Examination of C, Be, Mo, ^{238}U, Fe, and Zr using the RPI HES Data with Current ENDF, JEFF, and JENDL Evaluations

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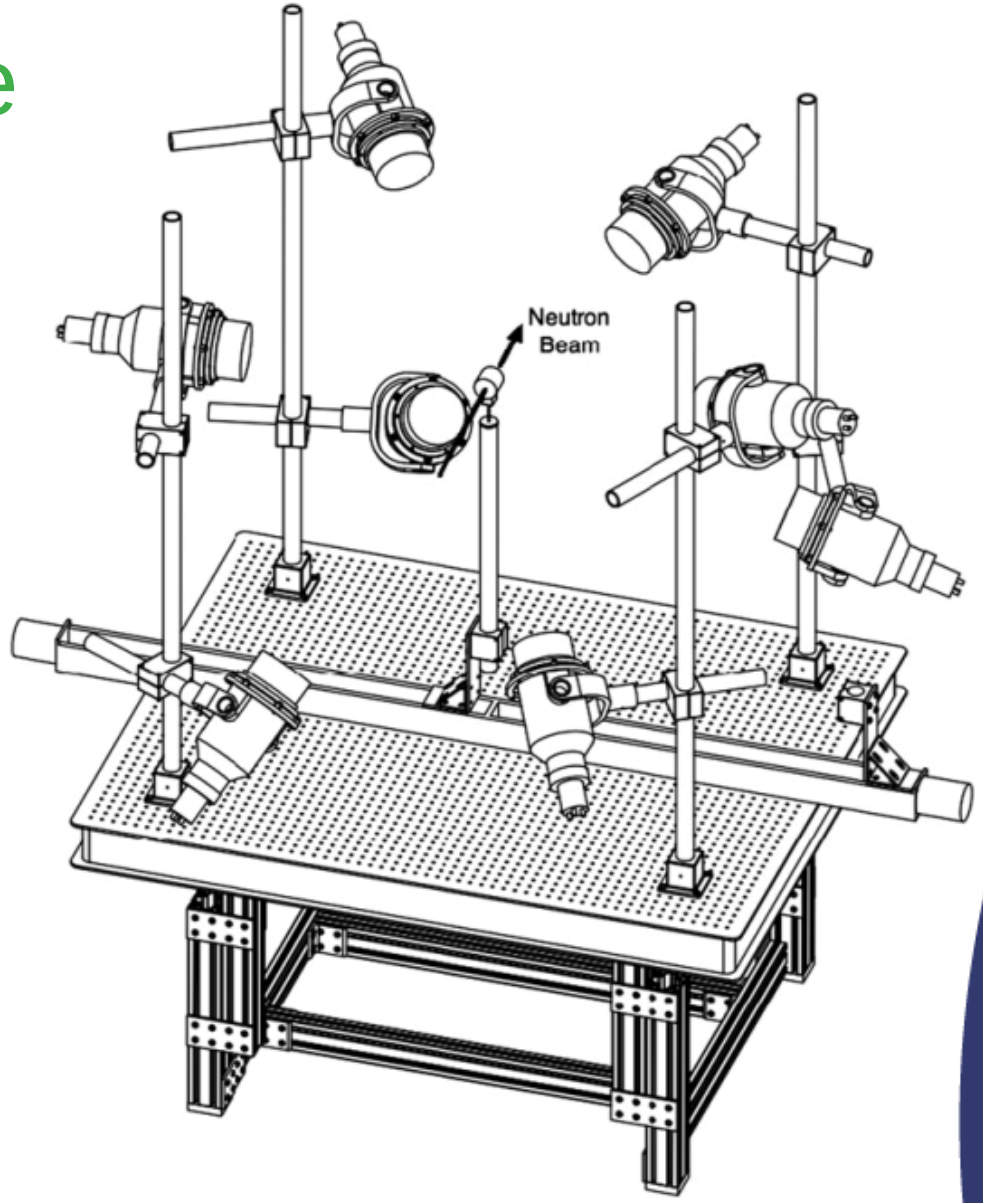
Outline

- RPI Gaerttner LINAC Center
  - LINAC specifications and history
  - Neutron production targets, detector systems, and capability matrix
- High Energy Scattering System
  - Eight EJ301 proton recoil fast neutron detectors
  - Neutron flux measurements and detector efficiencies
  - Data processing and reference sample
- High Energy Scattering Results
  - Carbon, molybdenum, zirconium, beryllium, ^{238}U, and iron



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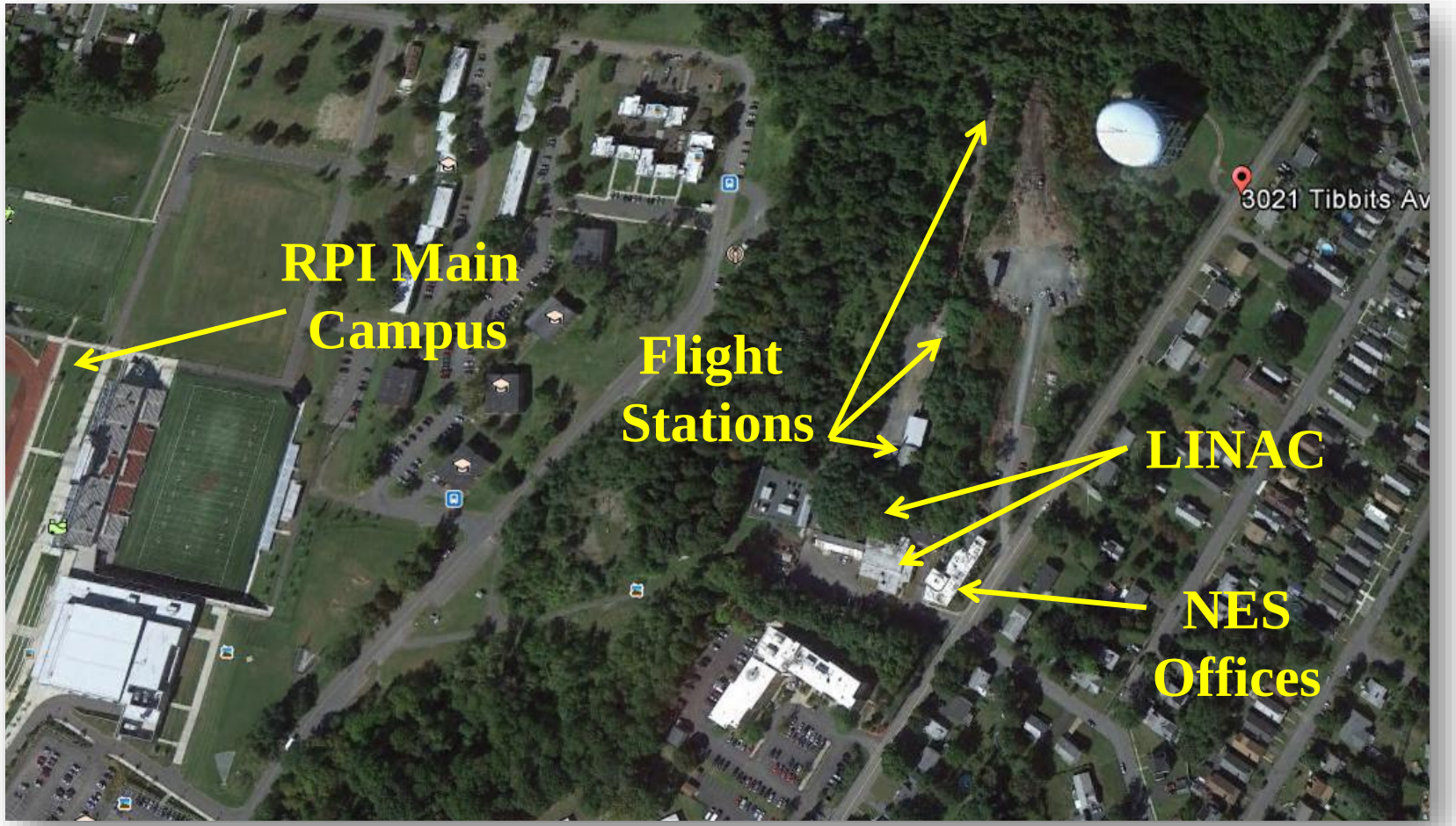
Where is the RPI Gaerttner LINAC Center?

It is on the highest point in Troy, NY



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The RPI Gaerttner LINAC Center

Electron LINAC

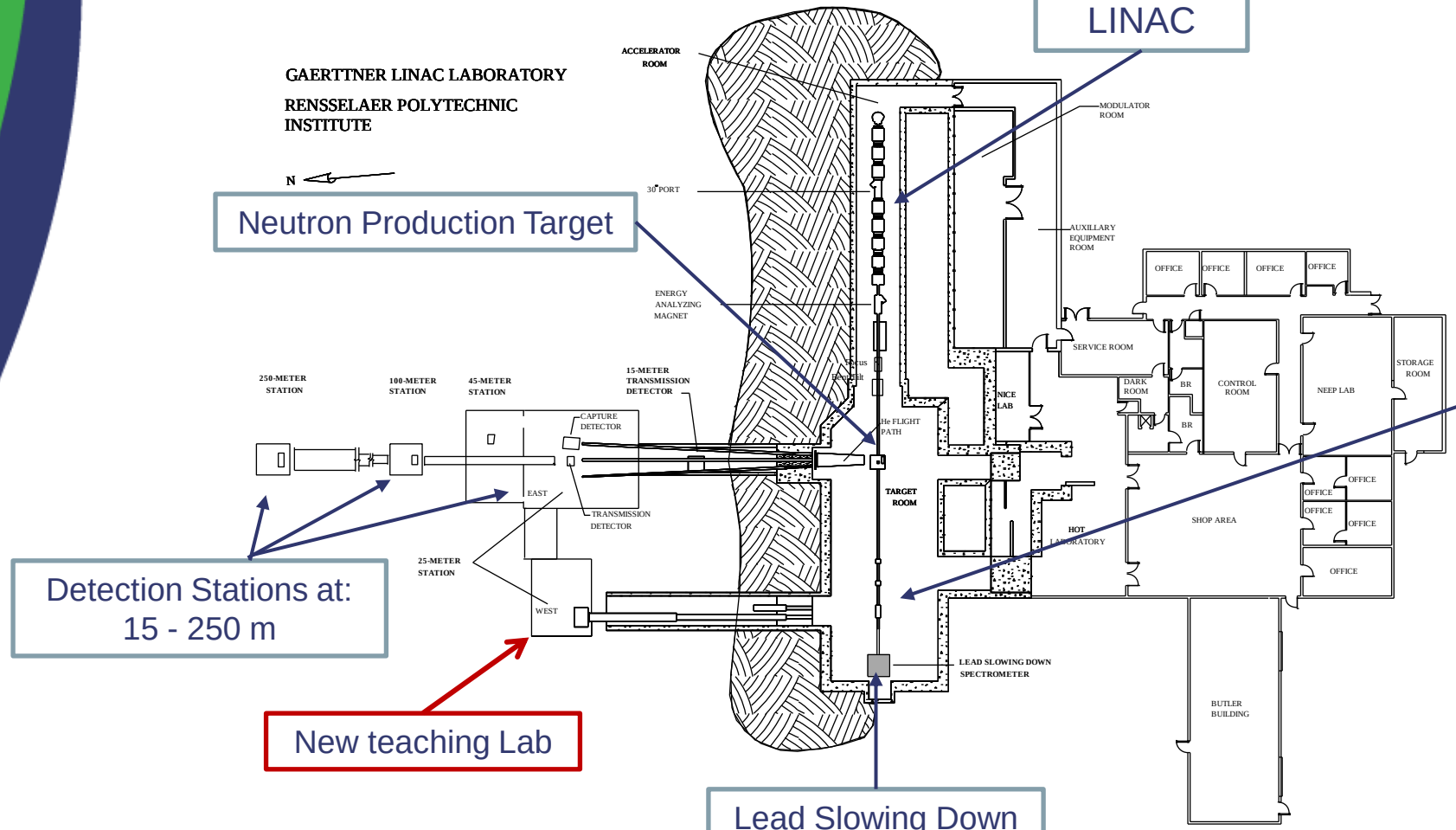
Neutron Production Target

Detection Stations at: 15 - 250 m

New teaching Lab

Lead Slowing Down Spectrometer

Target room



Current LINAC Specifications

	Three Sections (Low Energy Port)	Nine Sections (High Energy Port)
Electron Energy	5 to 25 MeV	25 to over 60 MeV
Pulse Width	6 to 5000 ns	6 to 5000 ns
Peak Current	3A (short pulse: 6 to 50 ns) 400 mA (long pulse: 50 to 5000 ns)	3A (short pulse: 6 to 50 ns) 400 mA (long pulse: 50 to 5000 ns)
Average Power	10 kw@ 17 MeV, 5000 ns	>10 kw@ 60 MeV, 5000 ns
Peak Dose Rate	$>10^{11}$ Rads/sec (in Silicon)	n/a
Neutron Production	n/a	**~4 X 10^{13} neutrons/sec**
Pulse Repetition Rate	Single pulse to 500 pps (short pulse) Single pulse to 300 pps (long pulse)	Single pulse to 500 pps (short pulse) Single pulse to 300 pps (long pulse)

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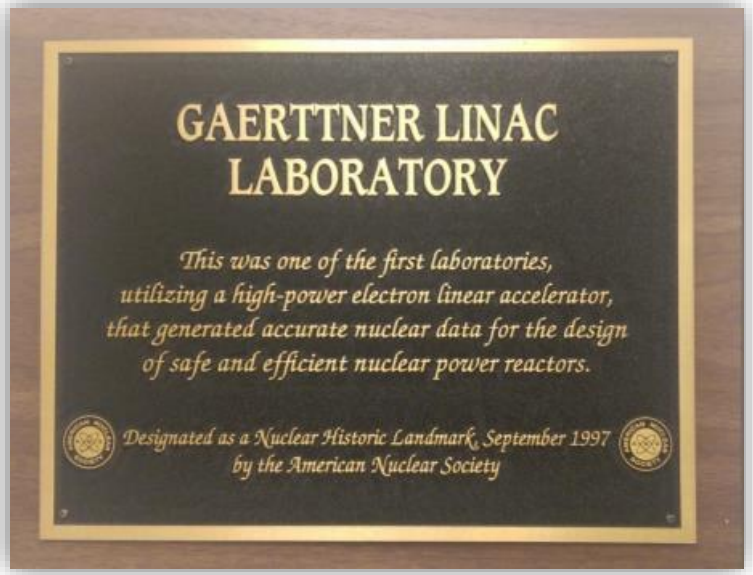
RPI LINAC History

December 1961 - The RPI LINAC started operation
Working "continuously" since.

September 1997- LINAC was designated as Nuclear Historic Landmark by the American Nuclear Society



Graduated over 190 students who utilized the LINAC as part of their graduate thesis research

Many years of accumulated experience

2014 - Started a major refurbishment and upgrade project

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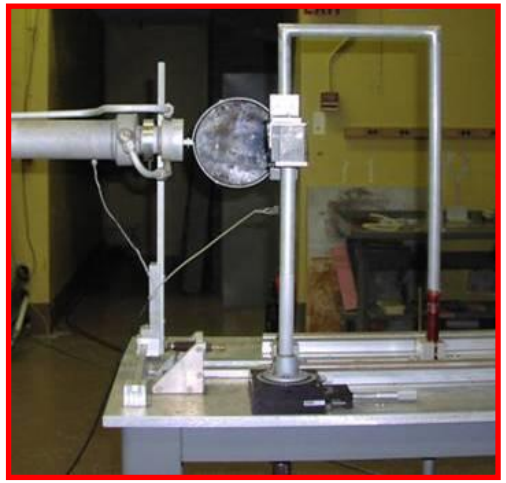
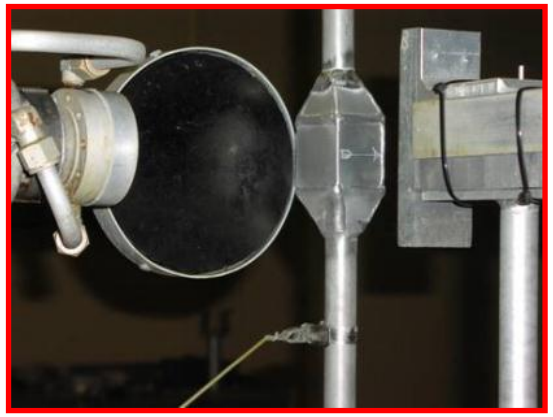
Neutron Production Targets (electrons → neutrons)

Bare Bounce Target (BBT)





Enhanced Thermal Target (ETT)

PACMAN target

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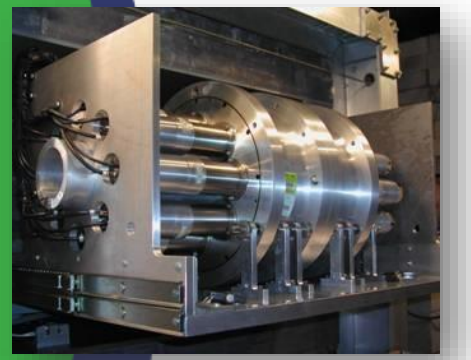
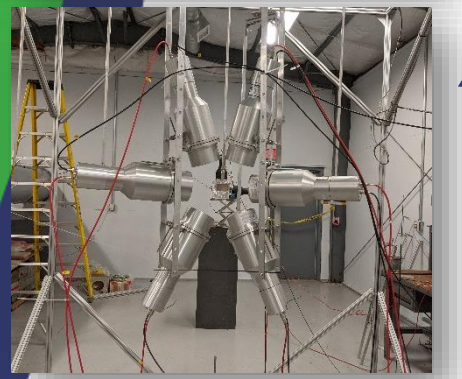
Detector Systems



25m

Capture/Multiplicity

45m



Neutron Scattering

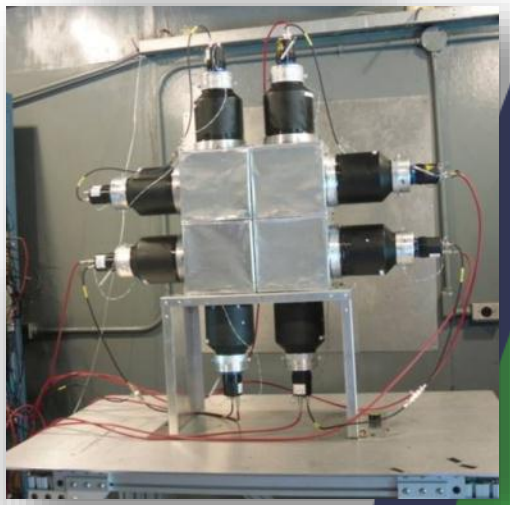
keV Scattering @ 35m

Fast Scattering and PFNS @ 30m

Transmission

35m

100m



250m

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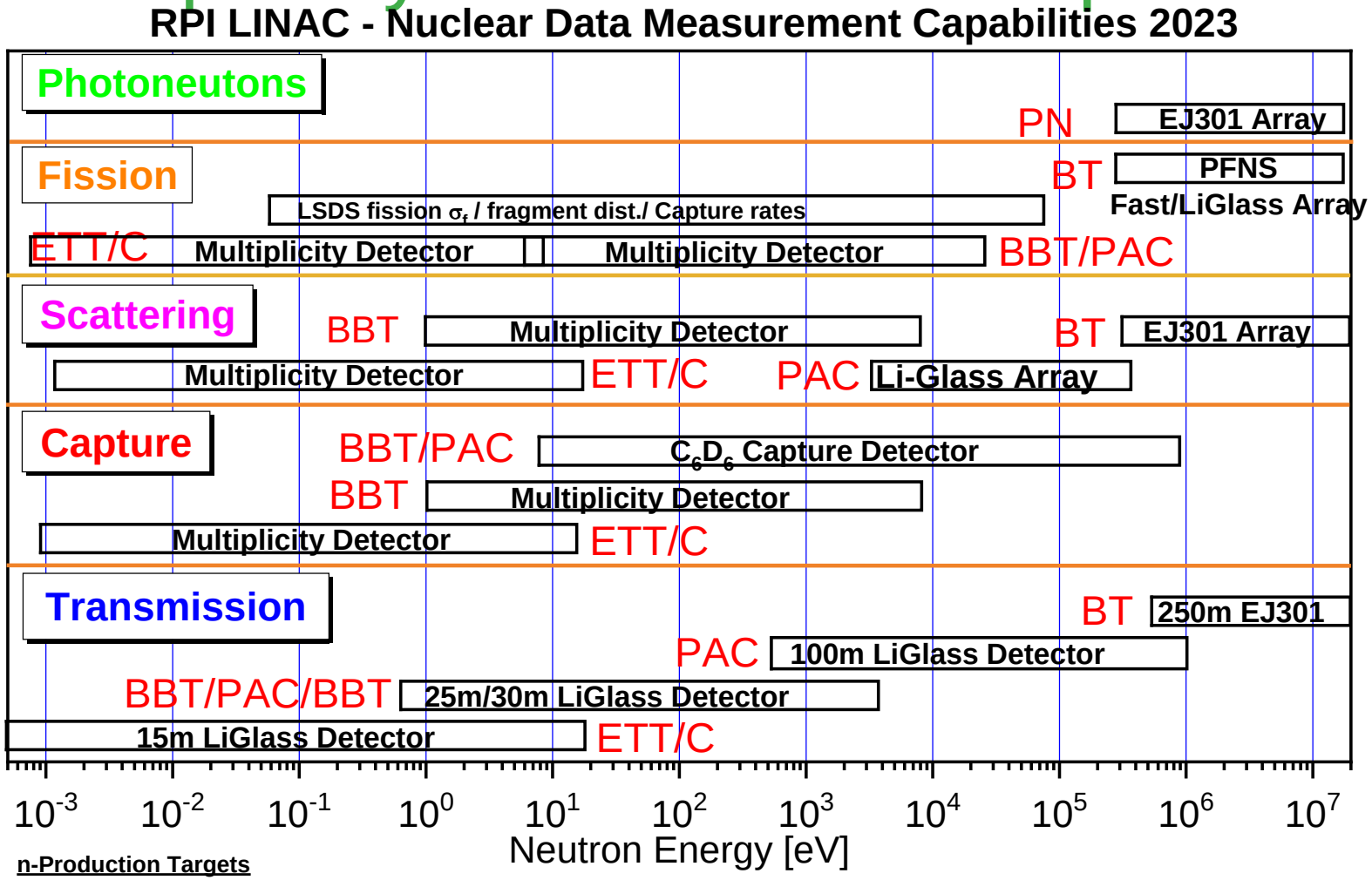
Capability Matrix and Development



n-Production Targets

ETT- Enhanced Thermal Target
ETTC - ETT + cold moderator
BBT - Bare Bounce Target
PAC - PacMan Target
PN - Photoneutron target
BT- Bare Target on Axis

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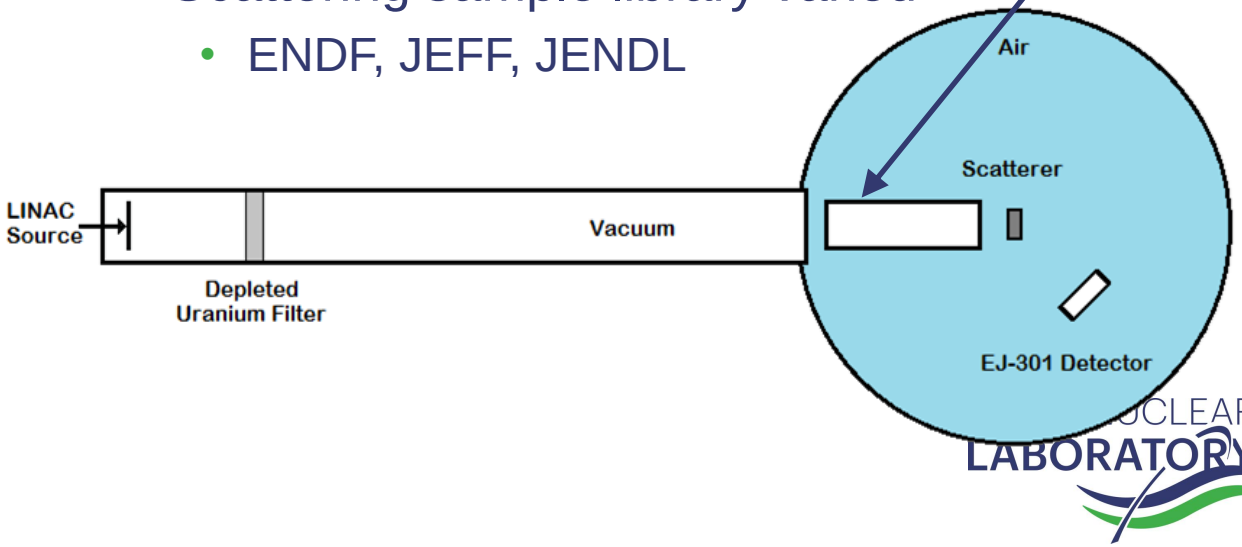
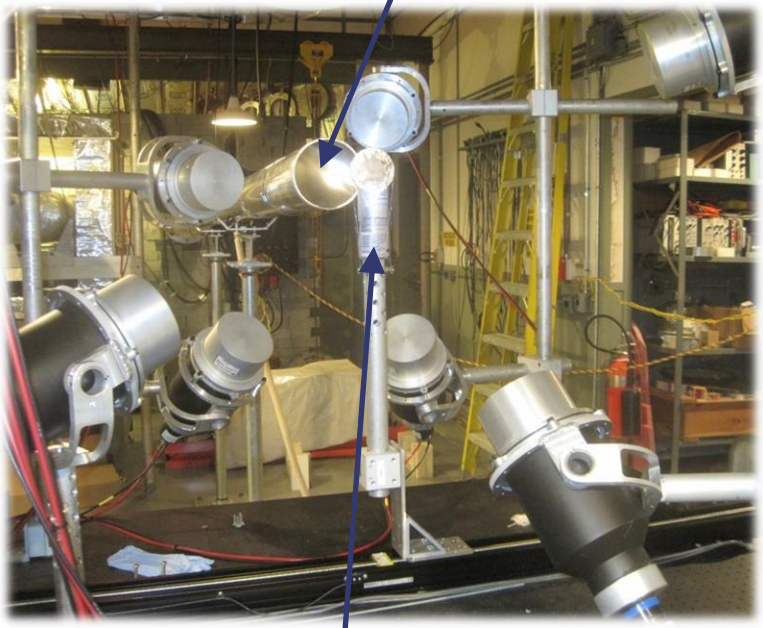
High Energy Scattering System

- Each experiment collected three sets of data:
  - Sample of Interest, e.g., ^{238}U or Iron
  - Graphite Reference Sample
  - Open Beam
- Fluctuations in neutron intensity recorded by beam monitors
- Experiments were modeled in MCNP
  - Scattering sample library varied
    - ENDF, JEFF, JENDL



Upstream vacuum reduced open beam contribution‡

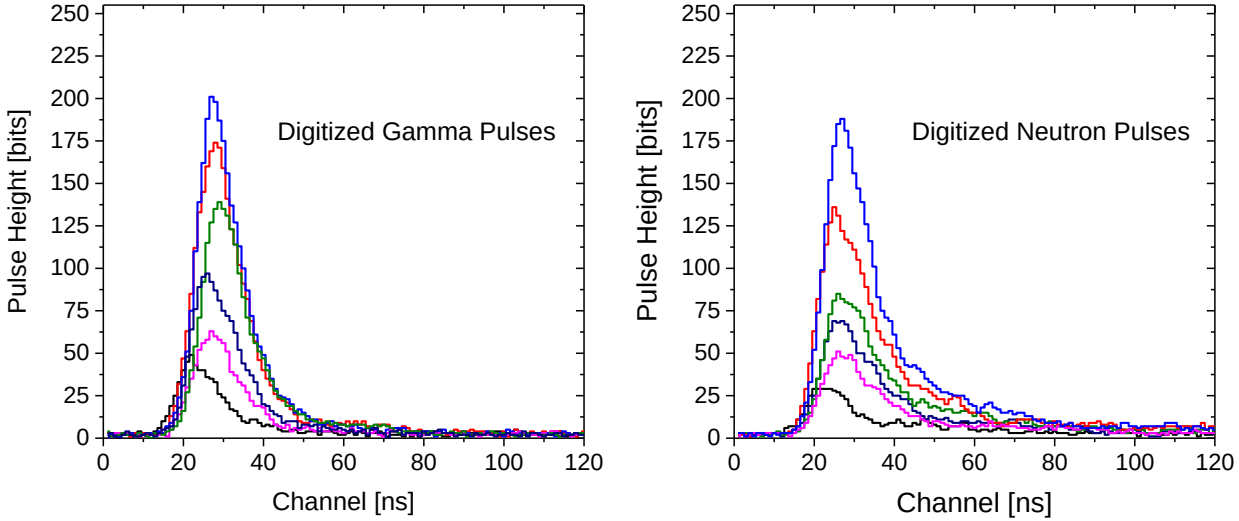


Low mass sample holder

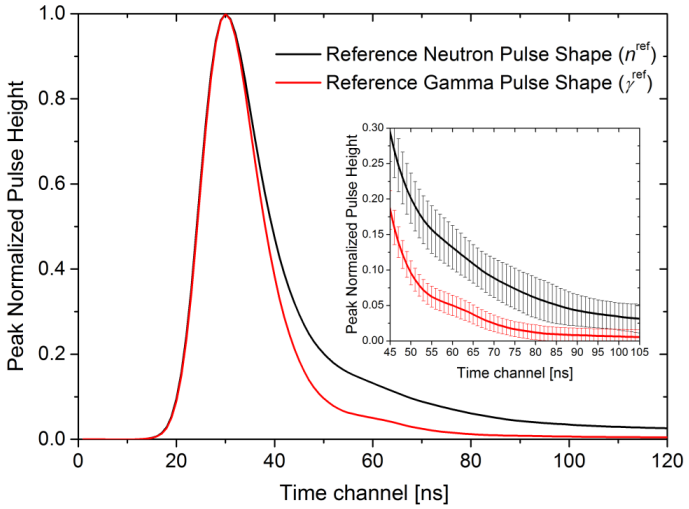
‡ Present after 2011

Data Processing and Analysis

- Acqiris AP240 DAQ Board:
  - Each digitized event contained 120 8-Bit data points that were used to reconstruct the waveform



- Each digitized event was analyzed to extract useful parameters:
  - Channel
  - Acquisition time
  - Area (pulse height)
  - Shape



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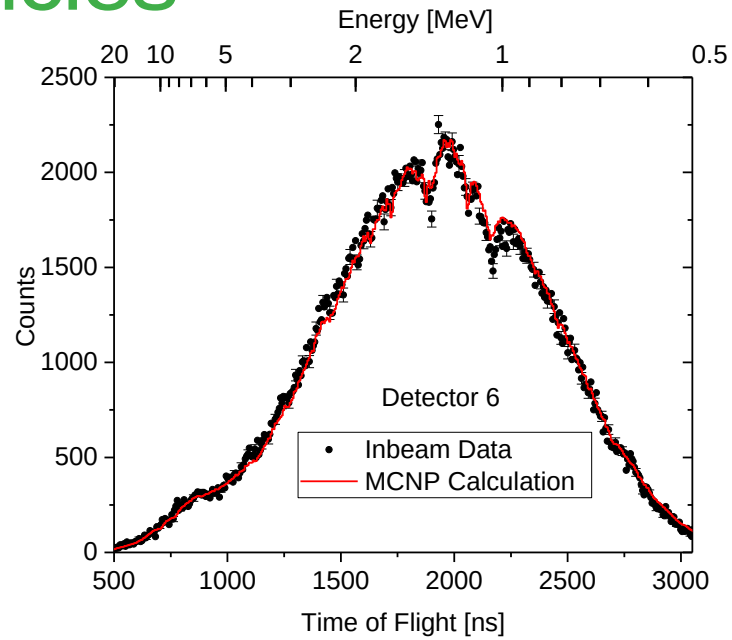
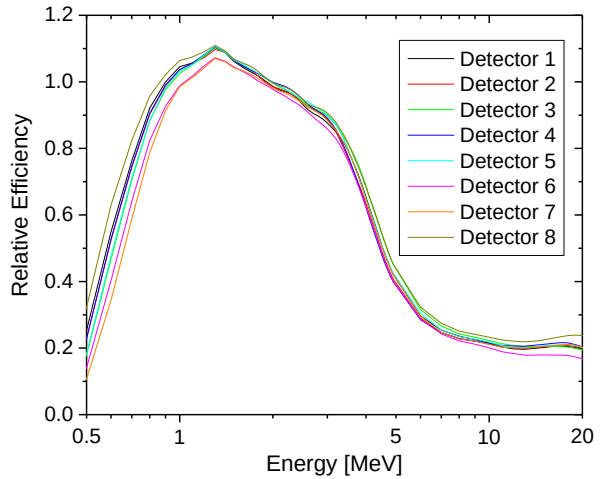
EJ-301 Detector Efficiencies

- Neutron flux measured with ^{235}U Fission Chamber
- Small variations between efficiencies are present
  - Lower-level discriminator
  - Scintillator-to-detector Coupling
  - Photomultiplier Tube Gain
- MCNP was used to calculate the measured flux shape at the in-beam detector position
  - Flux shape and count rate were used to calculate individual detector efficiencies

$$\eta_i(E) = \frac{R_i(E)}{\phi(E)}$$

  - Relative efficiencies were used in MCNP models





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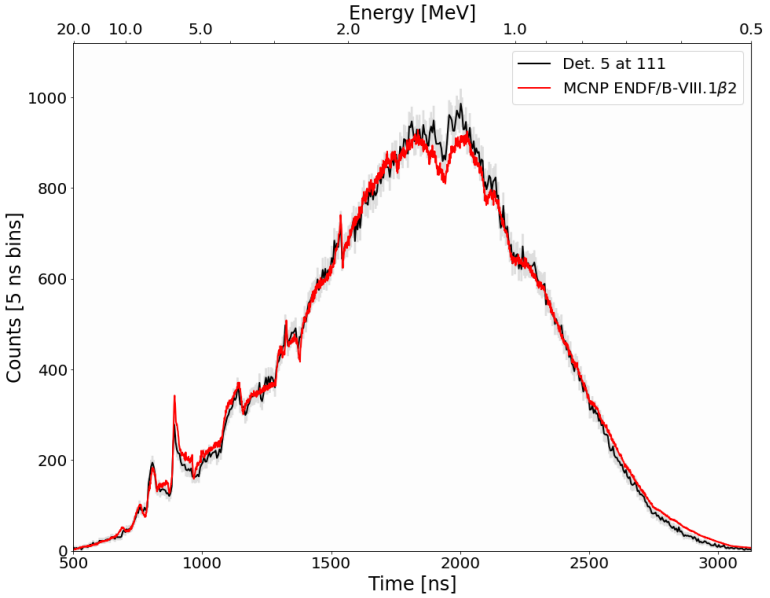
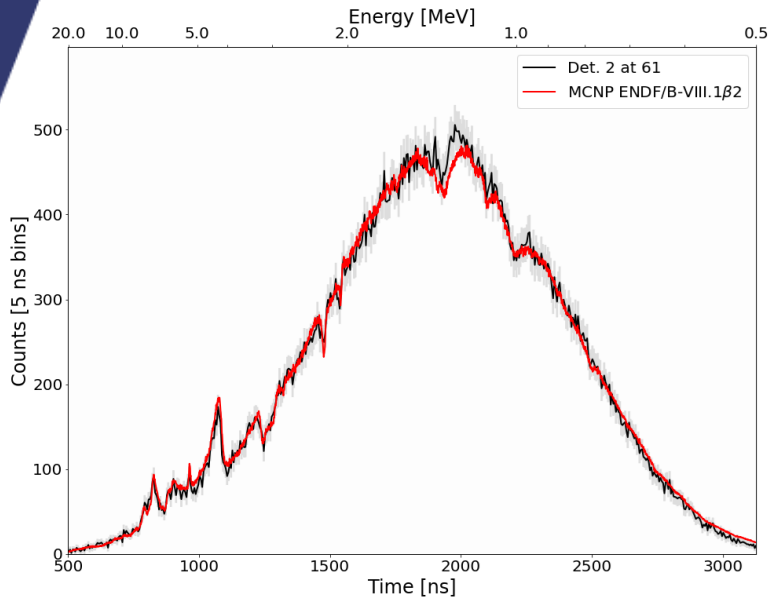
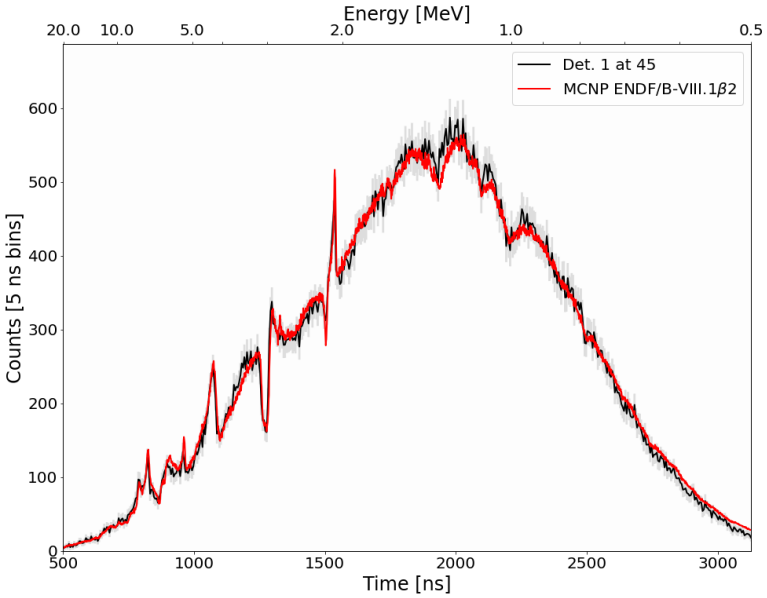
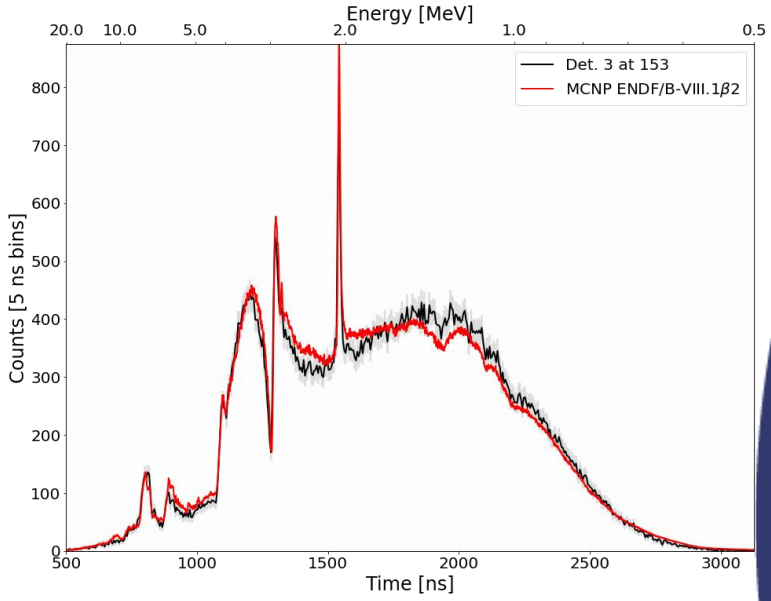
Carbon

- Carbon (graphite) was used as a reference sample with all high energy scattering measurements
- Generally good agreement between measured data and MCNP model









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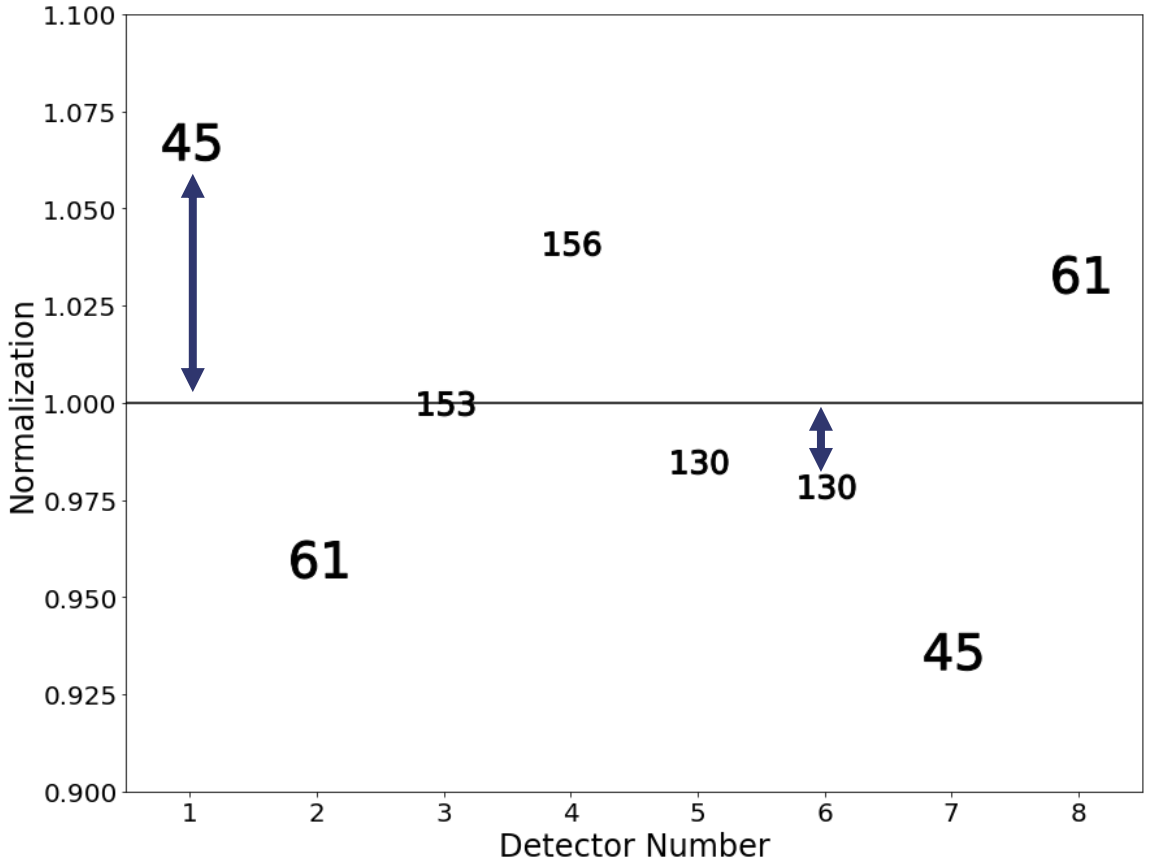
Carbon – Continued

- Each detector's relative normalization
  - Detector locations represented by plotted symbols
- Differences in the normalization are used to quantify systematic uncertainties



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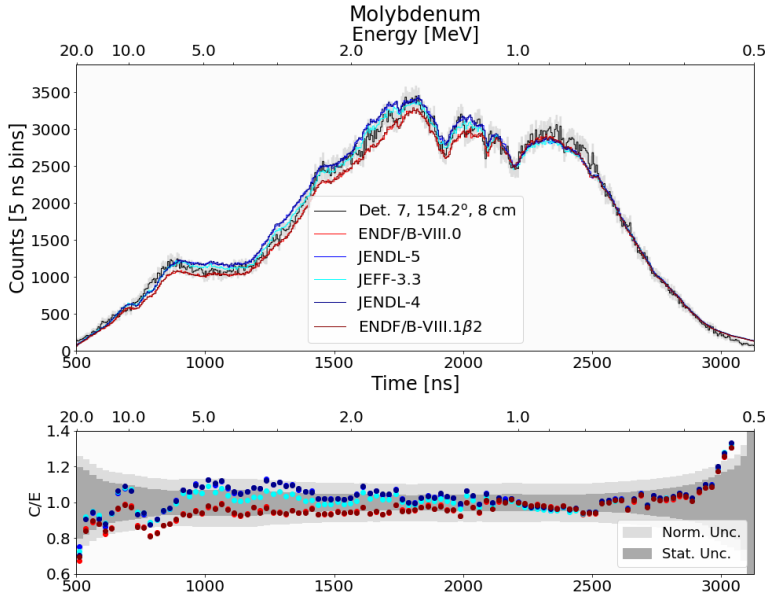
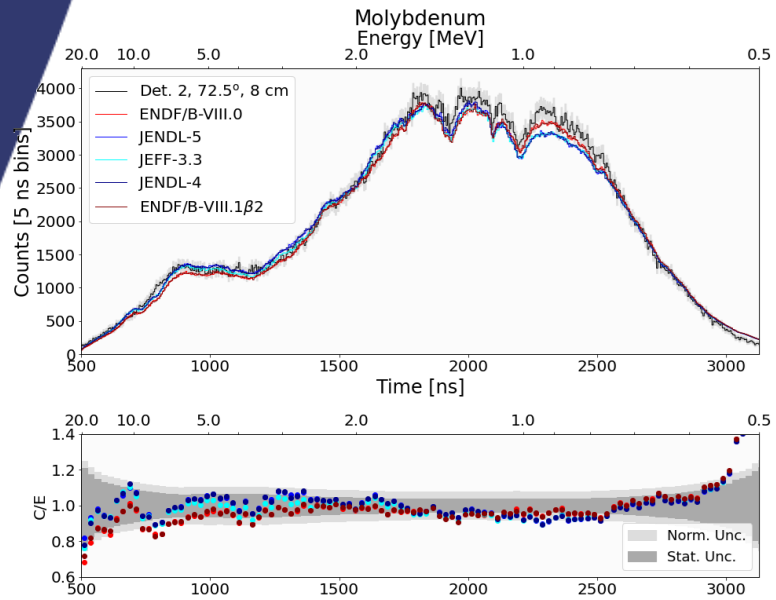
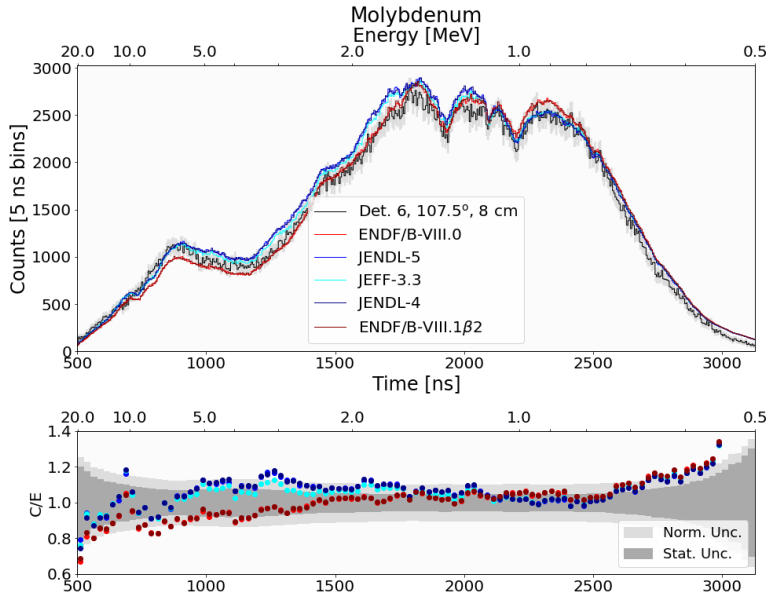
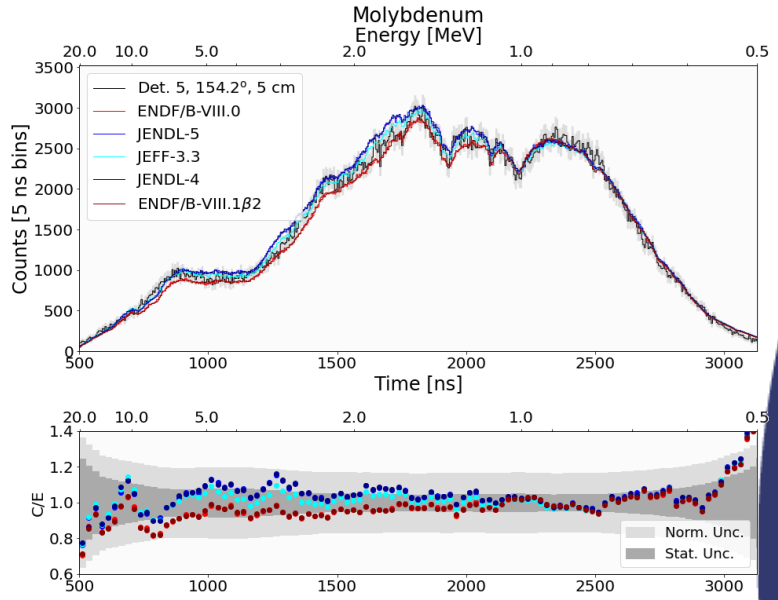
Molybdenum

- Two molybdenum samples, 5cm and 8cm, were originally measured in 2008
- Re-analyzed and presented at ND2016*









*Daskalakis et al., "Assessment of beryllium and molybdenum nuclear data files with the RPI neutron scattering system in the energy region from 0.5 to 20 MeV", *EPJ Web Conf.*, vol. 146, pp. 11037, 2017

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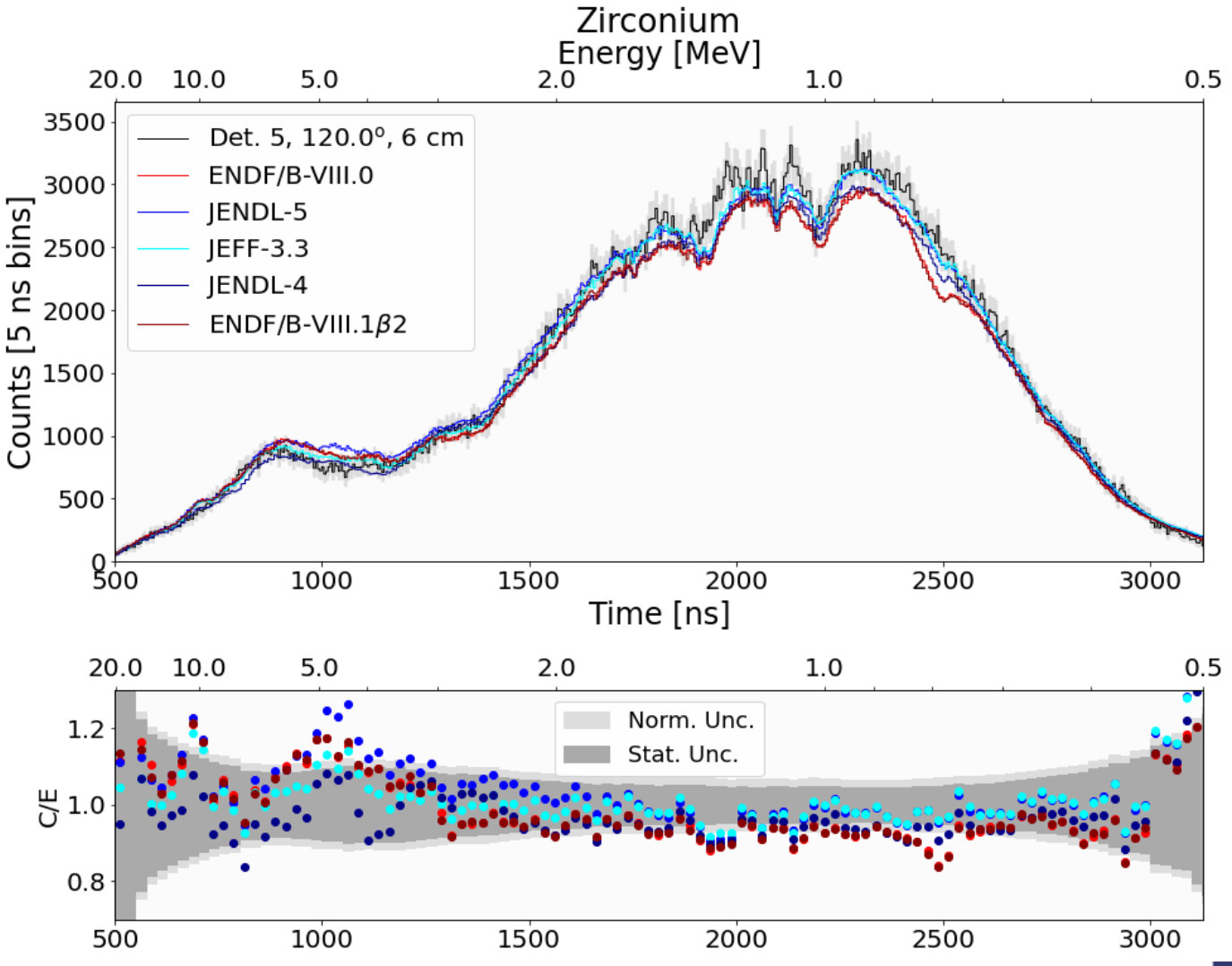
Zirconium

- Two zirconium samples, 6cm and 10cm, were measured in 2009*
- More zirconium results will be presented by G. Siemers



*Barry et al., "Quasi-Differential Neutron Scattering in Zirconium from 0.5 to 20 MeV", *Nuc*

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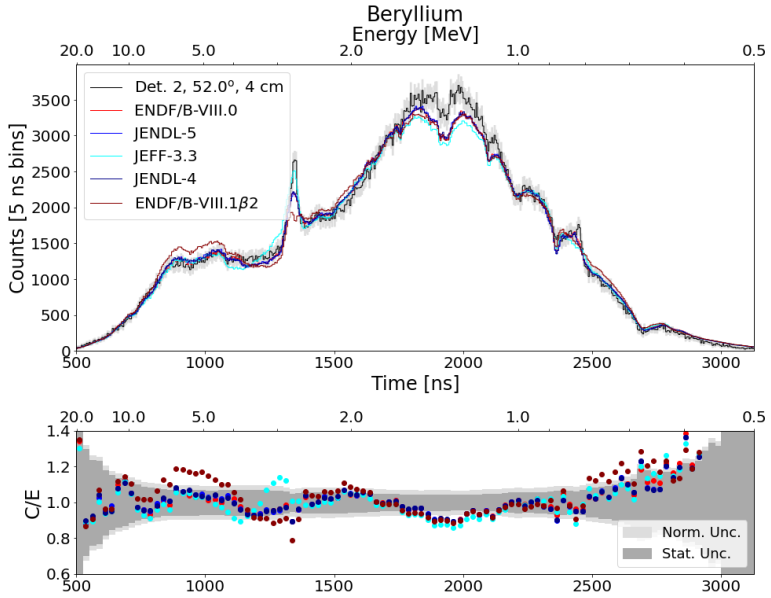
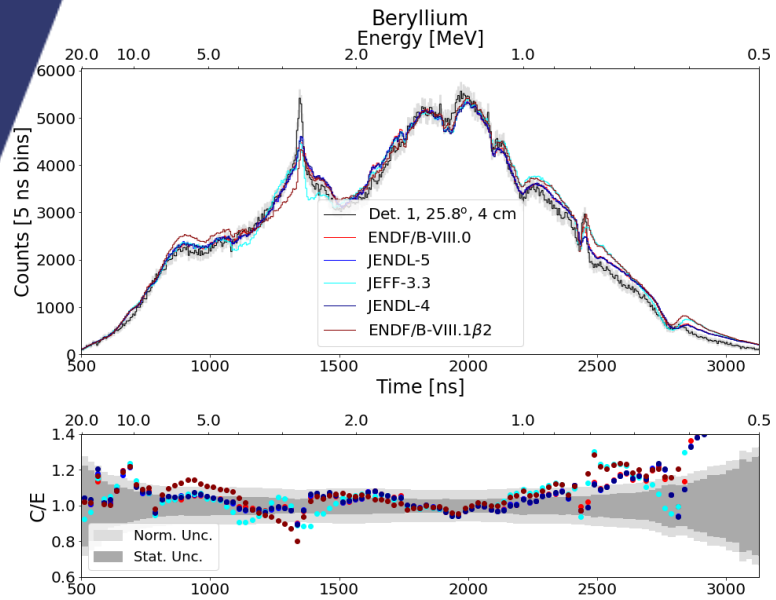
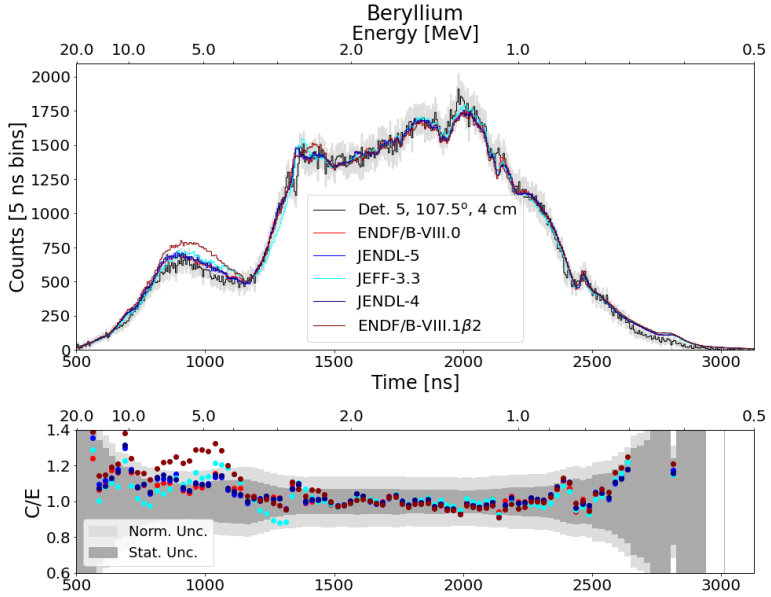
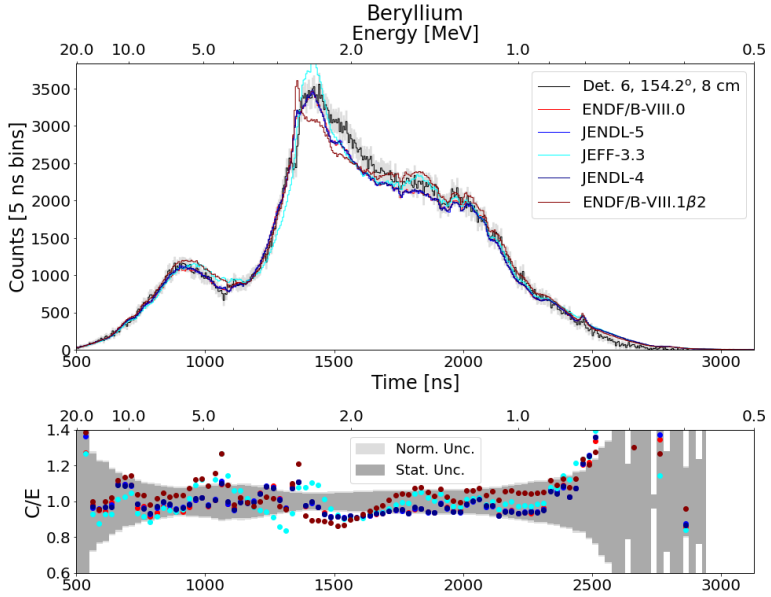
Beryllium

- Two beryllium samples, 4cm and 8cm, were originally measured in 2007
- Evaluations have difficulty between 2 and 3.5 MeV
- More beryllium results will be presented by P. Brain









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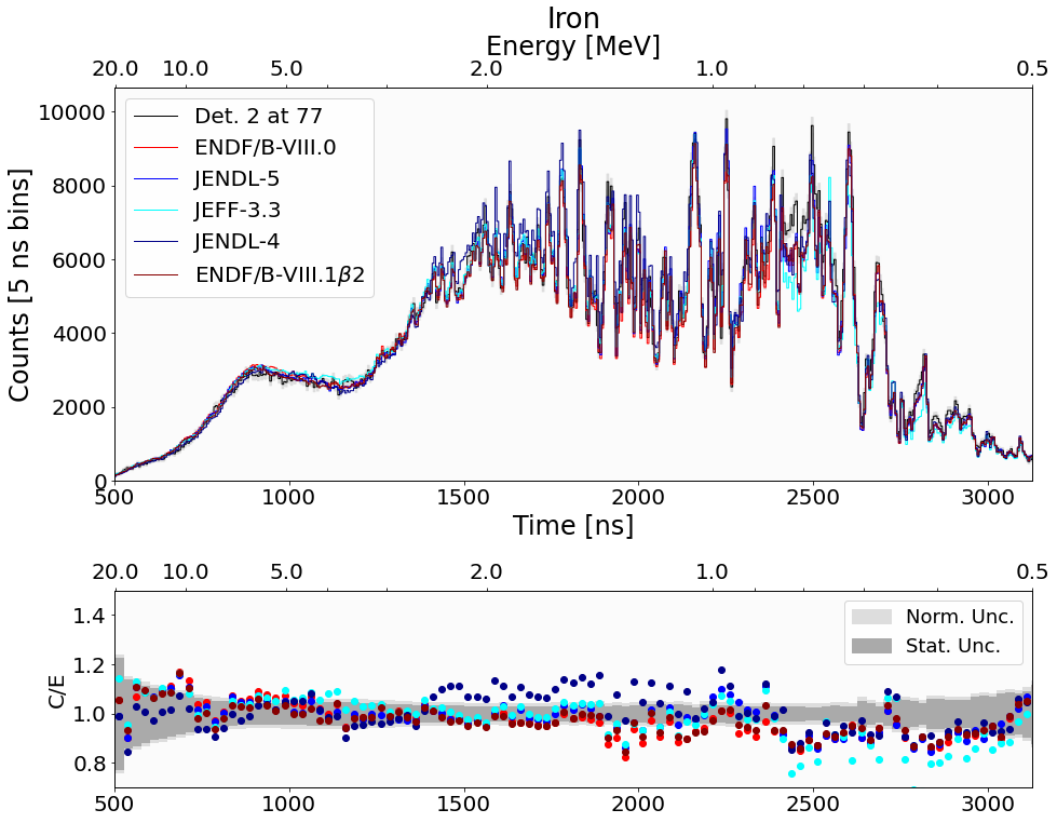
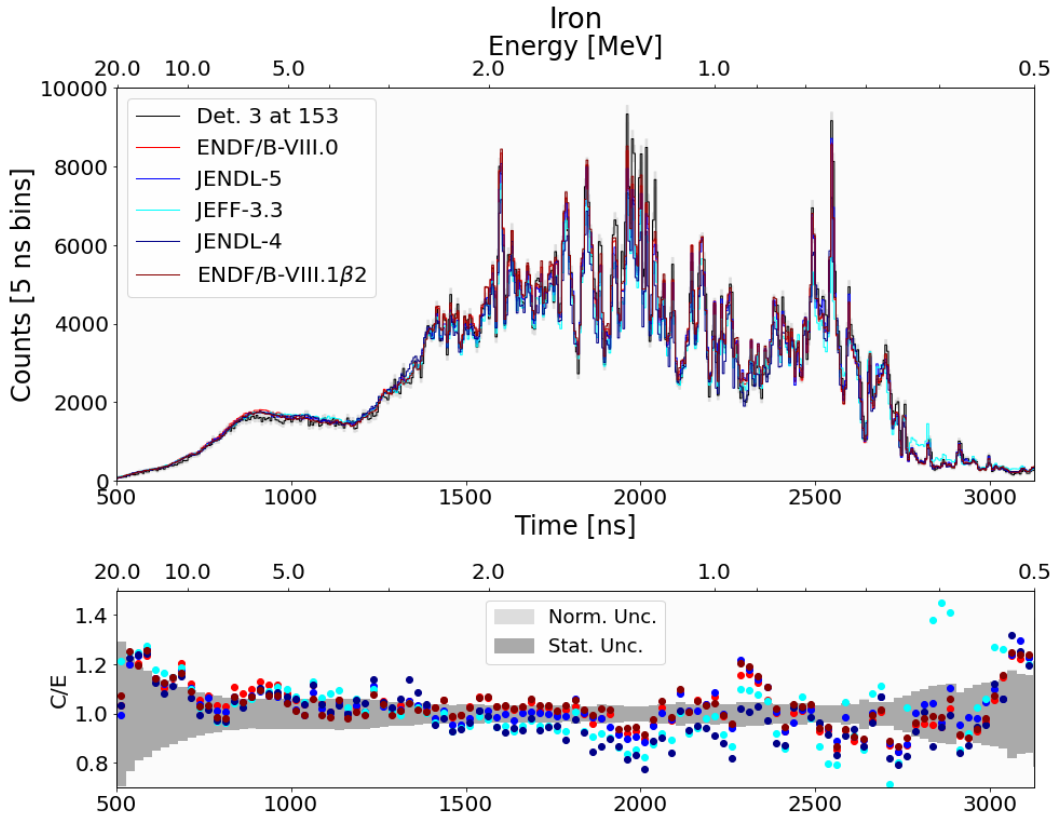
Iron

- Measured in 2012.
  - Total quasi-differential, inelastic-to-elastic ratios, and elastic-only
- Results first presented in Dresden at WINS2014





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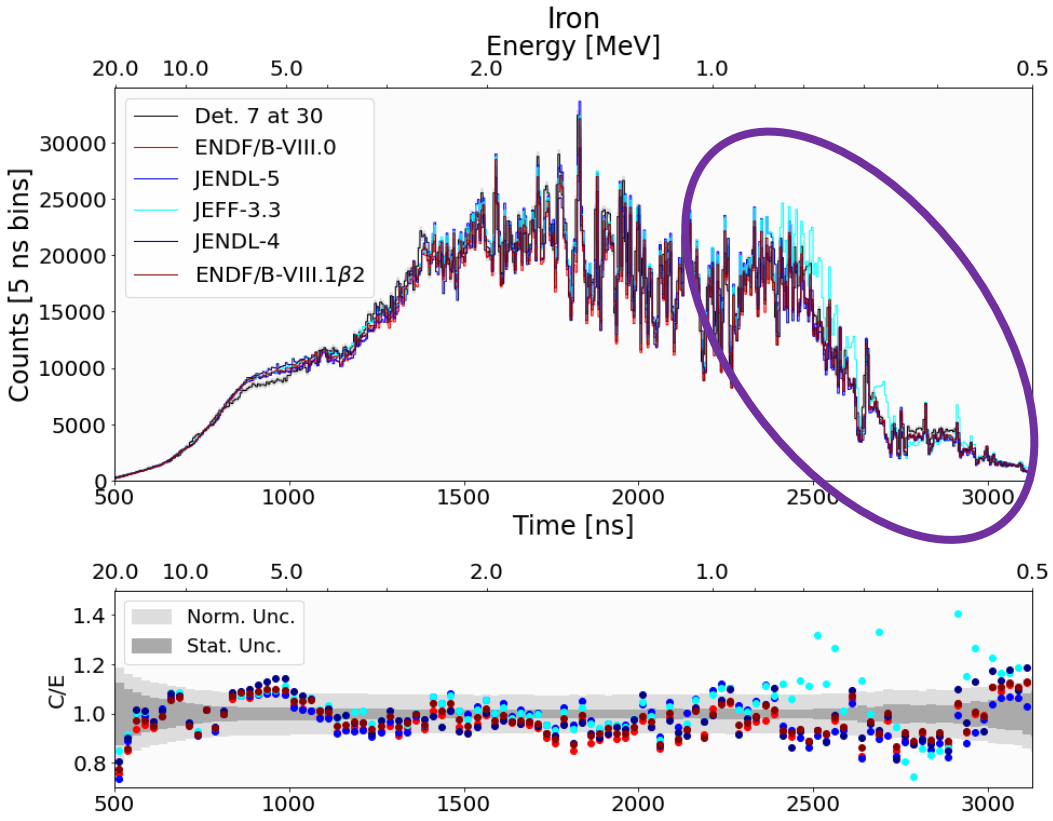
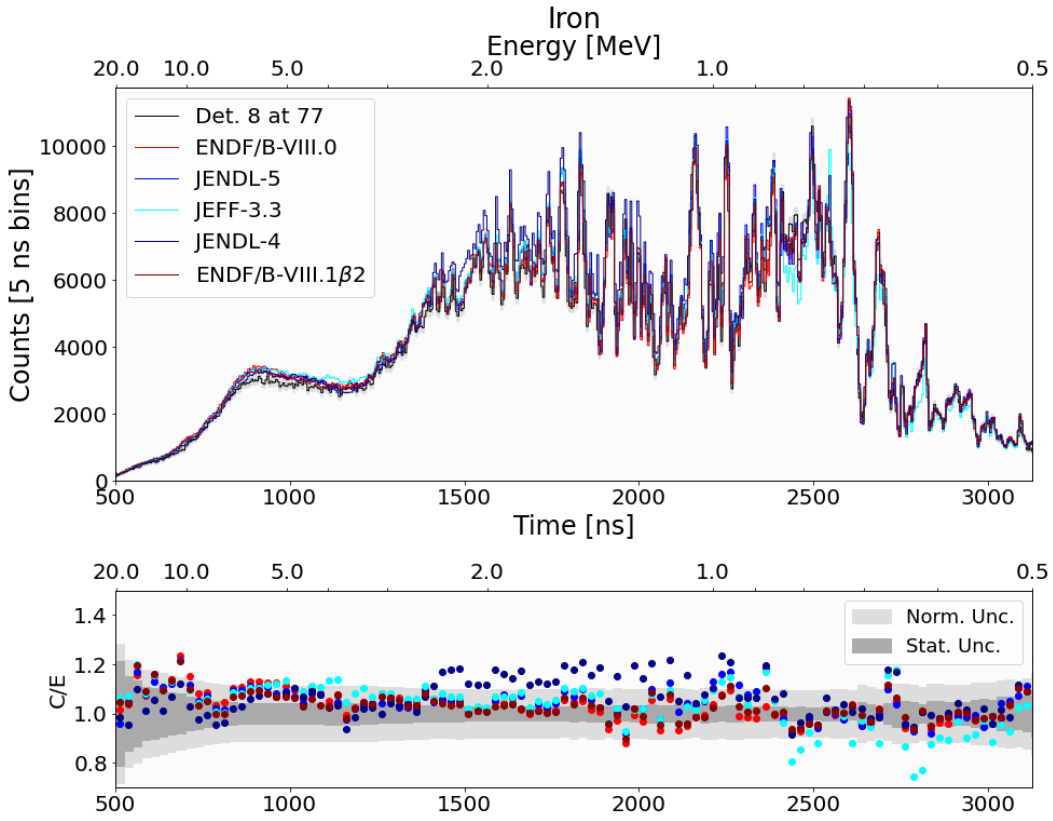
Iron – Continued

- Additional iron data





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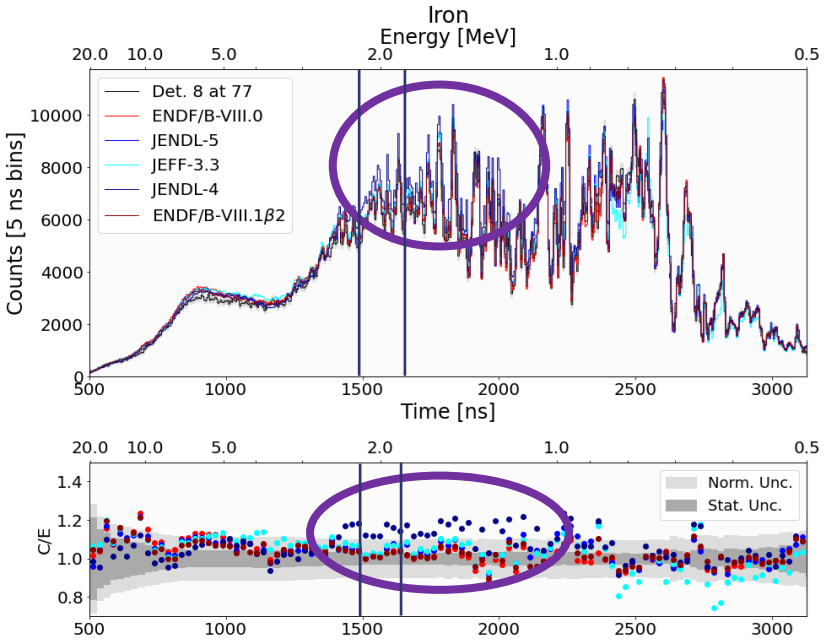
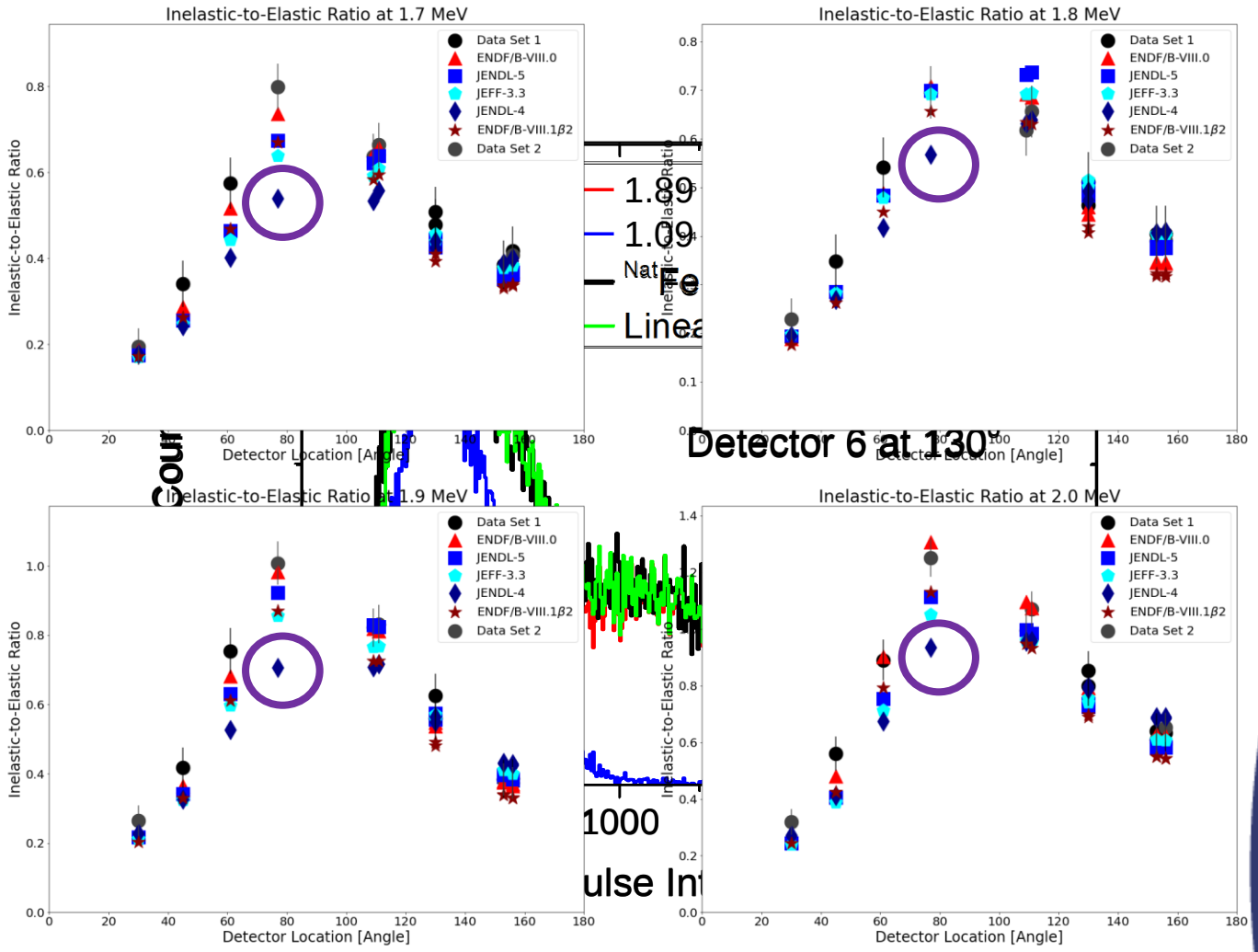
Iron – Continued

- Isolate narrow time bin approximating a monoenergetic neutron beam
- Inelastic-to-elastic ratios





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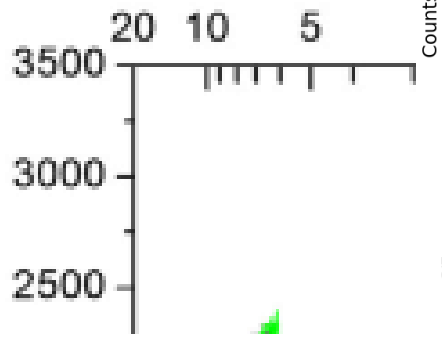
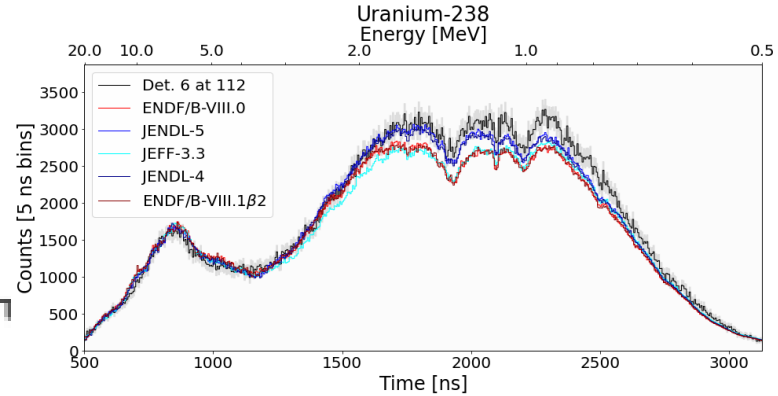
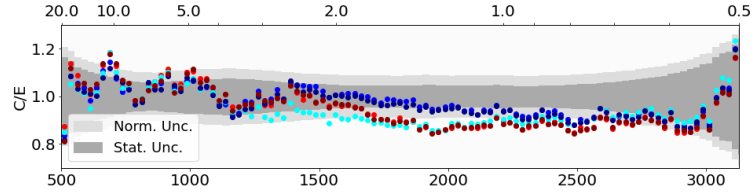
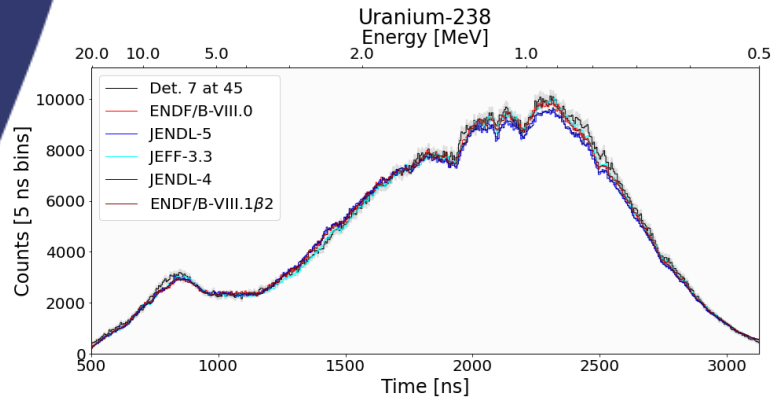
^{238}U – Continued

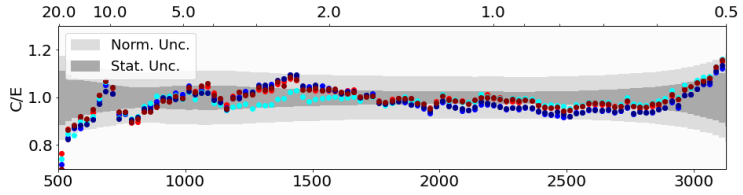
- Measured in 2011 and first presented in Boston at WINS2012*
- Collaboration with IAEA**

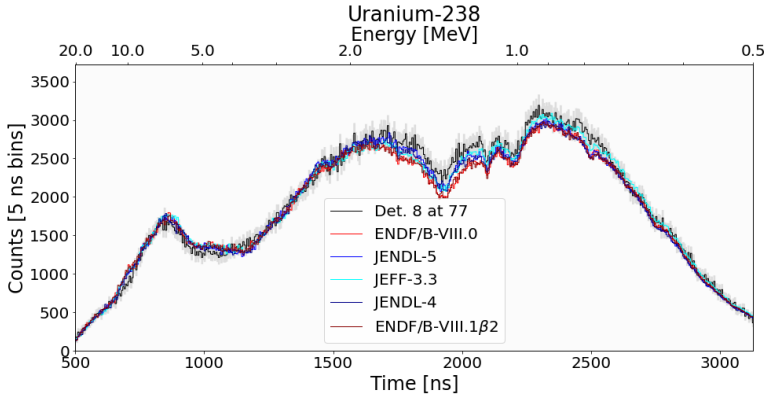


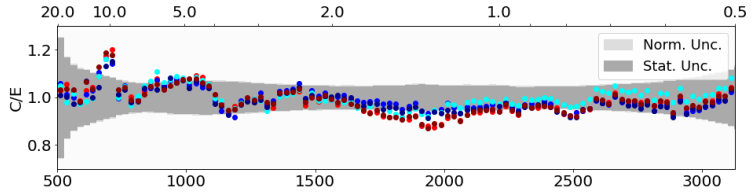


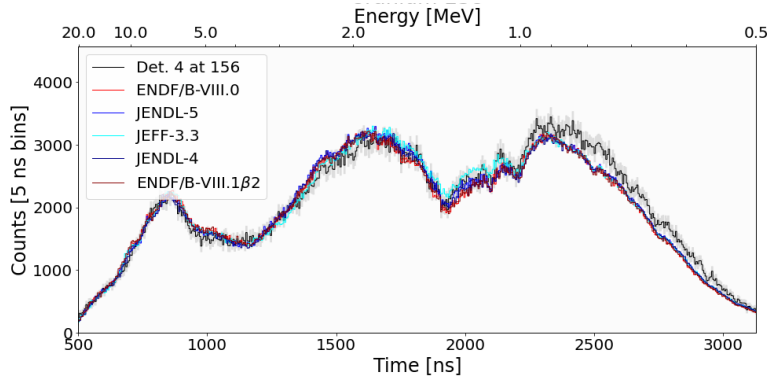


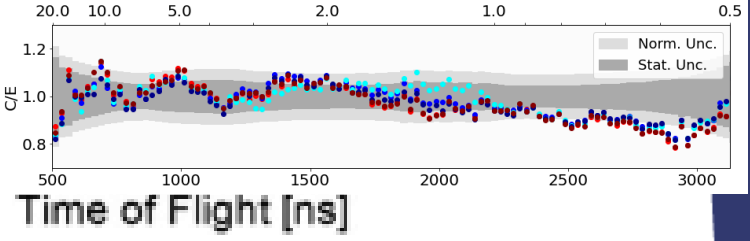












* Daskalakis et al., "Quasi-differential neutron scattering from ^{238}U from 0.5 to 20 MeV", *Ann. Nucl. Energy*, vol. 73, pp. 455-464, 2014

** Capote et al., "IAEA CIELO Evaluation of Neutron-induced Reactions on ^{235}U and ^{238}U Targets", *Nuclear Data Sheets*, vol. 148, pp. 254 - 292, 2018

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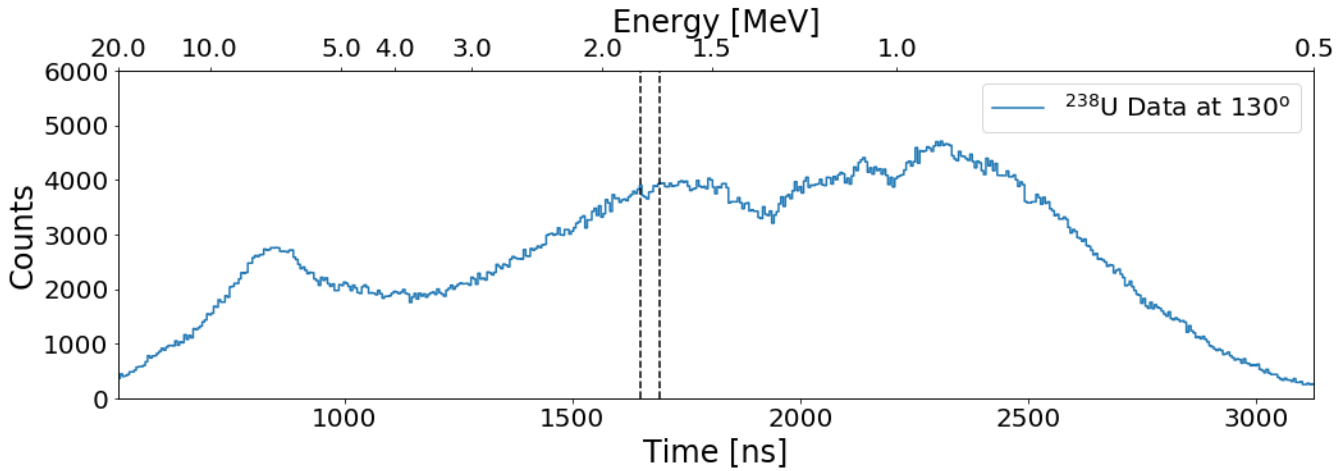
^{238}U

- Fission neutron ratios
- First presented at ND2022*



*Daskalakis et al., "Method to Compare Fission-to-Scattering Ratios using Uranium-238", *EPJ Web of Conf.*, vol. 284, pp. 01016, 2023

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Summary

- Differences observed between ENDF and JEFF/JENDL with Molybdenum
- ENDF/B-VIII.1β2 compares poorly to beryllium data relative to ENDF/B-VIII.0
  - Between 2 and 3.5 MeV
- JENDL4 compares poorly to iron data
  - Inelastic and elastic ratios between 1 and 2 MeV
  - Better agreement observed with JENDL5
- Most evaluations agree favorably with ^{238}U data
  - fission to total method further constrains

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