cases}$$

Input Covariance

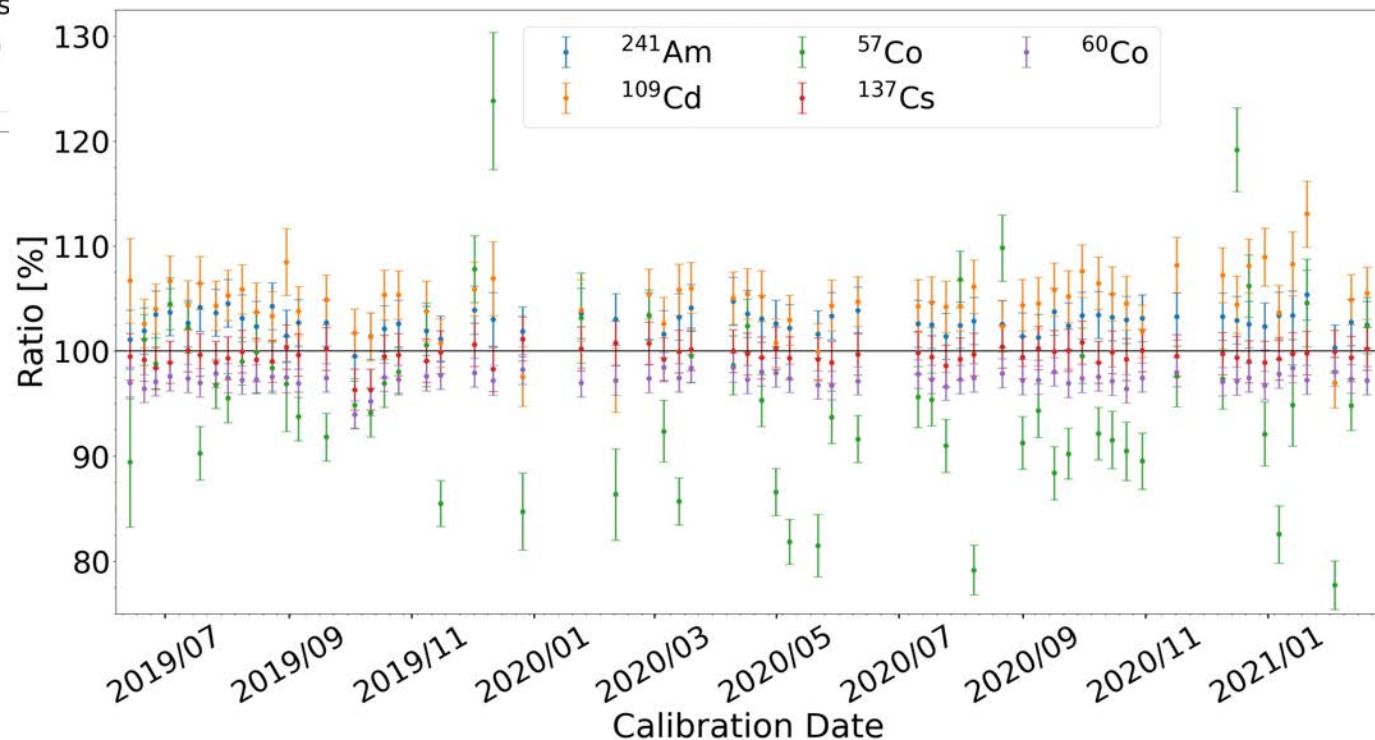
- R = Response Matrix (m x n)
 - m response functions
 - n bins per function
- I = Input term (Source Spectra)
- O = Observation (Detector spectra)
- p = m*n (convenience term)

Decomposition Example – Using HPGe Isotope Responses

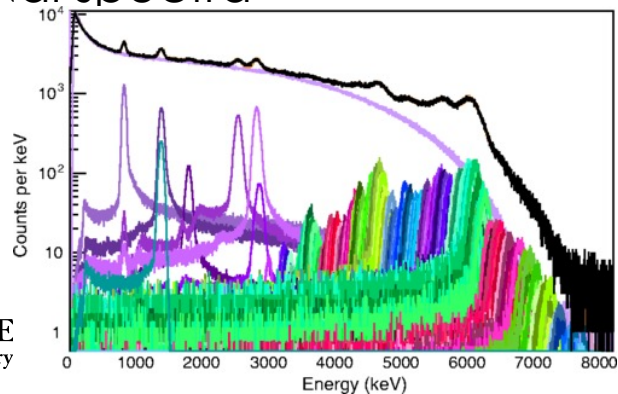


Decomposition of HPGe Spectrum using Responses to Isotopes (many not shown)

Ratios of decomposition predicted activity to source certificate activity for 68 spectra (^{57}Co was very weak)



Also used for decomposition of MTAS NaI spectra



Where we are and what's next

- All measurements have been processed calibrated and formatted so it can be used for GEANT4 simulations or other folks in the community
- All GEANT4 framework have been completed
- Response matrix: need to run large scale simulations. Waiting formal approval on NARSIL farm (NNSD) ... ~3.2 weeks on 12 nodes (x 128 cores)
- Unfolding calibrated times series spectra for each detector to produce GEANT4 input (quick)
- Publication(s)
- Final simulations exploring potential directional shielding configuration and comparing to potentially detected neutrino fluxes
- Make case for Large LDRD, NA22, etc...