Design and characterization of a deuterated-xylene spectrometer for the SPARC neutron camera

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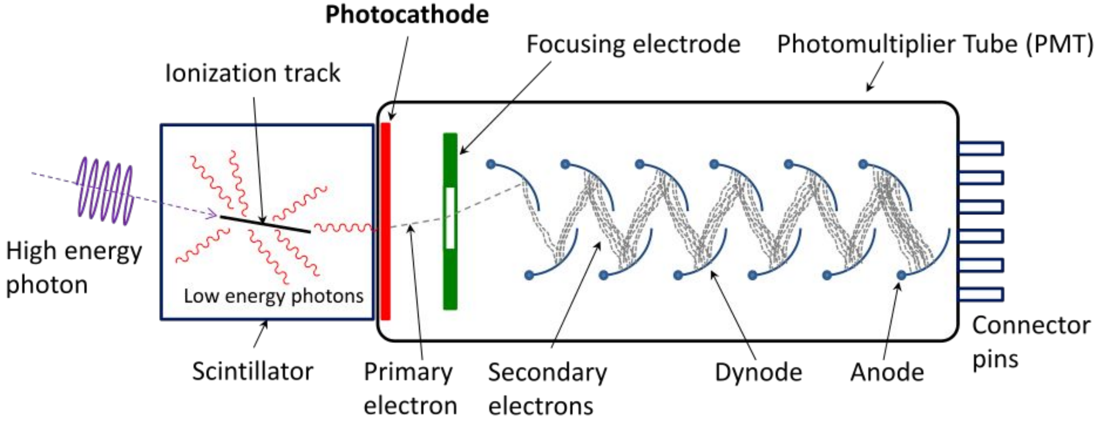
Liquid scintillators have a history of use in neutron cameras

- Have been deployed on JET[1], MAST-U[2], etc.
- High fast neutron efficiency
- Excellent gamma/neutron discrimination
- Relatively low cost
- **Difficult to do spectroscopy**

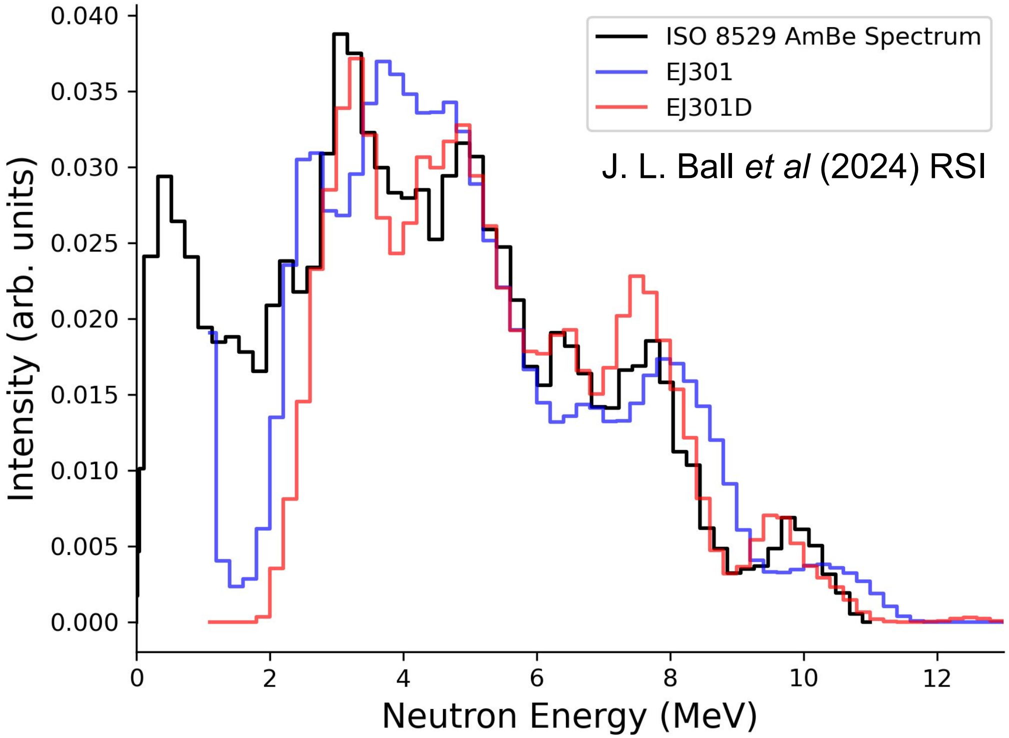


https://commons.wikimedia.org/wiki/File:PhotoMultiplierTubeAndScintillator.svg

[1]J. M. Adams *et al* “The JET neutron profile monitor” (1993) NIM A **329** 277-290
[2]M. Cecconello *et al* “The neutron camera upgrade for MAST Upgrade” (2018) RSI **89** 10|110

Deuterated scintillators improve spectrometry performance

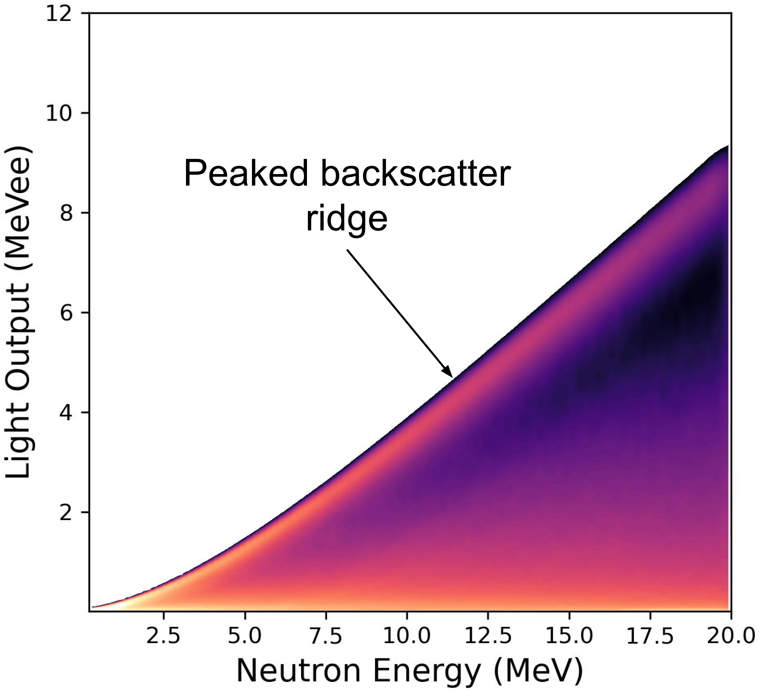
- Energy resolution needed for ion temperature measurements
- Neutron scattering on deuterium is **anisotropic**
- Anisotropy leads to better neutron energy to pulse height coupling, improving spectroscopic analysis[1,2]



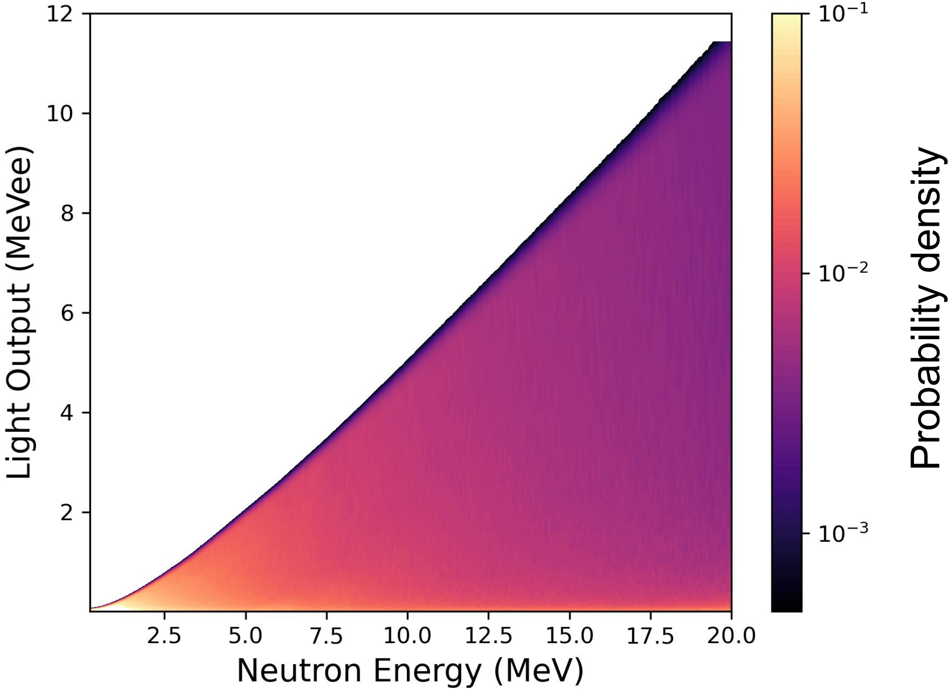
[1]C. C. Lawrence *et al* (2013) NIM A **729** 924-929
[2]J. L. Ball *et al* (2024) RSI **95** 123514

Deuterated scintillators improve spectrometry performance

Deuterated xylene



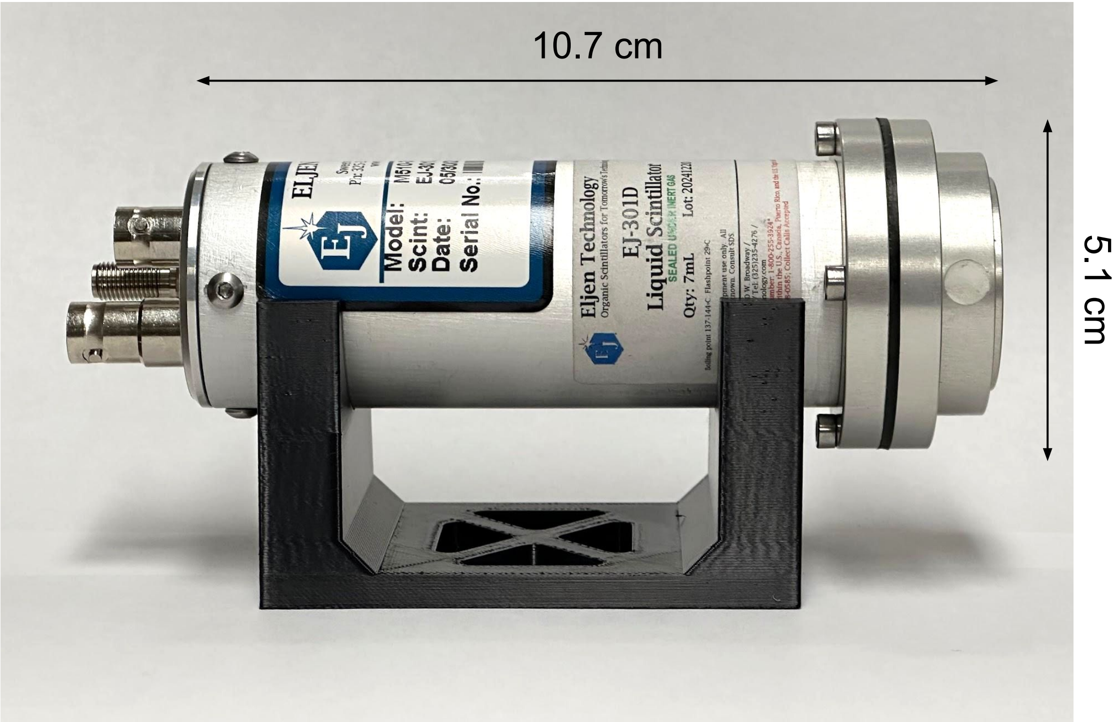
Protiated xylene



Figures reproduced from J. L. Ball *et al* (2024) RSI **95** 123514

A deuterated-xylene spectrometer is planned for SPARC

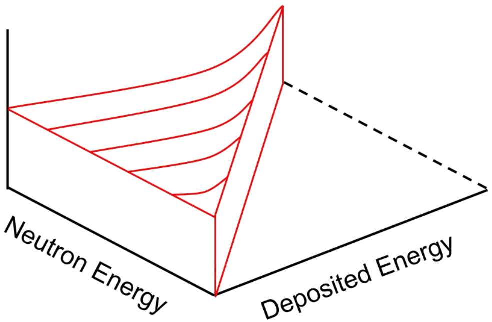
- Prototype procured from Eljen Technology
- 1 cm x 3 cm cylindrical active volume
- 25 mm ∅ Hamamatsu R1924A PMT
- Rear fiber optic port for gain monitoring
- Complementing sCVD diamond, focused on DD ion temp measurement

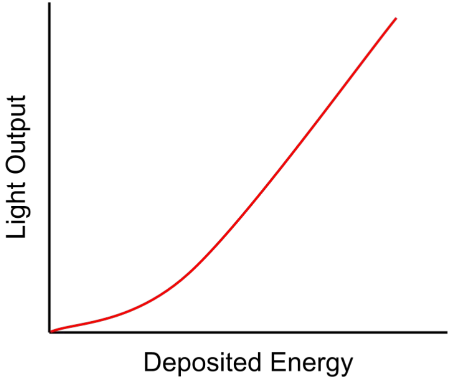


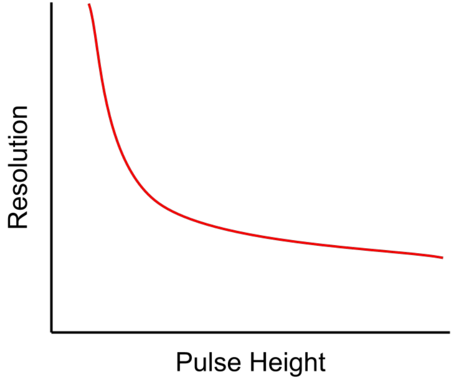
Good spectroscopy relies on knowledge of response matrix

- Taking a “semi-empirical” approach to response matrix generation, combining simulation and experimental characterization

Geant4[1] simulation of neutron scattering → Experimentally measured light output function[2,3] → Experimentally measured resolution function





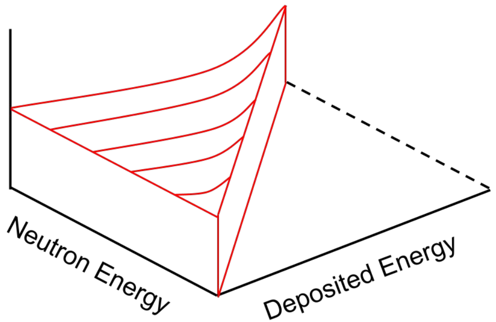


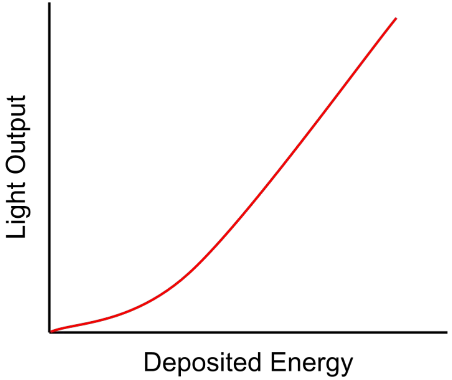
[1]J. Allison *et al* (2016) NIM A **835** 186-225
[2]F. D. Becchetti *et al* (2016) NIM A **820** 112-120
[3]A. Di Fulvio *et al* (2016) IEEE TNS **64** 1825-1832

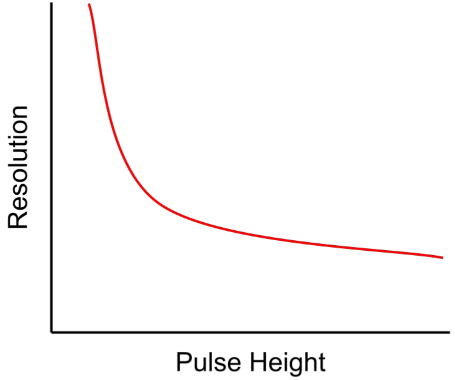
Good spectroscopy relies on knowledge of *intrinsic resolution*

- Taking a "semi-empirical" approach to response matrix generation, combining simulation and experimental characterization

Geant4[1] simulation of neutron scattering → Experimentally measured light output function[2,3] → Experimentally measured resolution function







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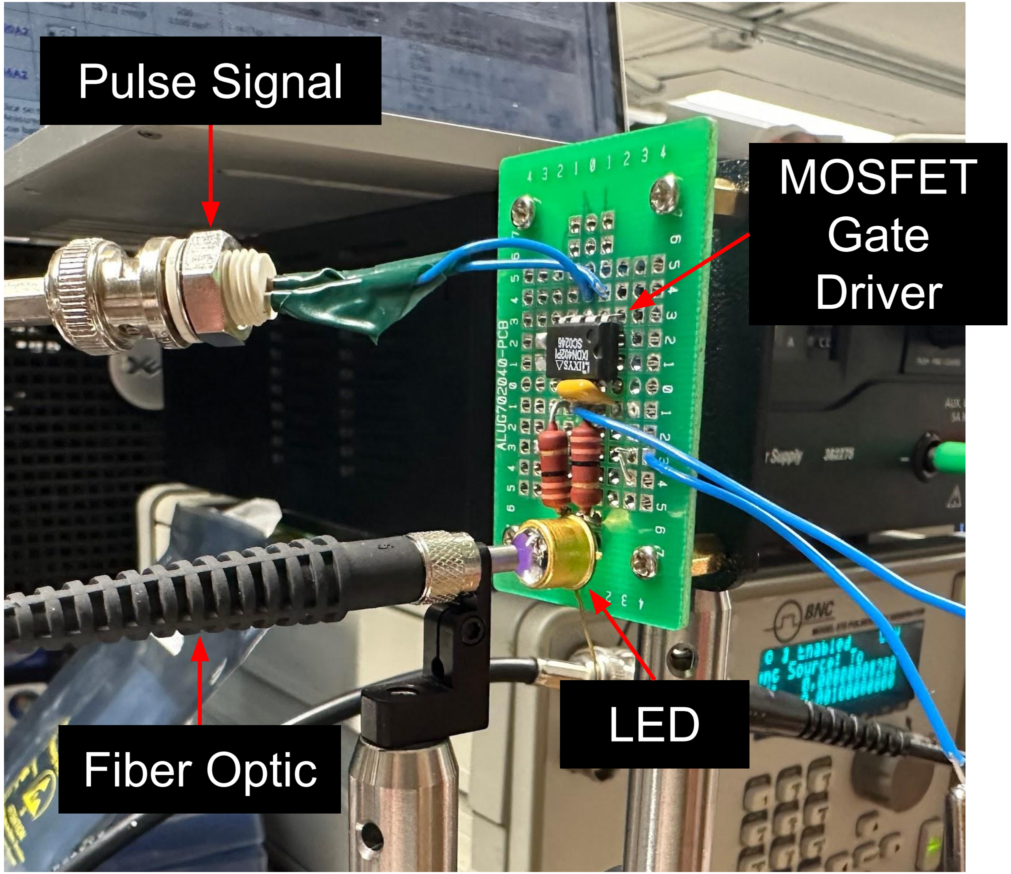
LED pulser could provide *in situ* resolution measurement

- LED pulser injects identical packets of light, simulating events of identical pulse height
- Can be deployed *in situ*, adjusting for changes in response **eliminating the need to remove detectors for re-characterization**
- Excludes scintillation physics, which may limit accuracy

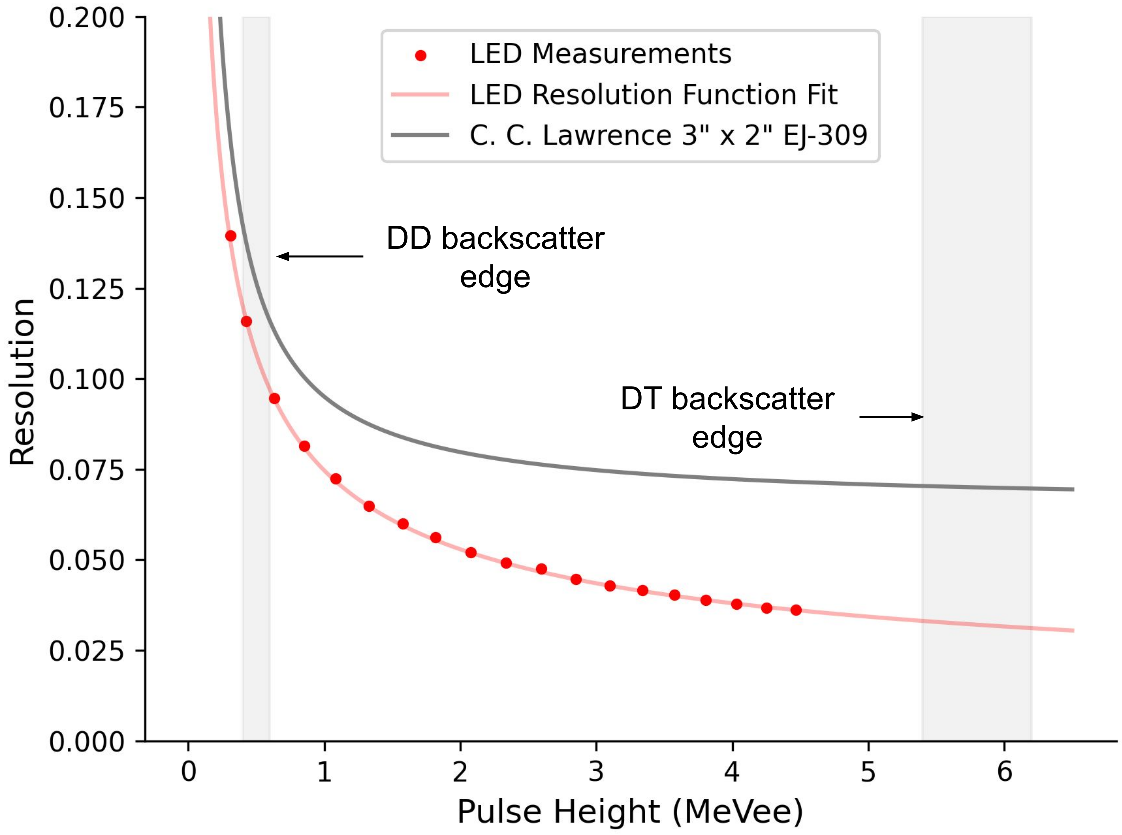


LED resolution measurement looks good for DD ion temp

$\Delta L/L = (\alpha^2 + \beta^2/L + \gamma^2/L^2)^{1/2}$

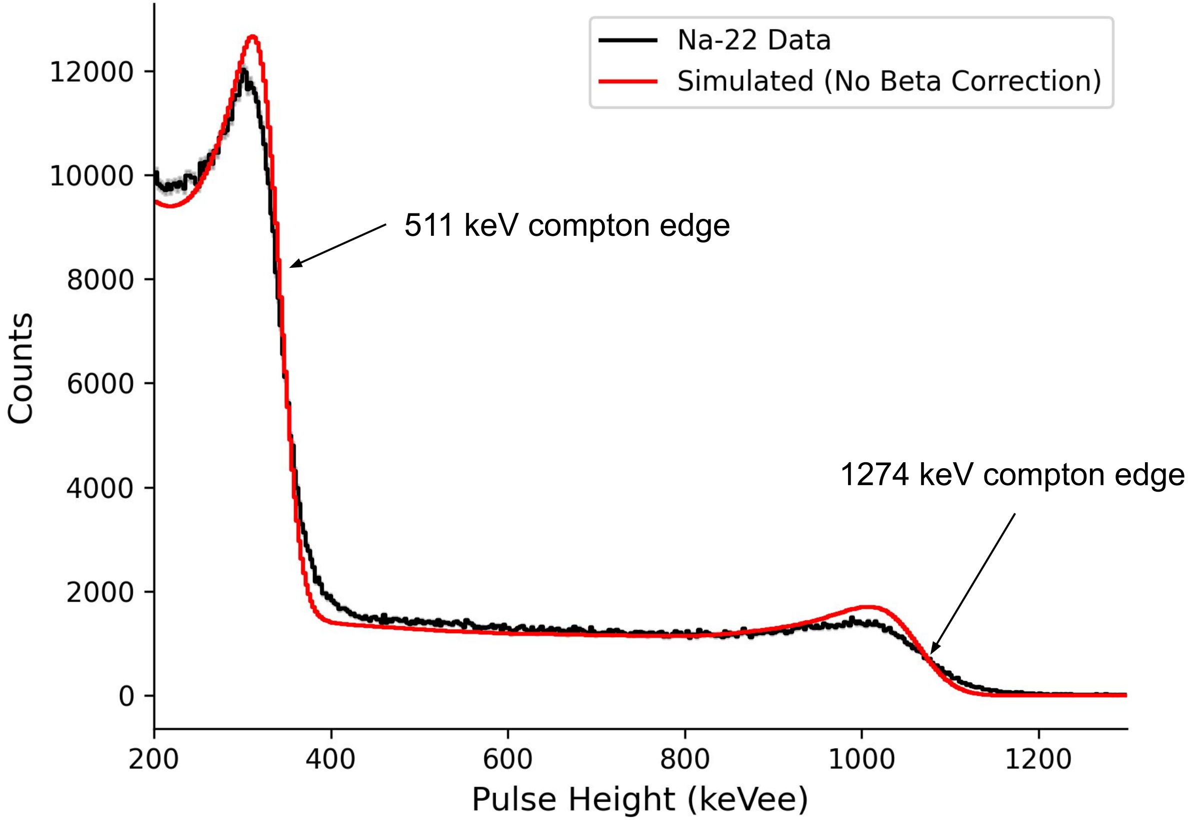
- ~30,000 pulses injected, fit with gaussian to get FWHM/mean

α	0.0106
β	0.0727
γ	0.0135



Na-22 shows LED resolution overestimates performance

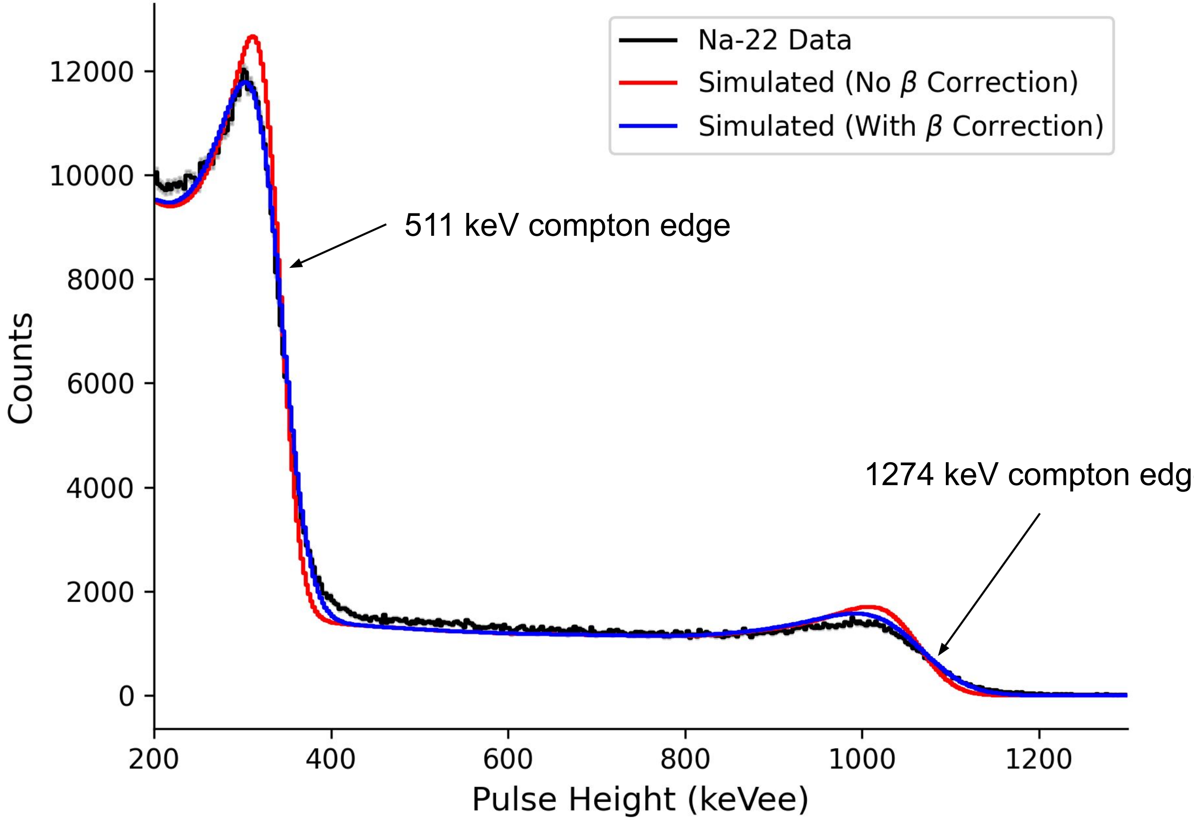
- Geant4 simulation of Na-22 source convolved with LED resolution function then fit to experiment
- Slope of both Compton edges is too steep, indicating incorrect resolution function



Fit can be improved by allowing β parameter to evolve

$\Delta L/L = (\alpha^2 + \beta^2/L + \gamma^2/L^2)^{1/2}$

- Nonlinear least squares technique used
- Compton edge slopes now show good agreement with experiment
- Bulk errors persist in low gradient regions
- $\beta = 0.0727 \Rightarrow \mathbf{0.102}$



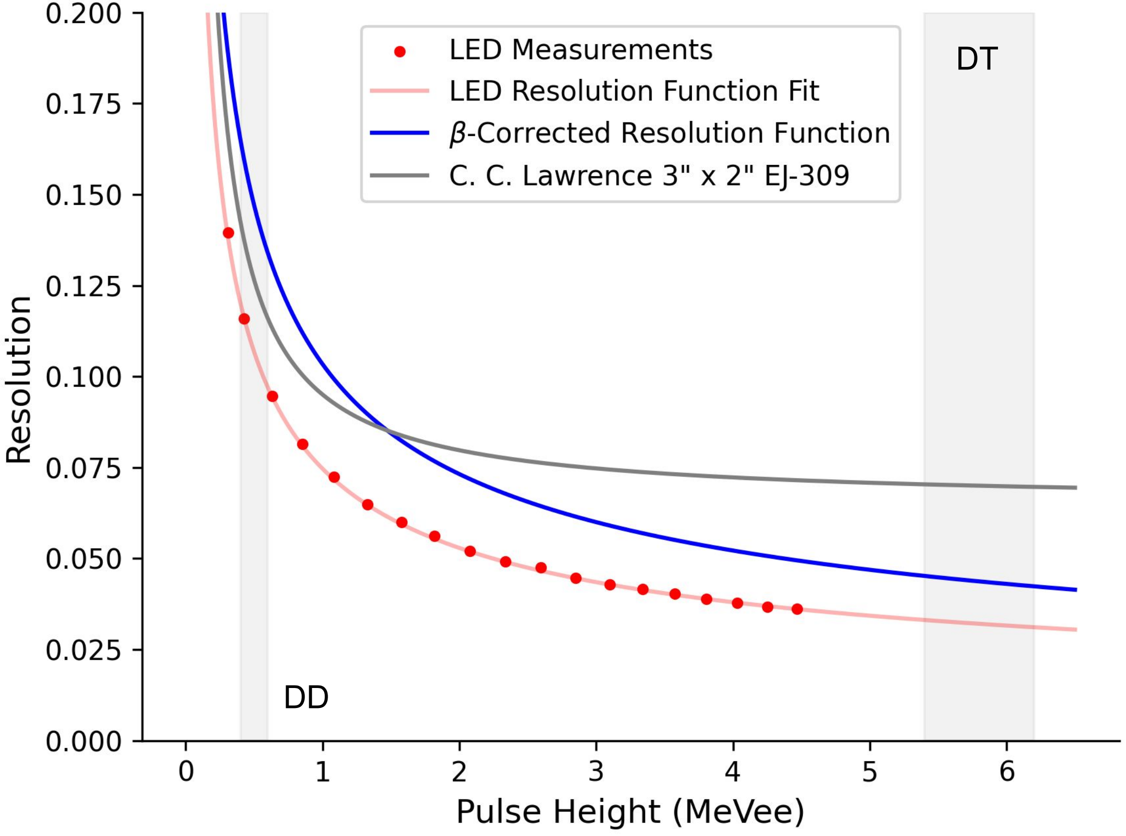
β-corrected resolution less optimistic for DD performance

SPARC

$$\Delta L/L = (\alpha^2 + \beta^2/L + \gamma^2/L^2)^{½}$$

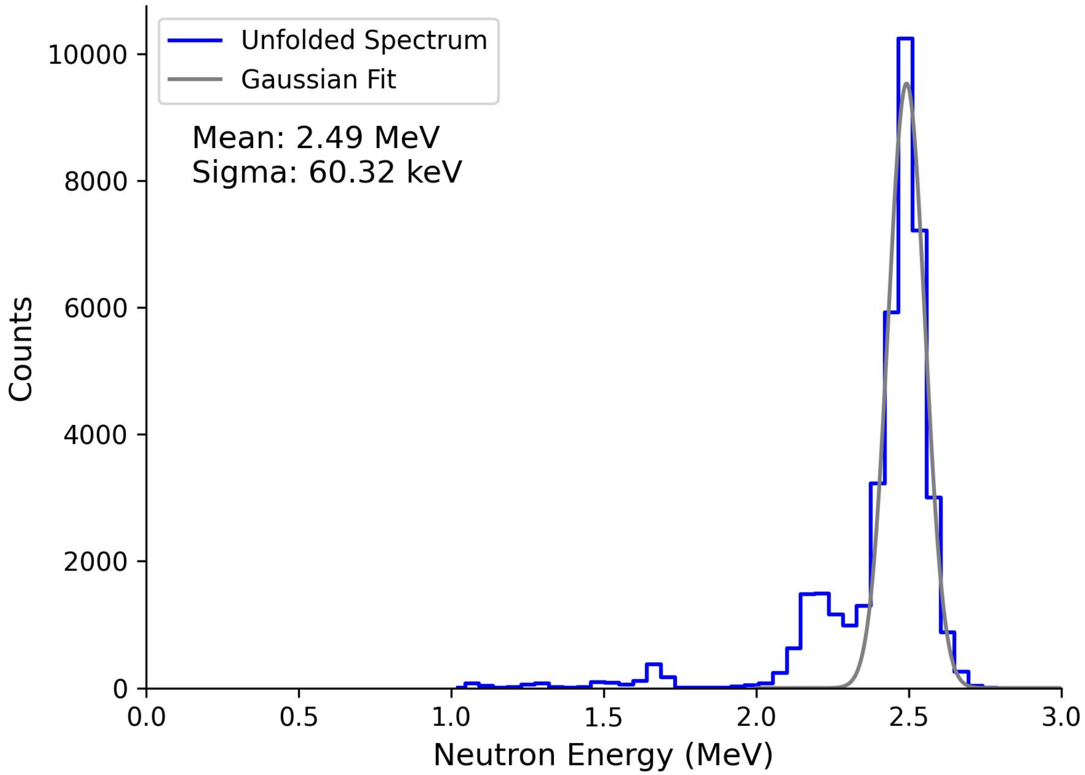
- In DD pulse height range corrected resolution appears worse than 2-in reference

α	0.0106
β	0.0727 ⇒ **0.102**
γ	0.0135



DD unfoldings achieved with 50 keV bin width

- $FWHM_{DD} \approx 82\ sqrt(T_i\ [keV])$[1]
- Gaussian fit to DD peak yields a FWHM of 142 keV
- **This would correspond to a T_i of ~3 keV, ergo this is the absolute minimum T_i that could be measured**
- Unfolded using TREVISO w/ MLEM algorithm, **no smoothing applied**



[1]H. Brysk (1973) *Plasma Physics* **15** 611

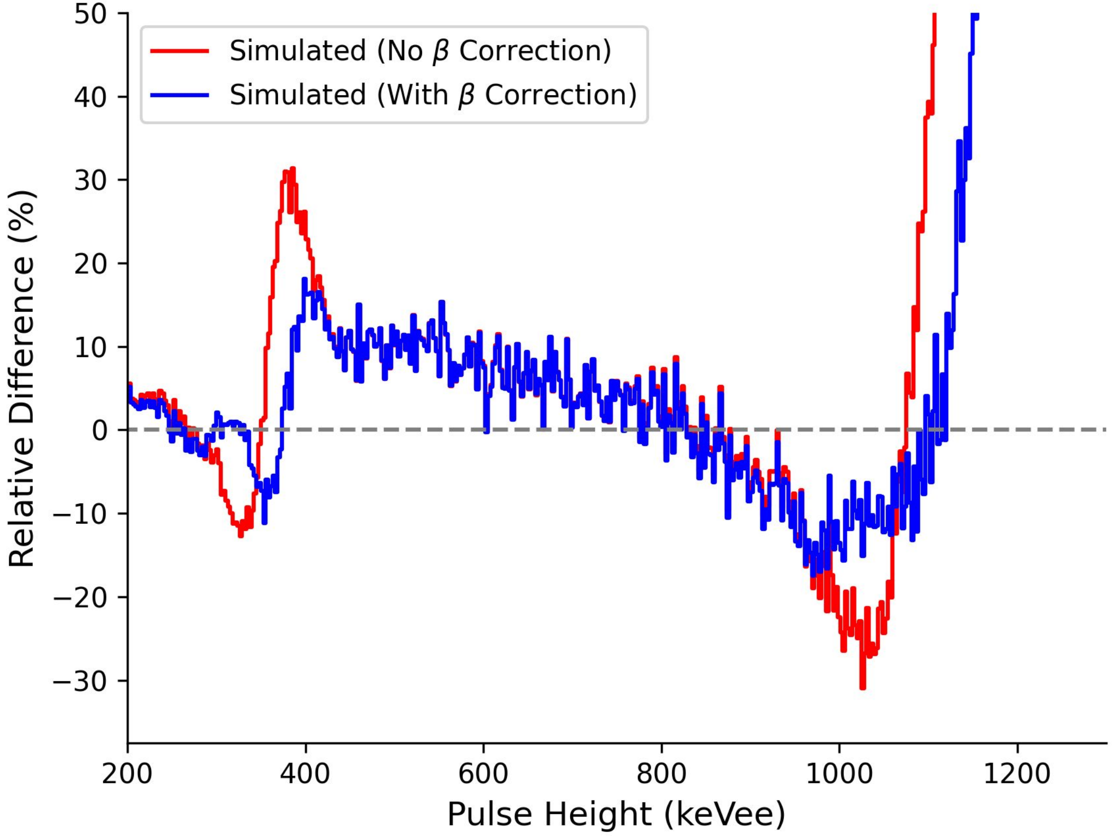
Conclusions

- Modern xylene-based deuterated scintillators are showing strong promise as low-cost high sensitivity DD (and DT) spectrometers
- A compact EJ301D spectrometer is being designed for the SPARC neutron camera to measure DD ion temperature (& low power DT)
- An *in situ* resolution characterization technique is being developed to correct for changes in detector response in time without moving the detector
- **Initial spectrum unfolding results from DD neutron generator show promise, suggest ~3 keV min T_i measureable**
- **Resolution measurements need to be verified using an independent technique (Coincident compton scattering or neutron ToF)**

BACKUP SLIDES

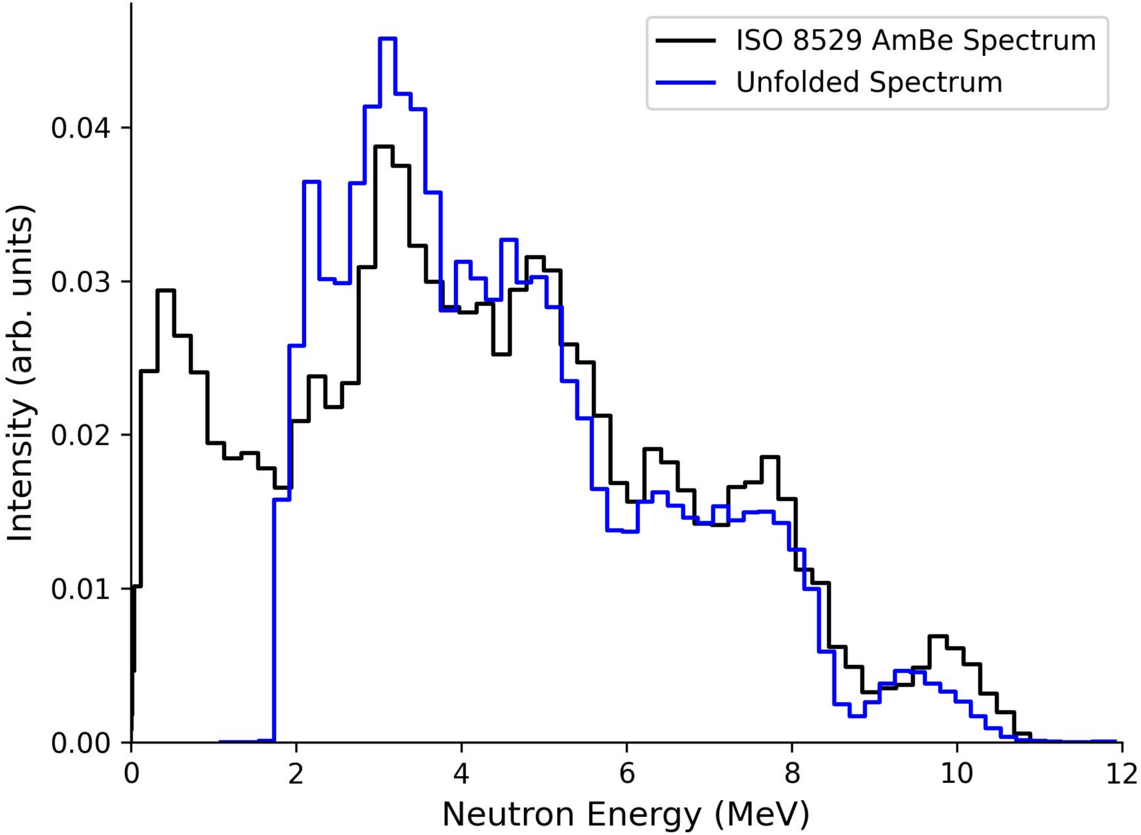
β-corrected fit shows difference < +/- 20% to measurement

SPARC



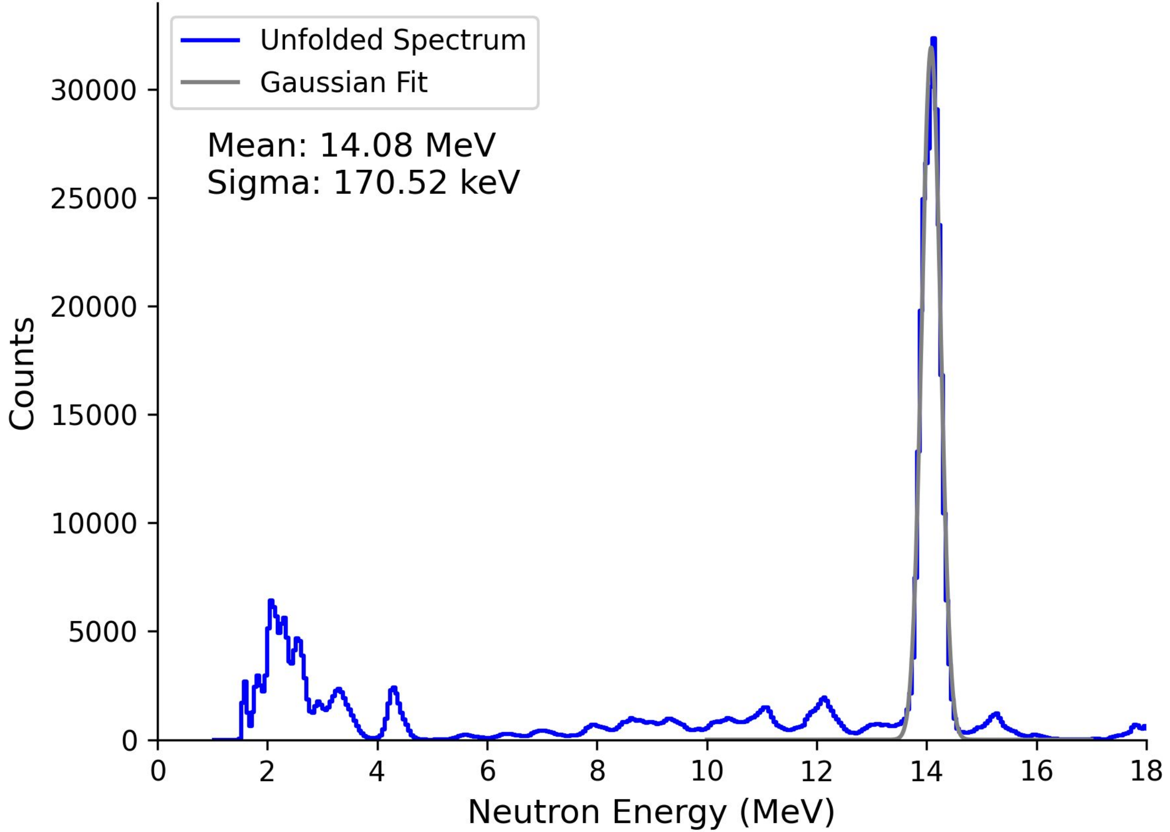
AmBe spectrum unfolding performance is promising

- Response matrix generated using β-corrected resolution function
- Unfolded using TREVISO code & MLEM algorithm
- Agreement is reasonable, not as good as 2-in EJ301D

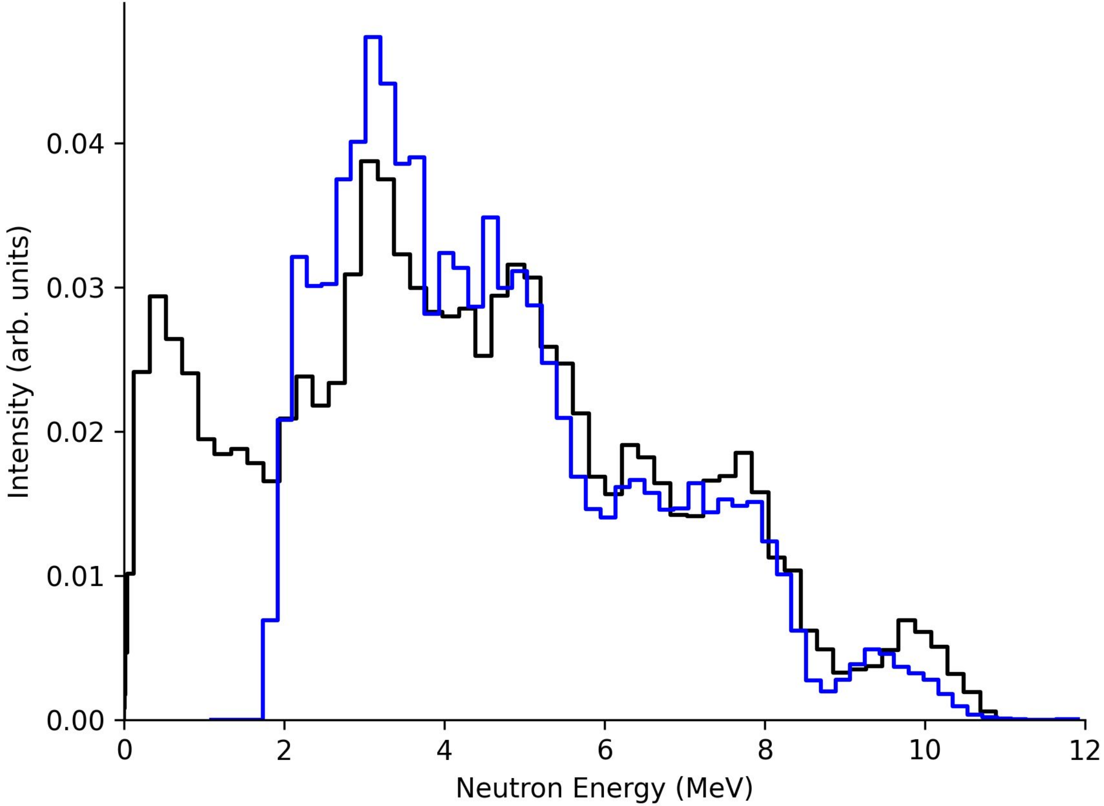


DT unfoldings with 50 keV energy bins

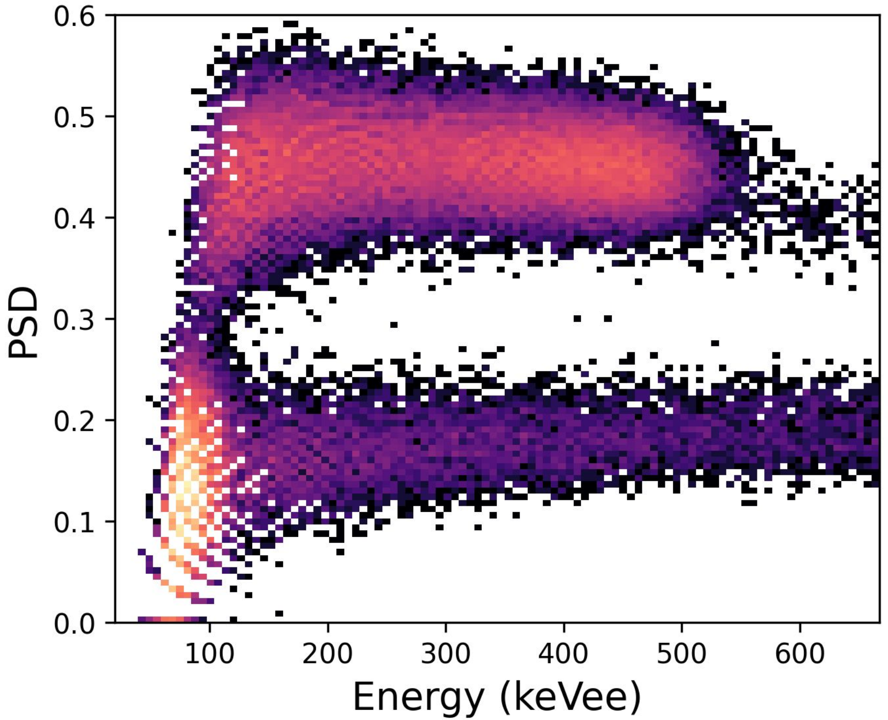
- FWHM of 400 keV corresponds to a 5 keV ion temperature, setting that as the minimum measurable ion temperature
- Smoothing applied

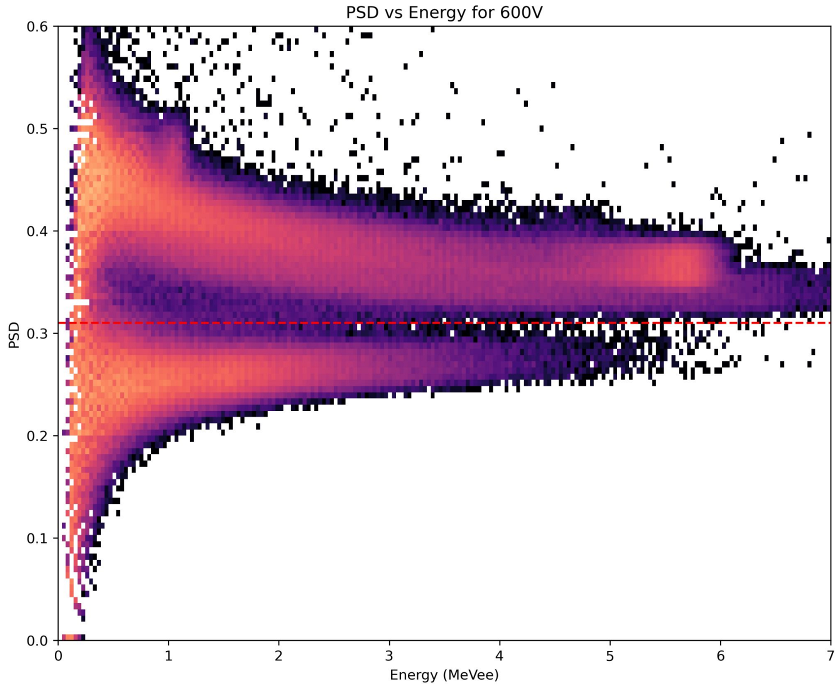


LED-only resolution function resp mat performs worse



Excellent PSD performance demonstrated for DD and DT





SPARC will field a spectrometric poloidal neutron camera