# Pulsed Neutron Die-Away Experiments (PNDA) for Nuclear Data Validation

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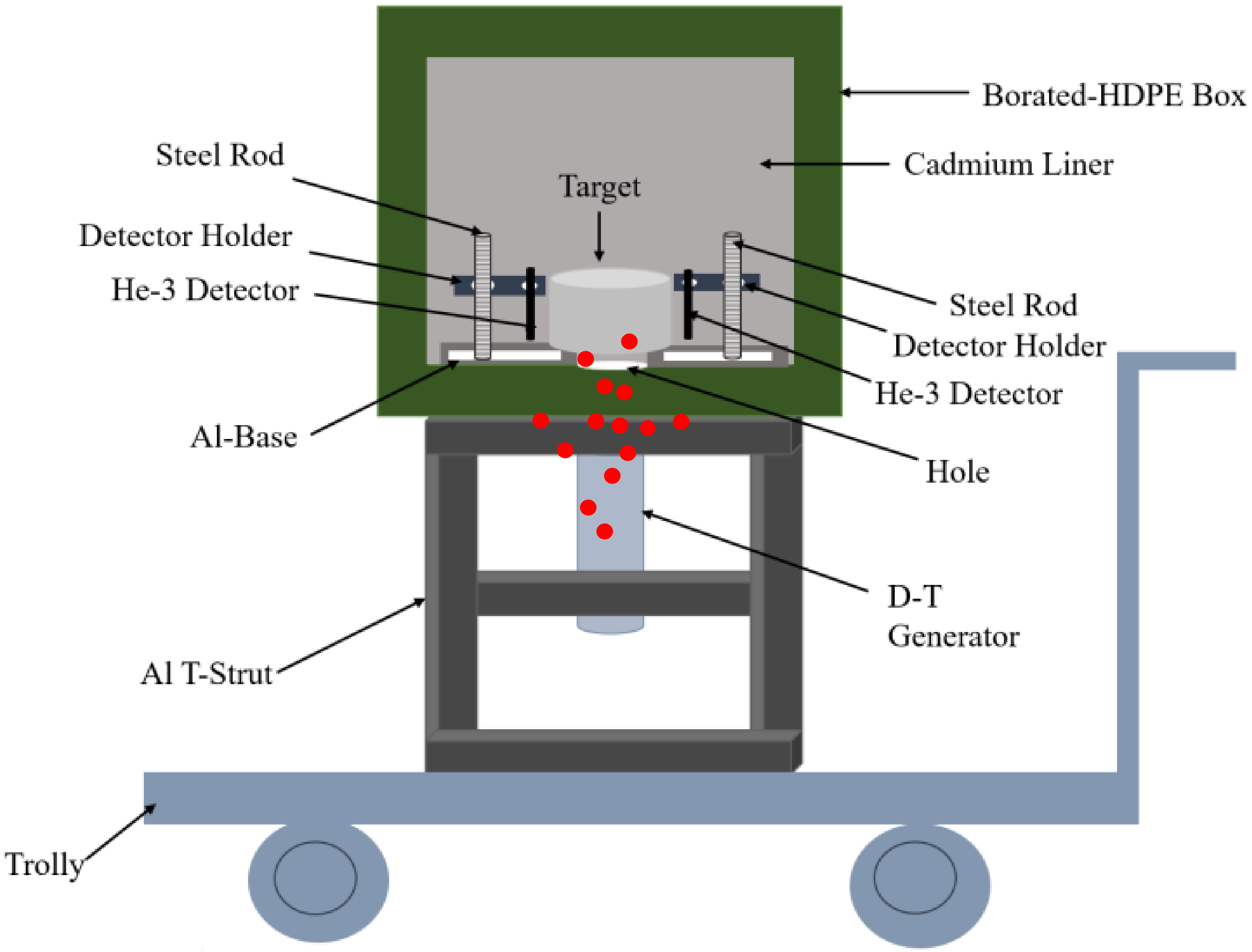
# PNDA for TSLs Validation

1. Inject Pulse of Neutrons
2. Neutrons thermalize
3. Neutrons spatially equilibrate
4. Measure exponential decay in fundamental mode.



# Experimental Parameters

- P383 D-T neutron generator
  - Maximum yield of 5 x $10^8$ neutrons/s
  - Minimum frequency of 150 Hz
  - Minimum pulse width of 10 µs
- Four He-3 tubes
  - Operated at 1100 V
  - 50 ns pulse width
- Time-tagging electronics
  - Provides time stamps of detected neutrons, generator pulse
  - ALMM, CAEN shift register (10 ns resolution)
- Box to limit room return
  - Borated high-density polyethylene
  - Cadmium lining

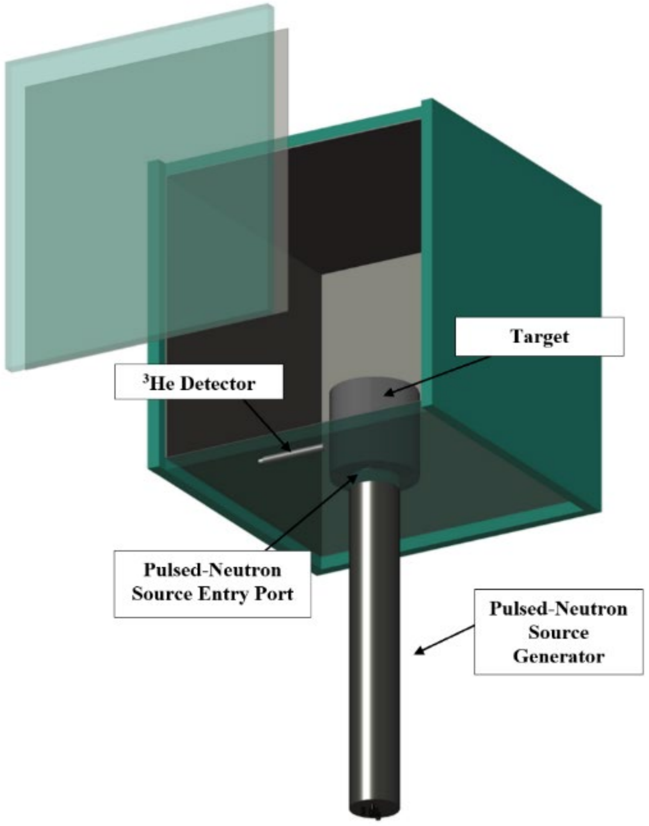



Figure: AutoCAD rendering of PNDA

# Why PNDA for TSL Validation?

- Does not require fissile material
  - Non-nuclear facilities, reduced costs, fewer regulations, safer

- Very simple target shapes and compositions
  - Reduced uncertainties in benchmarks
  - Reduced material costs
  - Easy to change temperature

- Only sensitive to absorption and scattering of target medium
  - Reduces uncertainties from other nuclear data and compensating effects
  - Tune target size to vary effect of absorption vs. scattering

- Well conducted experiments have uncertainties of 0.1% - 0.5%

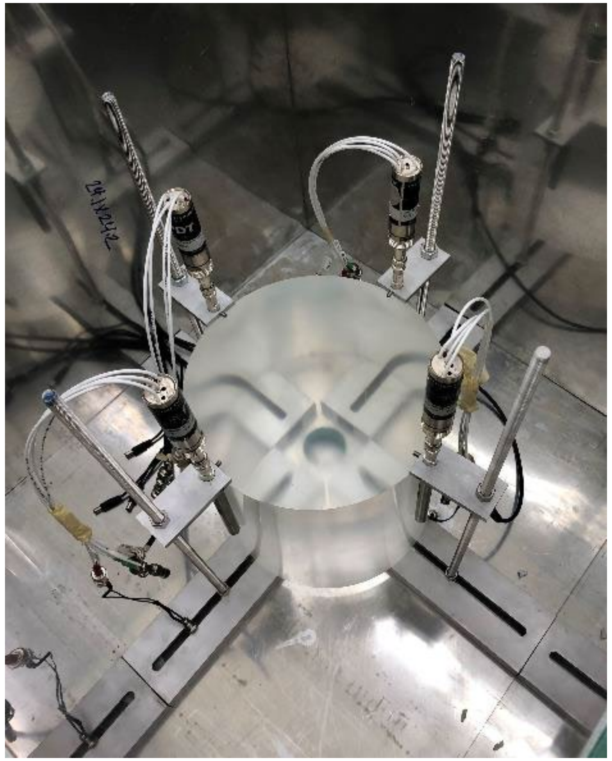


Figure: Measurement of Lucite target

# Integral Parameter: α eigenvalue

$$\phi(t) = \phi_0 \exp(-\alpha t) + R$$

$$\alpha = \overline{v\Sigma_a} + \overline{vD_0}\, B_0^2 - C B_0^4 + \cdots$$

- α: flux decay-time eigenvalue [$s^{-1}$]
- $D_0$ [$cm^2 s^{-1}$] is the asymptotic diffusion coefficient
- C: "cooling coefficient" [$cm^4 s^{-1}$]
- $B_0^2$: geometric Buckling [$cm^{-2}$]
- $v$ thermal neutron velocity (2.2 x $10^5$ cm/s)
- $\Sigma_a$ macroscopic absorption cross section [$cm^{-1}$]

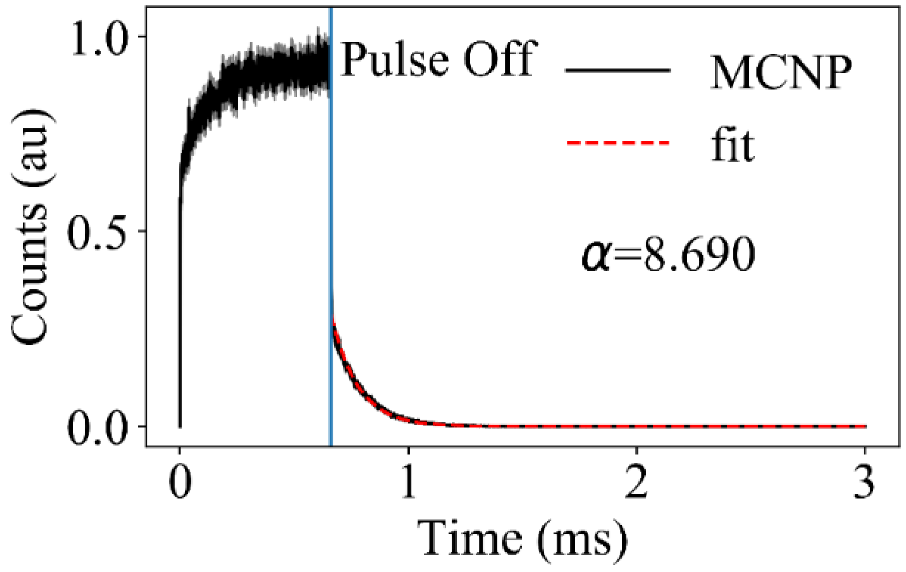
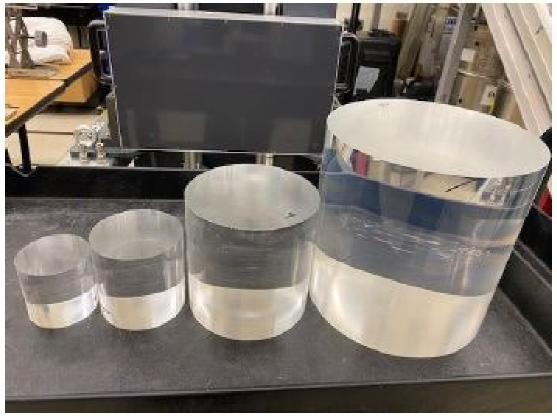



Figure: Example of pulsed-die-away curve modeled in MCNP

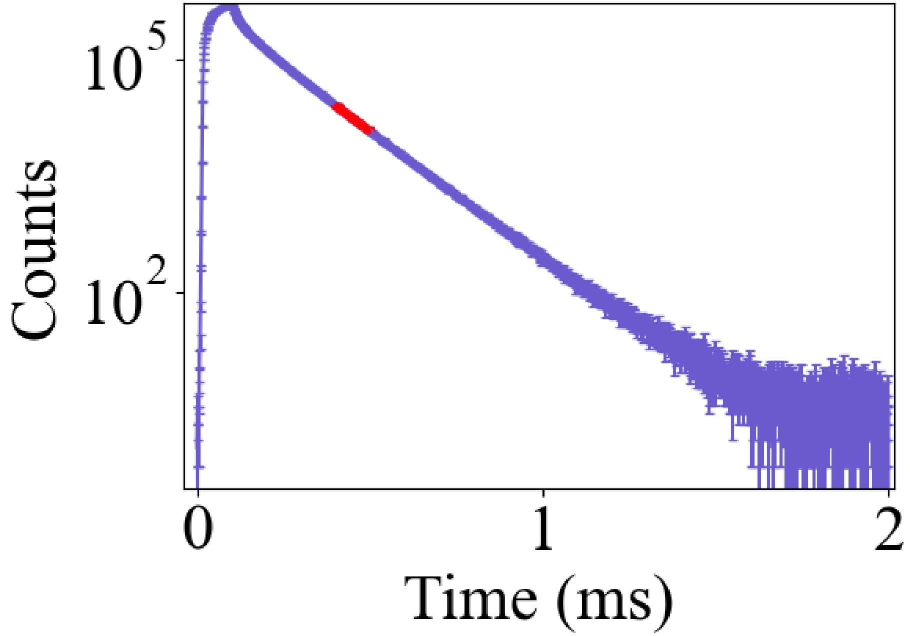
# Benchmarked Targets

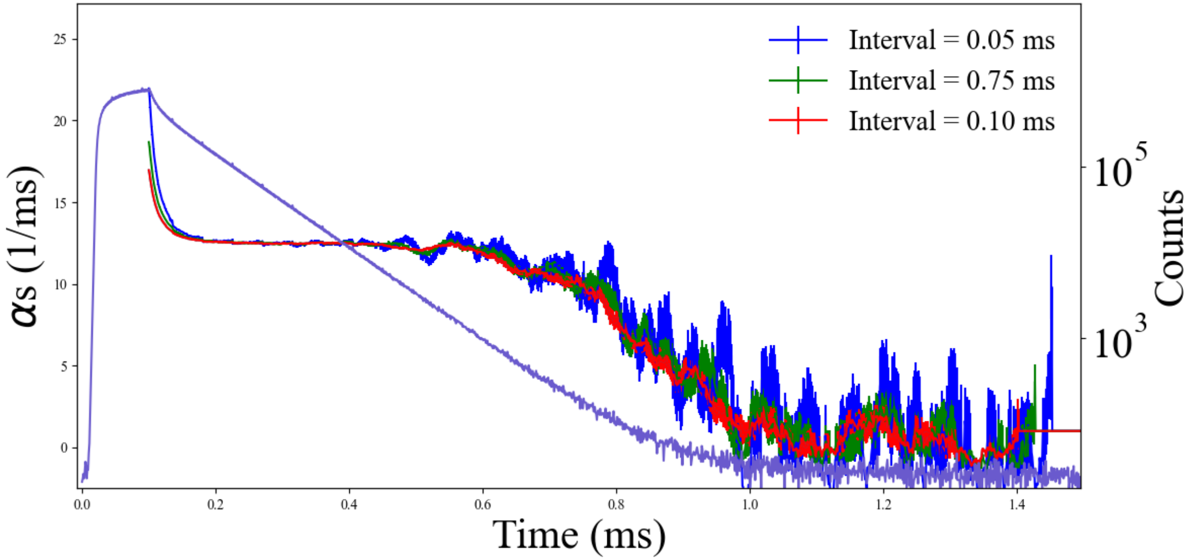
- High density polyethylene ($C_2H_4$).
- Polymethyl Methacrylate ($C_5H_8O_2$).

| Case | Material | Diameter (cm) | Height (cm) |
|---|---|---|---|
| 1 | HDPE | 7.76 | 7.65 |
| 2 | HDPE | 10.75 | 10.81 |
| 3 | HDPE | 15.61 | 15.53 |
| 4 | HDPE | 23.69 | 22.89 |
| 5 | PMMA | 7.63 | 7.62 |
| 6 | PMMA | 10.18 | 10.17 |
| 7 | PMMA | 15.24 | 15.25 |
| 8 | PMMA | 22.92 | 22.87 |



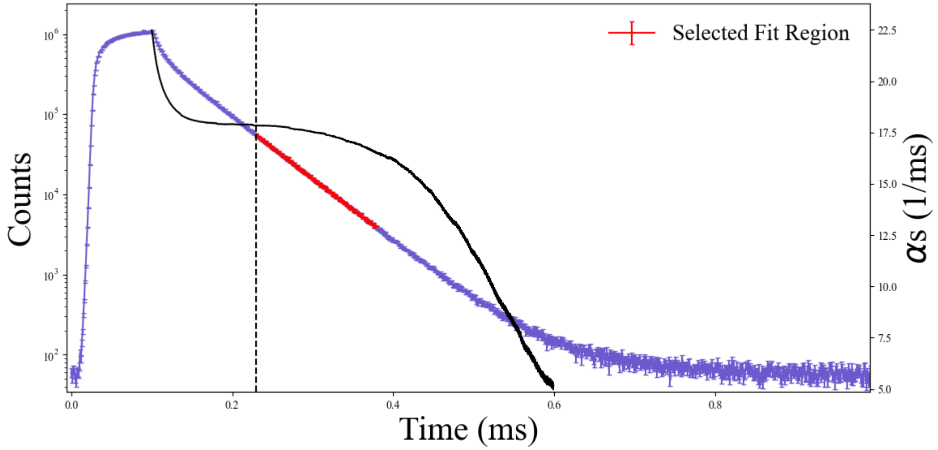
# Determining α Eigenvalue



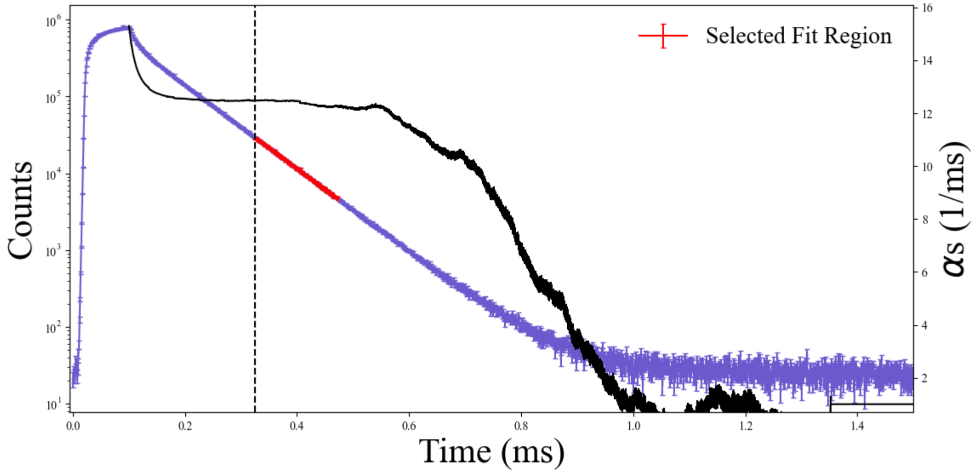



# Determining α for HDPE cases

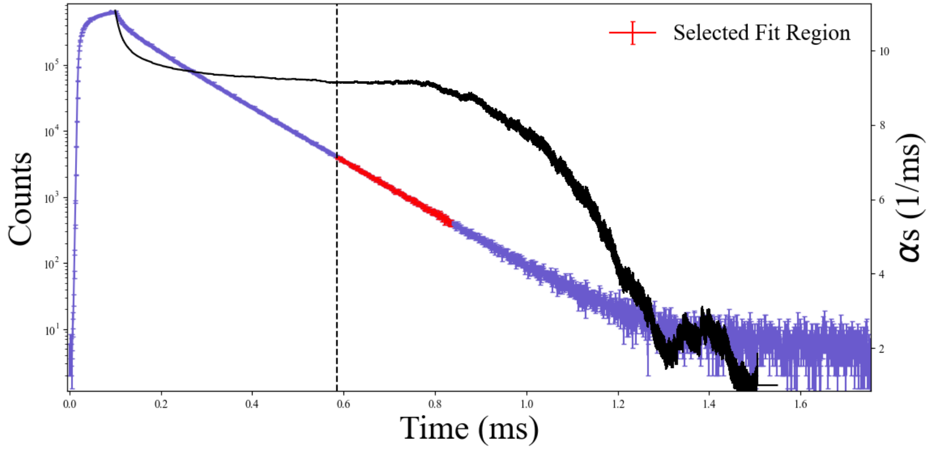
## Case 1



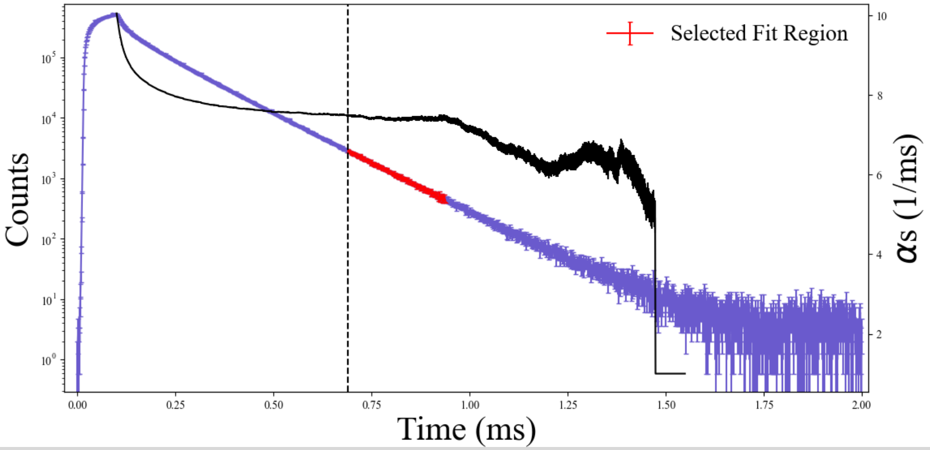

## Case 2



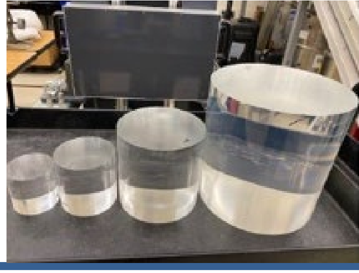

## Case 3



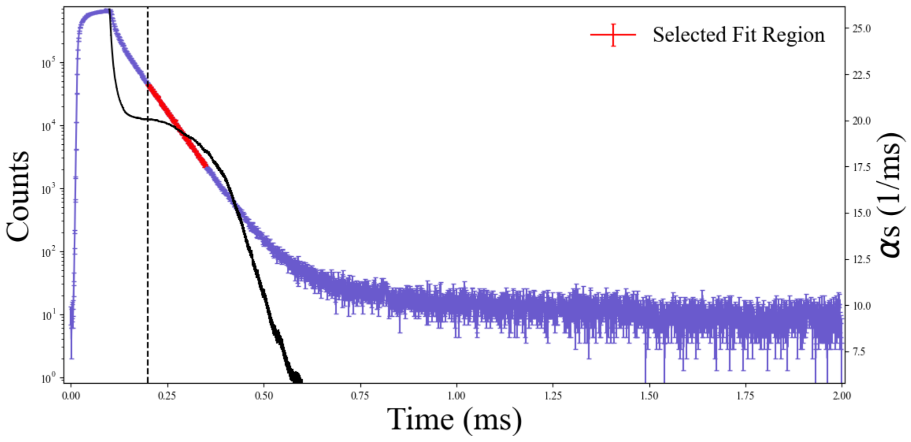

## Case 4



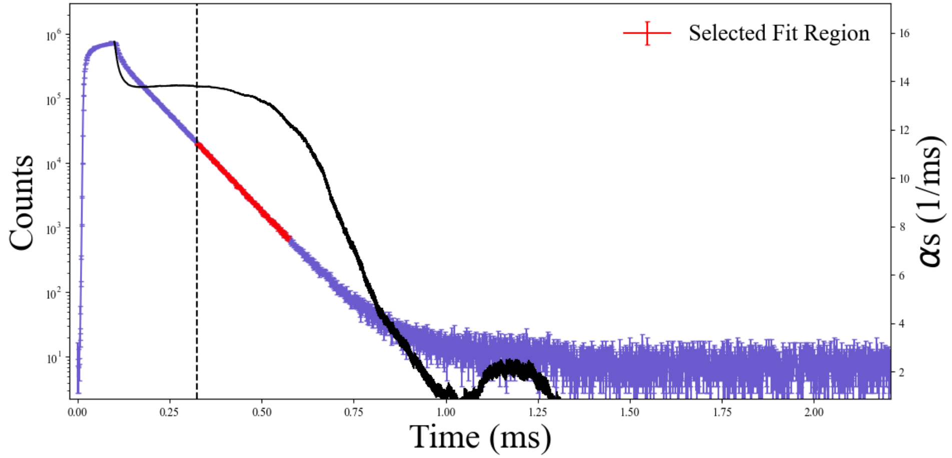
# Determining α for PMMA cases



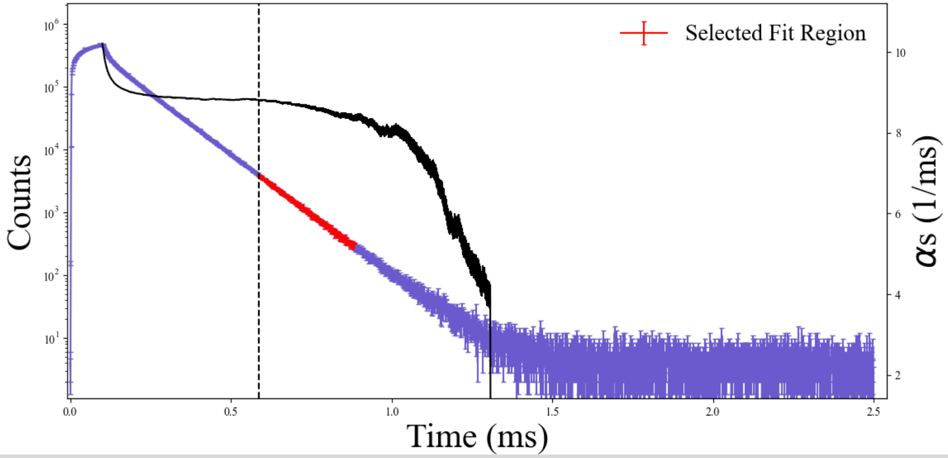
## Case 5



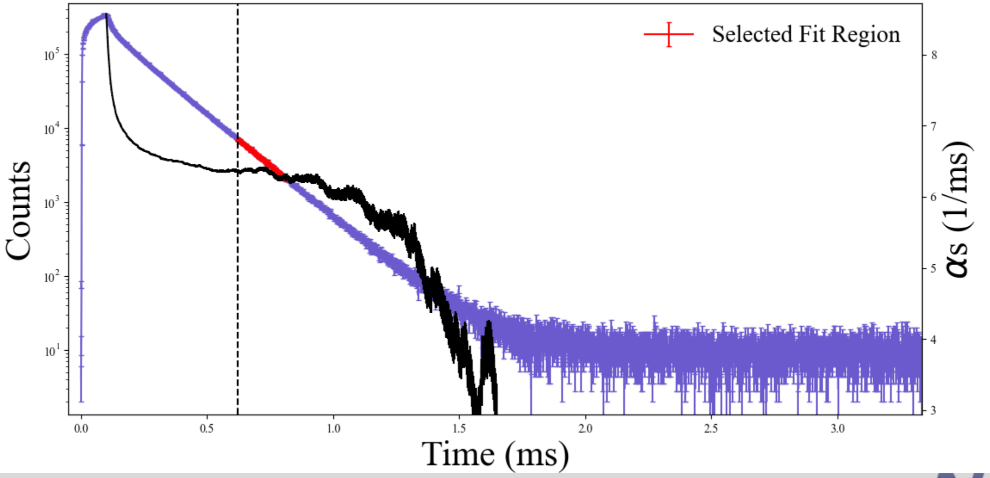

## Case 6




## Case 7




## Case 8



# Benchmarking of PNDA

- MCNP® 6.2.0 Monte Carlo simulation code was used with ENDF/B-VIII.0 nuclear data library.
- The number of particle histories in each MCNP simulation was determined to obtain a statistical uncertainty in the calculation that was significantly less than the experimental measurement uncertainty. ~1 x $10^{12}$ particles.
- Neutron flux tallied using a track length estimator for four detectors. $^{3}$He absorption cross section was applied to the tallied neutron flux to calculate the $^{3}$He absorption reaction rate.
- The methodology used to obtain α was kept the same for both experiment and models to avoid unwanted bias.
- The uncertainty in α from simulations was determined by propagating the statistical uncertainty in MCNP with the uncertainty in the fit

# Experimental Uncertainty Characterization

- Dimensional uncertainty:
  - Box thickness.
  - Box length and width.
  - Cd liner thickness.
  - Target Length.
  - Target Diameter.
  - Detector Height.
  - Detector radial position.
  - Alignment with the source.
- Composition Uncertainty:
  - Target impurities.
  - Borated HDPE Box impurities
- Mass Uncertainty:
  - Target density.
  - Detector fill density.
  - Borated HDPE box density.
  - Cd liner density.
- Temperature Uncertainty.
- Detector Efficiency.
- Detector Dead Time.
- Worth Studies:
  - Detector internals.
  - SHV connectors.
  - Source description.
  - Steel rods.
  - Al-struct.
  - Al-base.
  - Trolly.

# Important Considerations for Benchmarking

- Simulations performed with
  - Requested dimensions from manufacturer, assumed density of 1.18 g/cm$^3$
  - Measured dimensions, measured weight, measured density

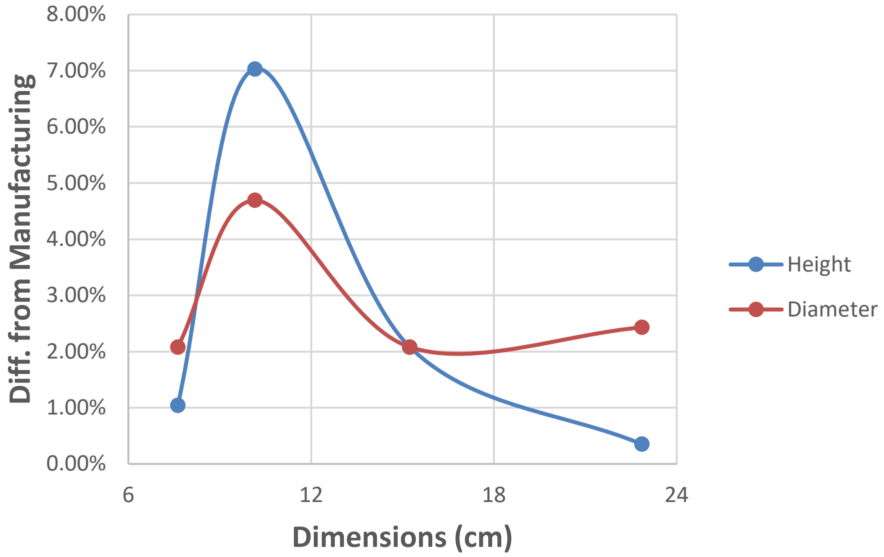



Figure: Variation of measured vs. procured dimensions

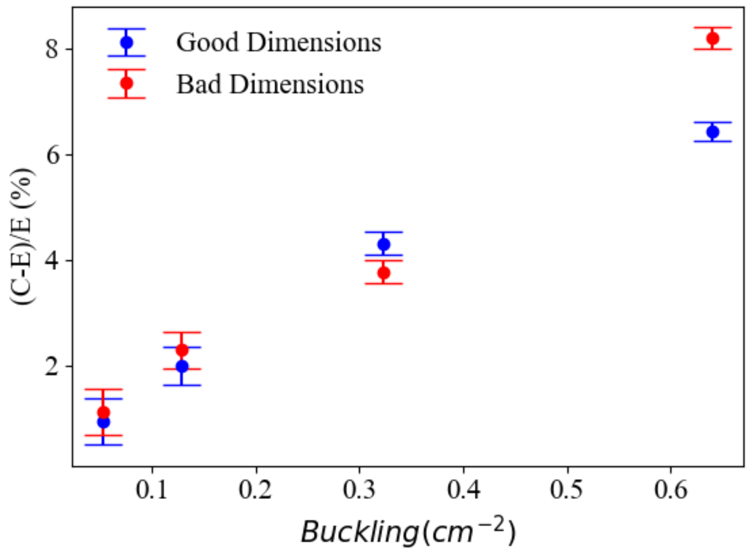
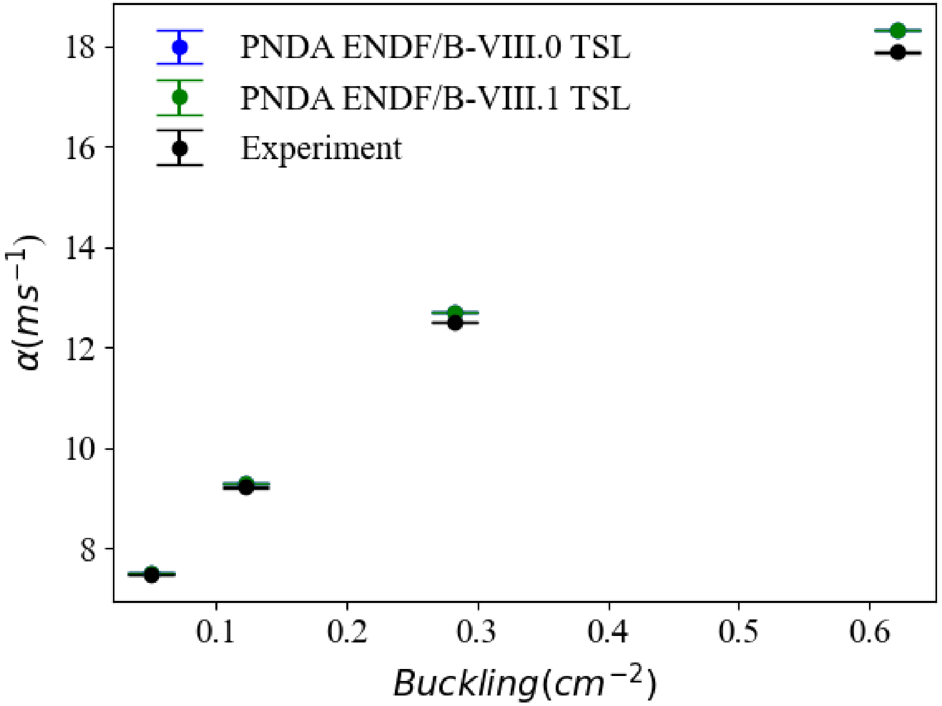
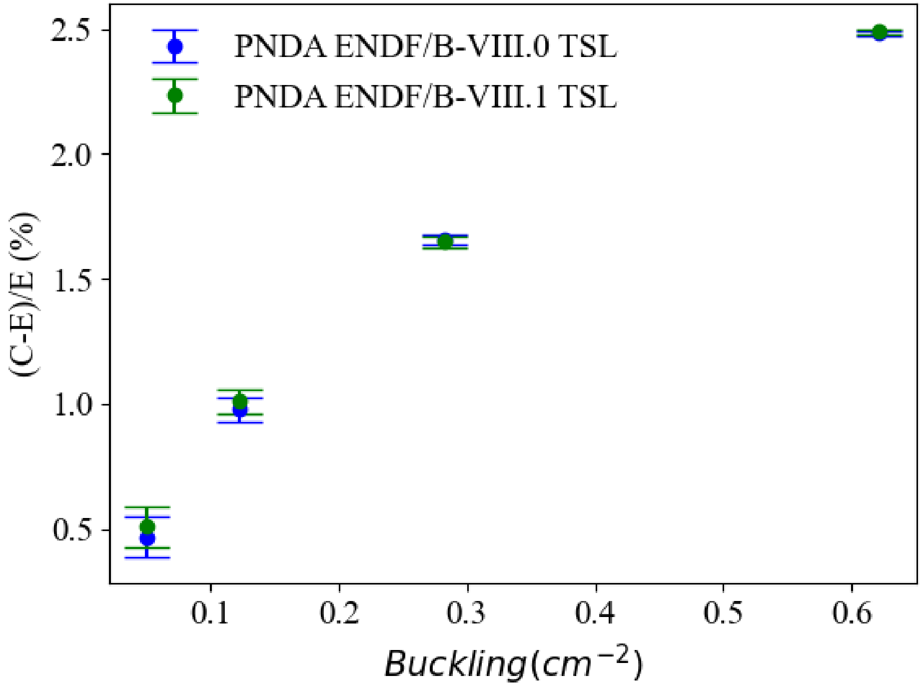



Figure: Variation of bias with measured vs. procured dimensions

# HDPE Validation

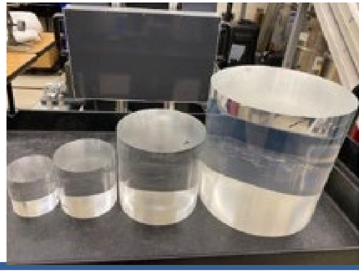


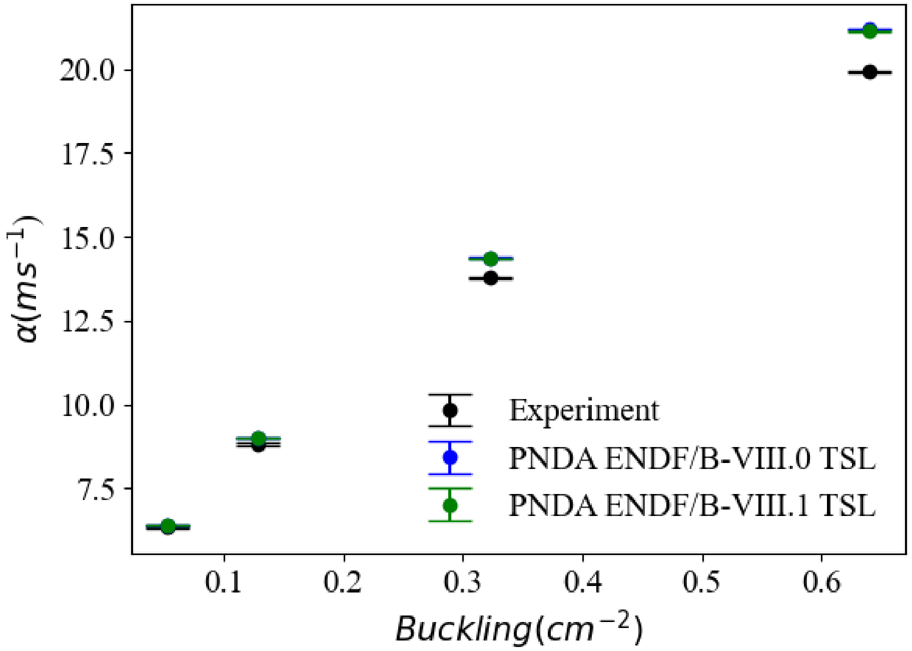



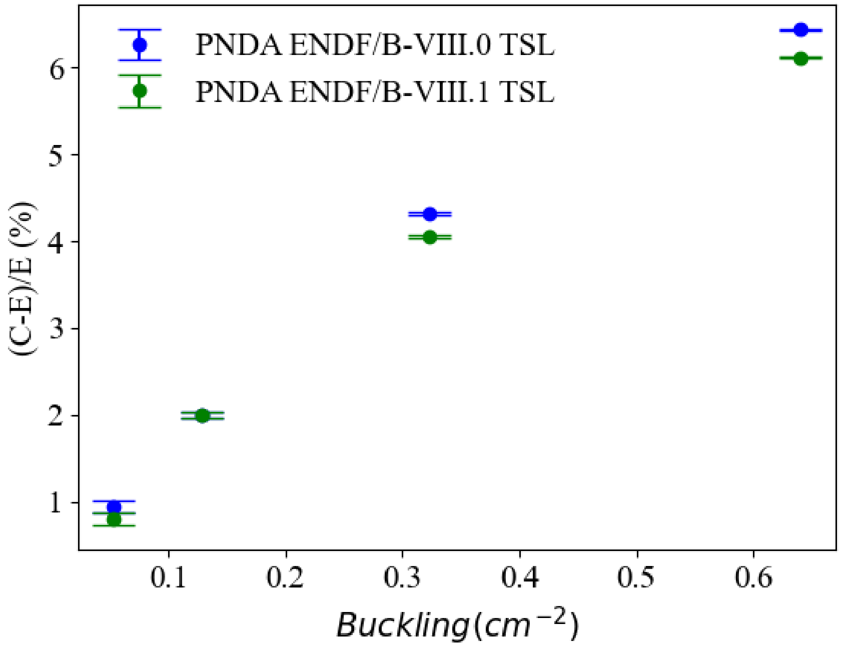

- General trend of increasing bias with smaller sampler size (larger buckling)

# Lucite Results

Polymethyl Methacrylate





# Questions, Comments, Discussion

- **References:**


  - G. von Dardel and N. G. Sjostrand, "Diffusion Parameters of Thermal Neutrons in Water," Physical Review, vol. 96, no. 5, pp. 1245-1249, 1954.
  - J. Holmes, M. Zerkle and D. Heinrichs, "Benchmarking a first-principles thermal neutron scattering law for water ice with a diffusion experiment," *EPJ Web of Conferences,* vol. 146, p. 13004, 2017.
  - J. Holmes, M. Zerkle and A. Hawari, "Validation of Thermal Scattering Laws for Light Water at Elevated Temperatures with Diffusion Experiments," in *PHYSOR 2020: Transition to a Scalable Nuclear Future*, Cambridge, United Kingdom, 2020.
  - D. Siefman, E. Heckmaier, W. Zwyiec, D. Heinrichs, "IER-501 CED-1: Preliminary Design of a New Pulsed-Neutron Die-Away Experimental Testbed for Thermal Scattering Law Benchmarks (PNDA)," *Lawrence Livermore National Laboratory*, LLNL-TR-820718, 2021

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# Sensitivity Depends on Target Size

- Small targets (large Bucklings) are more sensitive to scattering
- Large targets (small Bucklings) are more sensitive to absorption

$$B_0^2 = \left(\frac{\pi}{H + 2\delta}\right)^2 + \left(\frac{2.405}{R + \delta}\right)^2$$

$$\alpha = \underbrace{\overline{v\Sigma_a}}_{\text{Absorption}} + \underbrace{\overline{vD_0}\, B_0^2 - CB_0^4}_{\text{Scattering}}$$

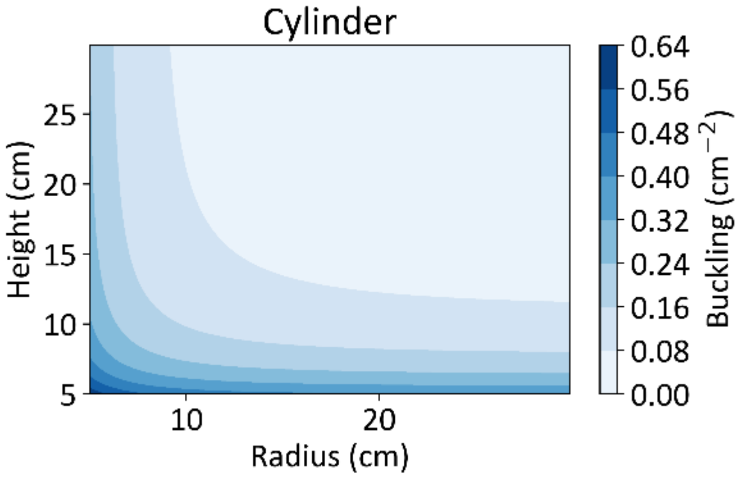


Figure: Buckling vs. cylinder dimensions

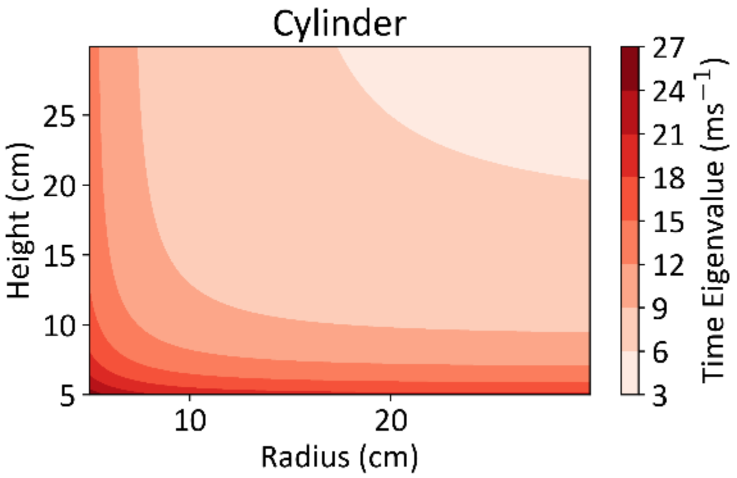


Figure: α vs. cylinder dimensions

# Uncertainty Analysis Characterization

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  - Source description.
  - Steel rods.
  - Al-struct.
  - Al-base.
  - Trolly.

# Sensitivity to TSLs

- Example: Historical water experiment in cylindrical geometry
  - A. Bracci & C. Coceva, "The diffusion parameters of thermal neutrons in water." *Il Nuovo Cimento*, **4** (1956)

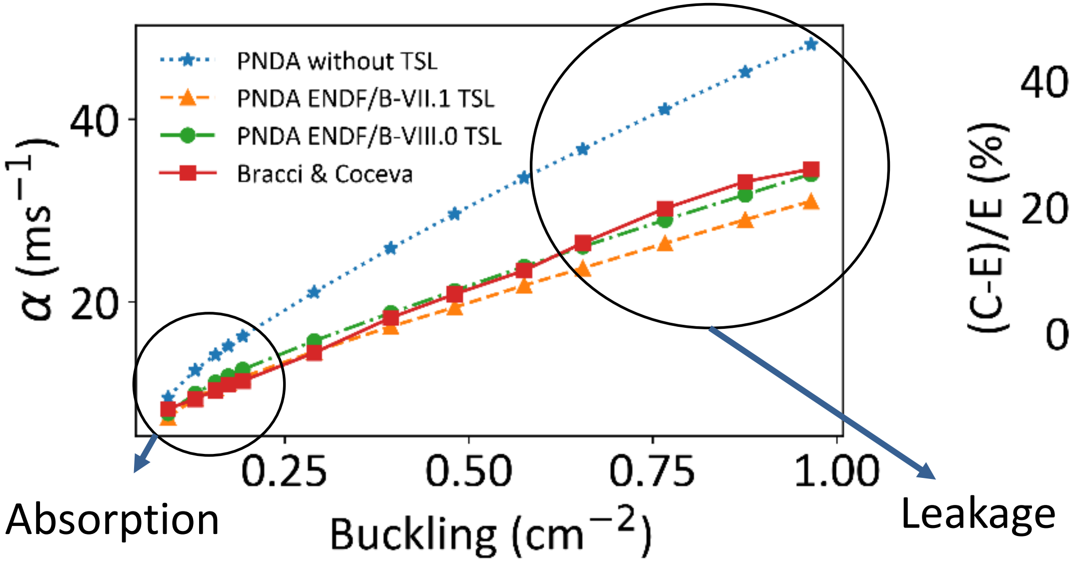



Figure: α vs. Buckling curve for experimental and simulated data

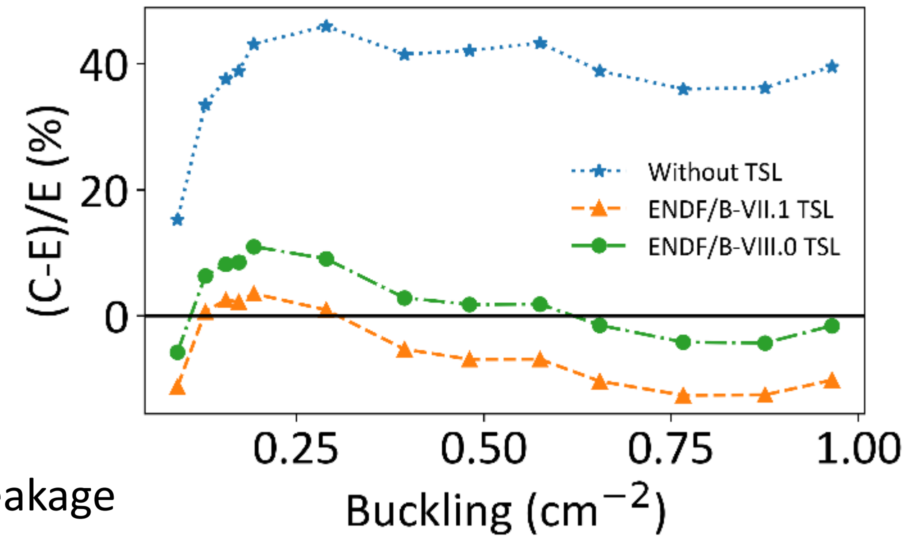
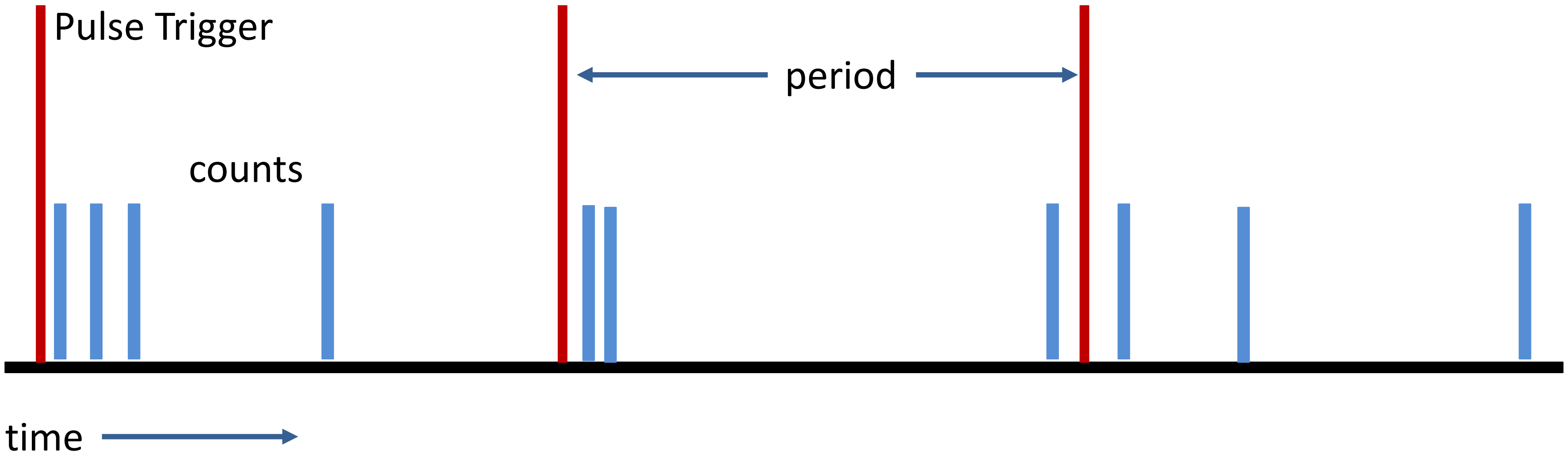


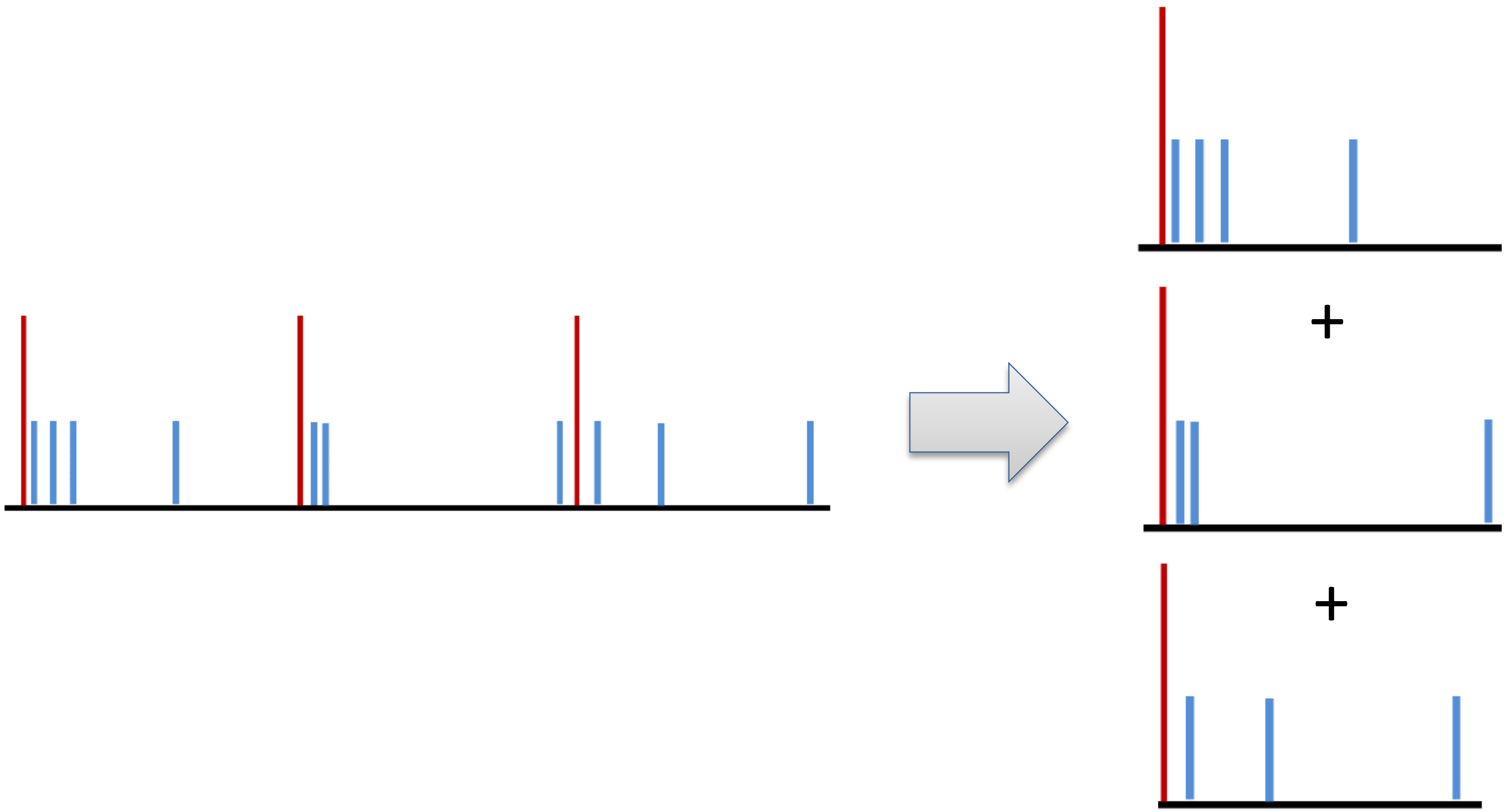

Figure: Bias of simulations without TSLs, with ENDF/B-VII.1, and with ENDF/B-VIII.0 TSLs

# Algorithm

- Neutron counts and generator trigger recorded as list mode data
- Few counts per pulse, but many pulses allows to reconstruct die away curve
- Trigger is initiating event, $t_{trigger}$
- Sum counts in bins on die away curve as $t_{tag} - t_{trigger}$ in histogram



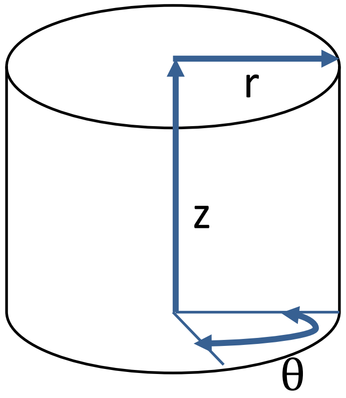
# Algorithm: Sum pulse counts to construct curve

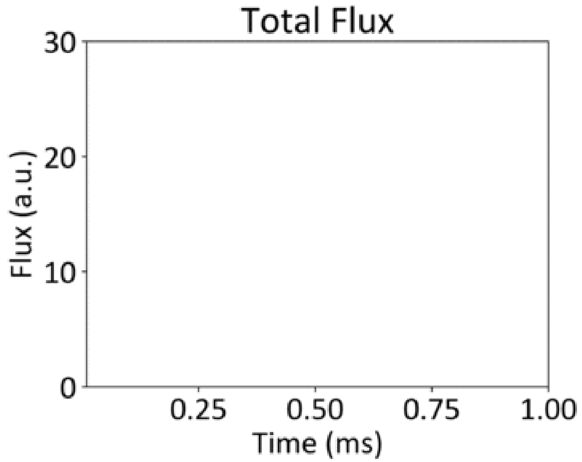


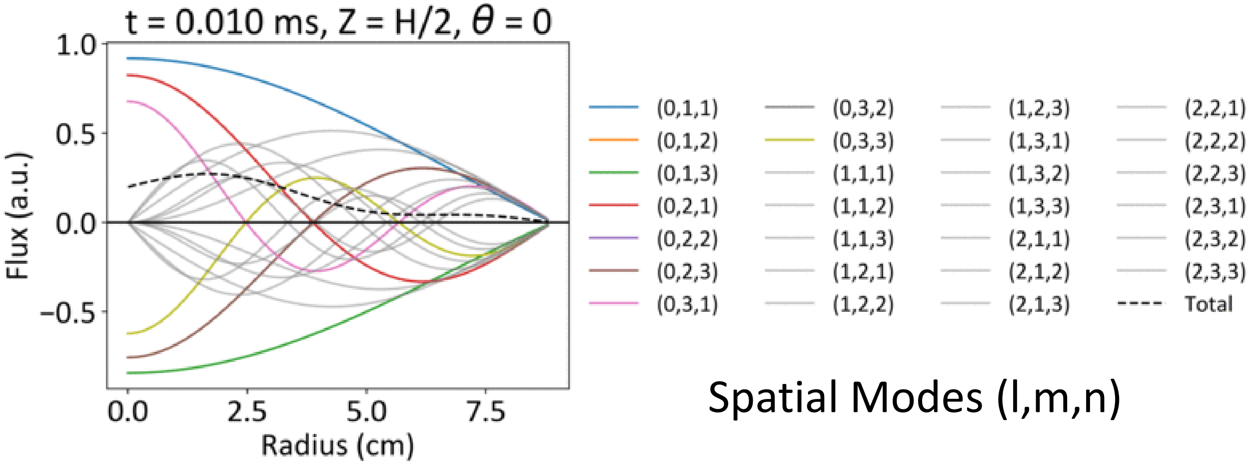
# Decay to Fundamental Mode

## Large Cylindrical Sample

$$\phi(r,\theta,z,t) = \sum_{l,m,n} C_{l,m,n} \sin\left(\frac{n\pi}{H} z\right) J_l(a_{l,n} r) \cos l\theta \exp\left[-\underbrace{(\overline{v\Sigma_a} + \overline{vD_0} B^2_{n,m,l})}_{\alpha_{l,m,n}} t\right]$$



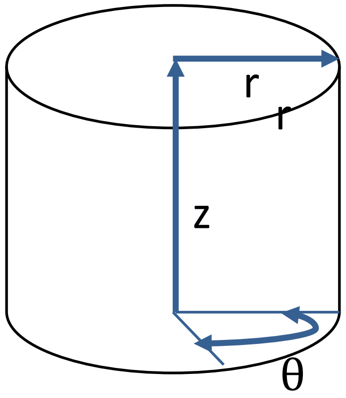




Spatial Modes (l,m,n)

# Decay to Fundamental Mode
## Large Cylindrical Sample

$$\phi(r,\theta,z,t) = \sum_{l,m,n} C_{l,m,n} \sin\left(\frac{n\pi}{H} z\right) J_l(a_{l,n} r) \cos l\theta \exp\left[-\left(\underbrace{\overline{v\Sigma_a} + \overline{vD_0}\, B^2_{n,m,l}}_{\alpha_{l,m,n}}\right)t\right]$$




Focusing only on modes of Bessel function: