Estimating the Neutron Spectrum from Neutron Time of Flight Data Using the Richardson-Lucy Deconvolution Method

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Essex Bond, Richard Lerche, Dave Munro, Mike Moran

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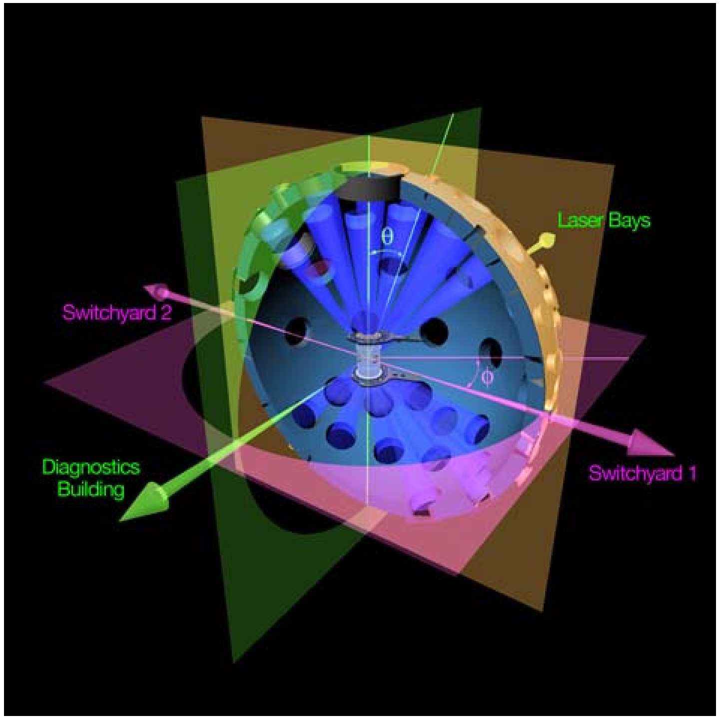
Deterium-Tritium fusion experiments are being conducted at the NIF

- Purpose: further the understanding of the physics underlying the use of inertial confinement fusion for safe, clean energy production

- A cylindrical Hohlraum target is located at the center of a 10 m diameter spherical target chamber

- Target has a laser entrance hole at the top and bottom

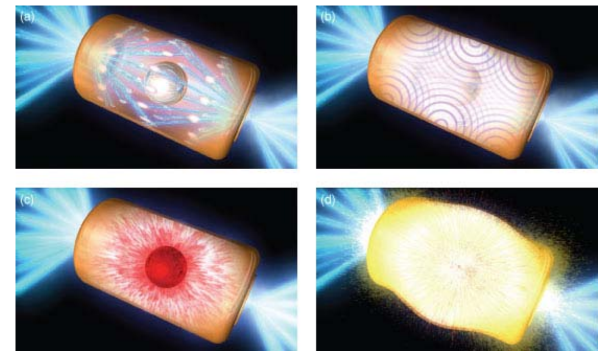
- 192 laser beams radiate and heat the inside walls of the target resulting in X-rays being released



Upper lasers directed at target
http://lasers.llnl.gov

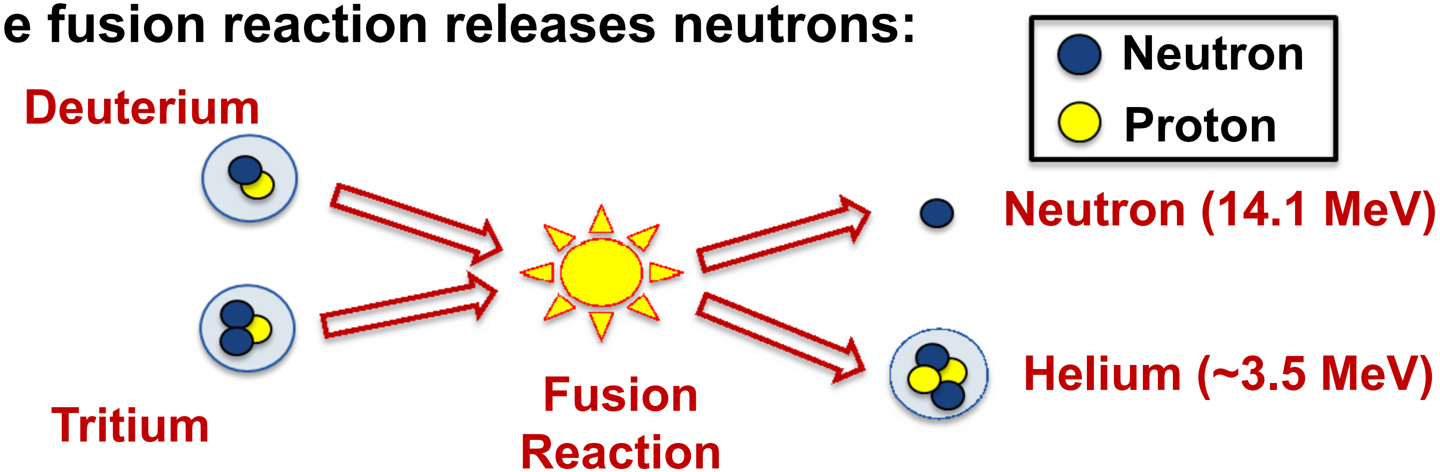
Deuterium-Tritium reaction produces neutrons

- X-rays heat a cryogenically-cooled capsule (shell) inside the target containing Deuterium and Tritium



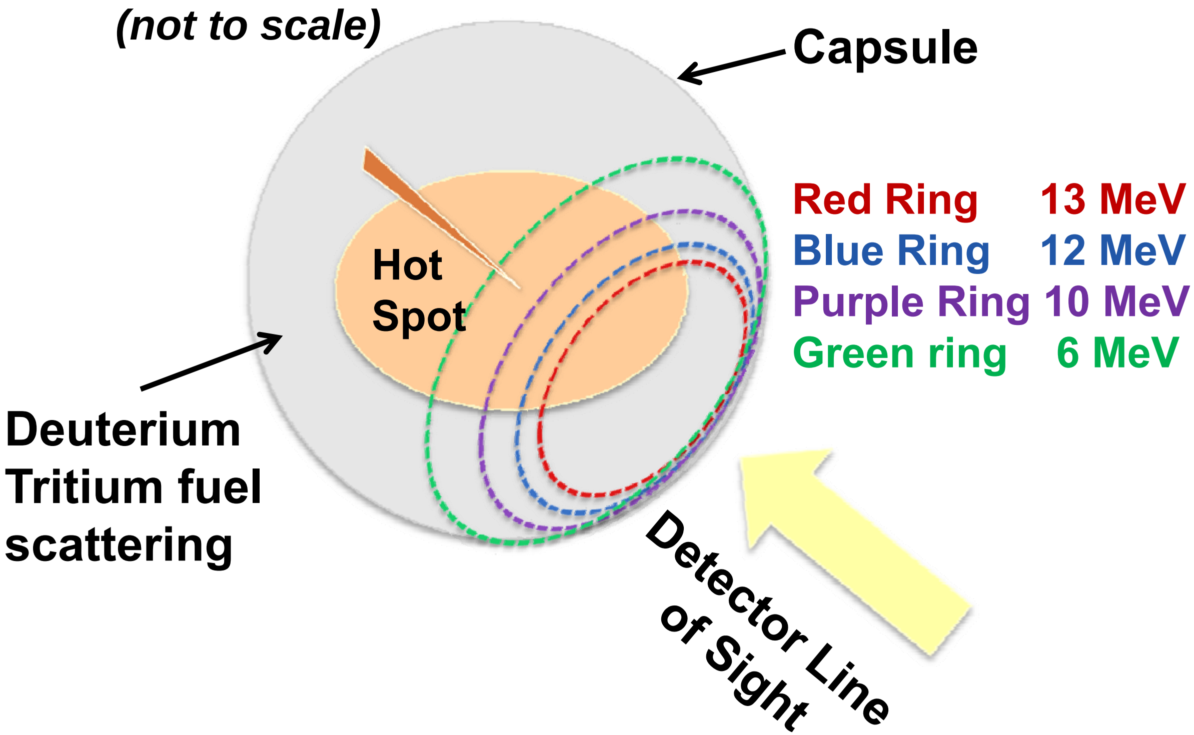
- Capsule compresses, implodes, and fuses

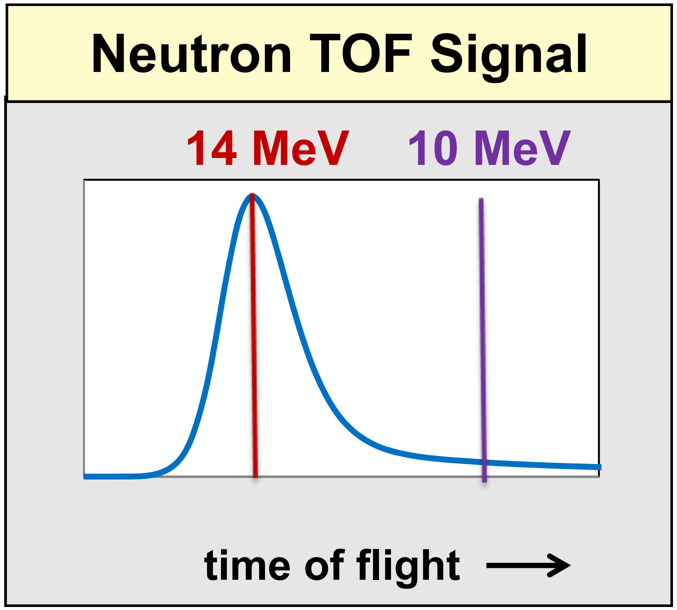
- The fusion reaction releases neutrons:



Note: 1 MeV = 1.602e-13 Joules. Characteristic of energy changes in nuclear processes

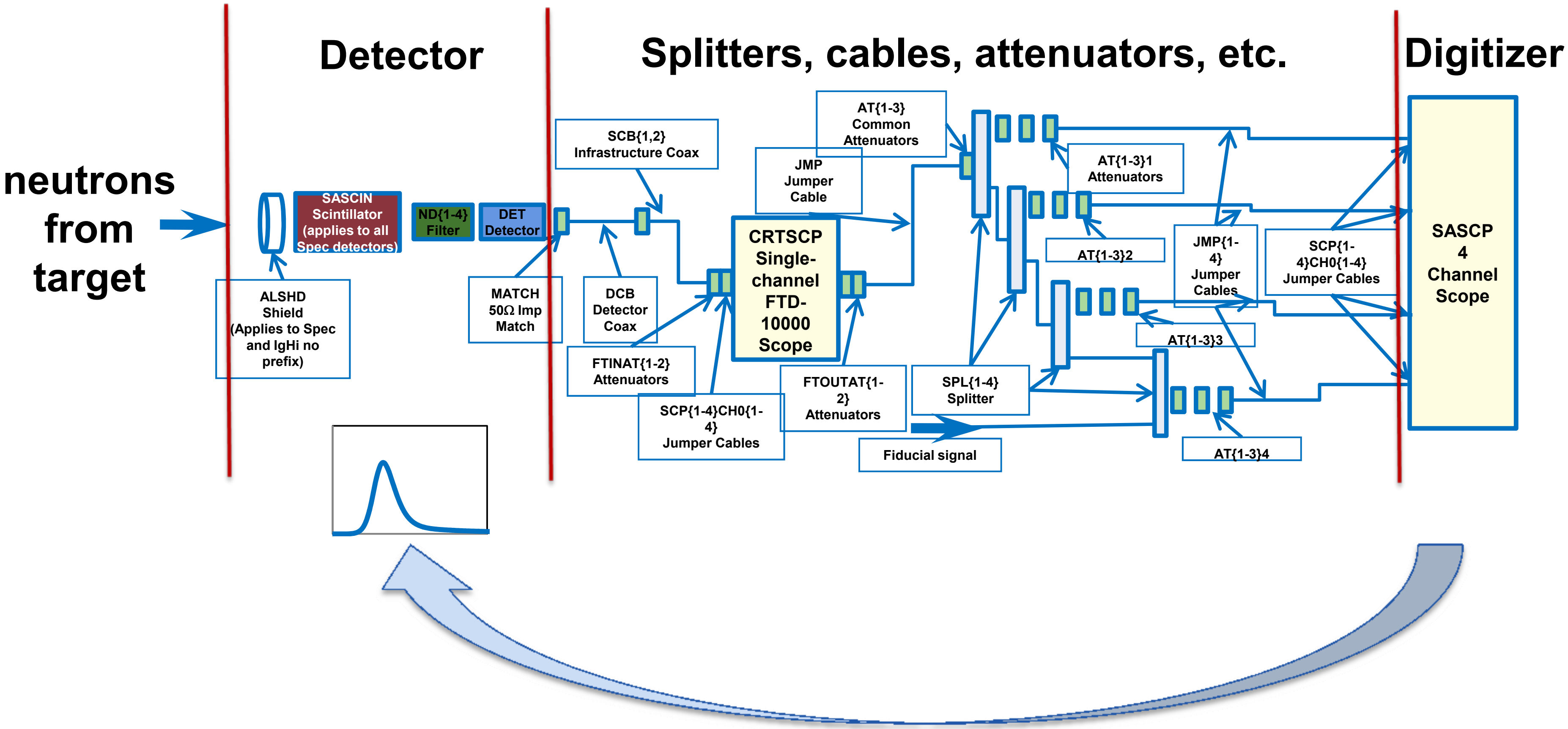
Neutron Time of Flight (nTOF) detector measures prompt 14 MeV neutrons and scattered lower energy neutrons





- *Time-of-flight* technique: The arrival time at a detector corresponds to the energy of the neutron along a line of sight
  - Initial 14 MeV (within red ring) neutrons escape from the reaction and travel to a detector without collisions in the dense fuel
  - Scattered neutrons occur between green and blue rings and have less energy; therefore they arrive later in time

Recorded neutron signal includes the response of the hardware between detector and digitizer



Deconvolution can be used to unfold the impulse response function (IRF) of the hardware components out of the recorded nTOF signal to approximate the signal at the detector

Richardson-Lucy (R-L) Iterative, Time-Domain Deconvolution

- **Forward Convolution Model:**

$$m_k = \sum_{\ell} h_{k-\ell} n_\ell + p_k$$

  — m: measured data
  — h: IRF
  — n: neutron time-of-flight signal
  — p: Gaussian-distributed noise

- **The R-L method determines the *most likely* n[k] given the measured data m[k] and IRF h[k]**
- **Maximum-likelihood solution obtained and is positive for positive output data**
  — Fister, et al., "Deconvolving instrumental and intrinsic broadening in core-shell X-ray spectroscopies", Phys. Rev. B, 2007 (and the many references therein)

Richardson-Lucy Iterative Solution

- **Deconvolved signal: the update of n[k] at the i+1 iteration is**

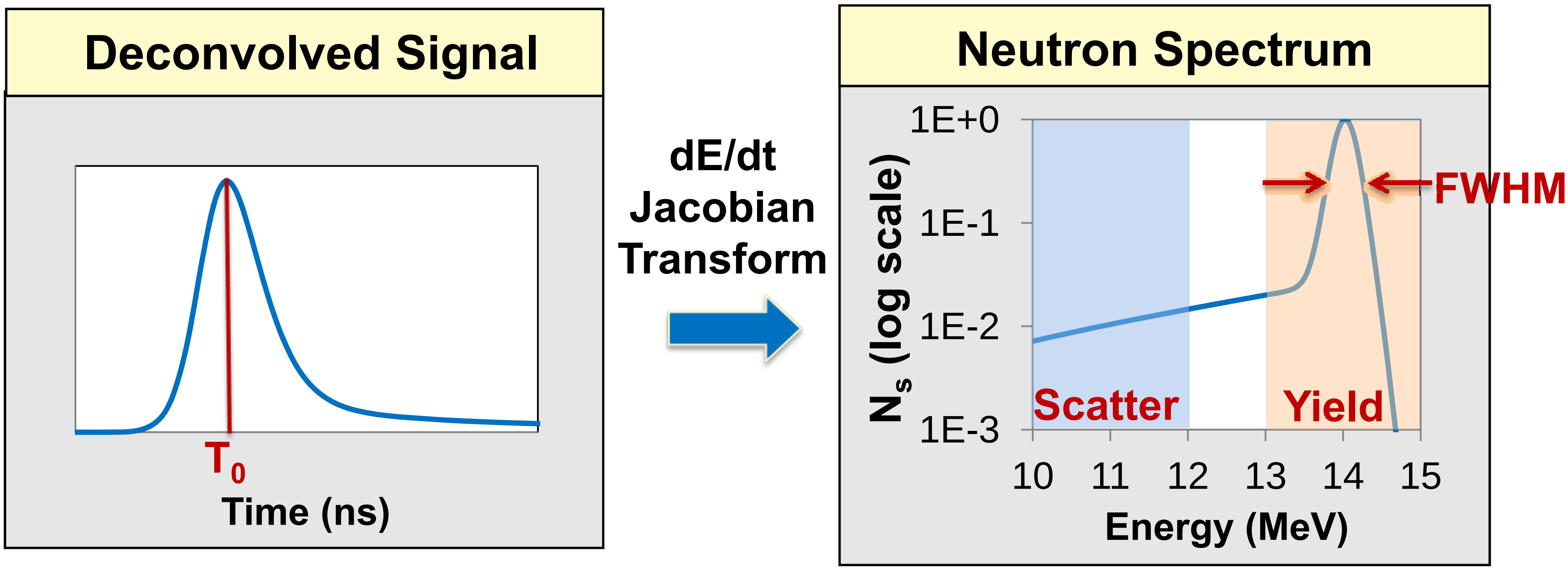
$$n_k^{(i+1)} = n_k^{(i)} \sum_{\ell} \frac{m_\ell}{\hat{m}_\ell^{(i)}} h_{k-\ell} \qquad \text{where} \qquad \hat{m}_\ell^{(i)} = \sum_j h_{\ell-j} n_j^{(i)}$$

  - **The $\hat{m}^{(i)}$ is the convolution of the deconvolved neutron signal with the IRF and is an estimate to the measured data**
  - **The $\hat{m}^{(i)}$ approaches the measured data at each sample with increasing number of iterations**
  - **The ratio in braces approaches unity and n(i+1) ≈ n(i) for a unit integral IRF**

- **Exit criterion:**

$$\frac{\chi^2_{(i)} - \chi^2_{(i-1)}}{\chi^2_{(i-1)}} < \eta \qquad \text{where} \qquad \chi^2_{(i)} = \sum_\ell \frac{\left(m_\ell - \hat{m}_\ell^{(i)}\right)^2}{m_\ell}$$

Key nuclear metrics can be computed using the deconvolved signal

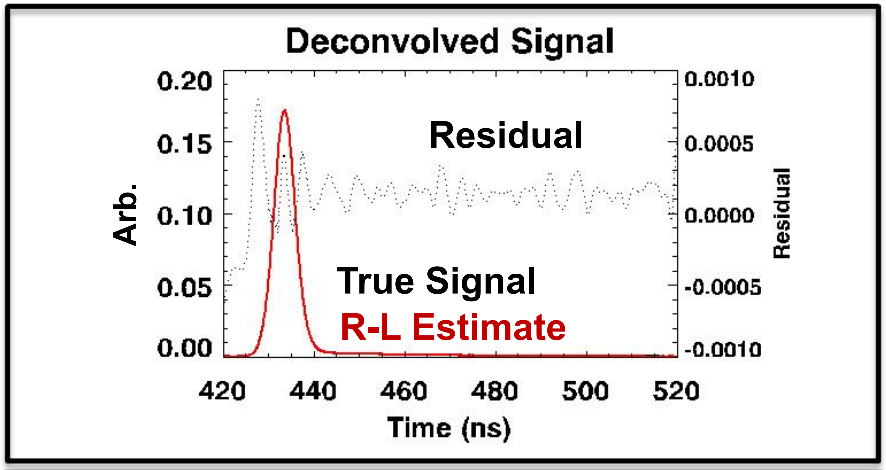


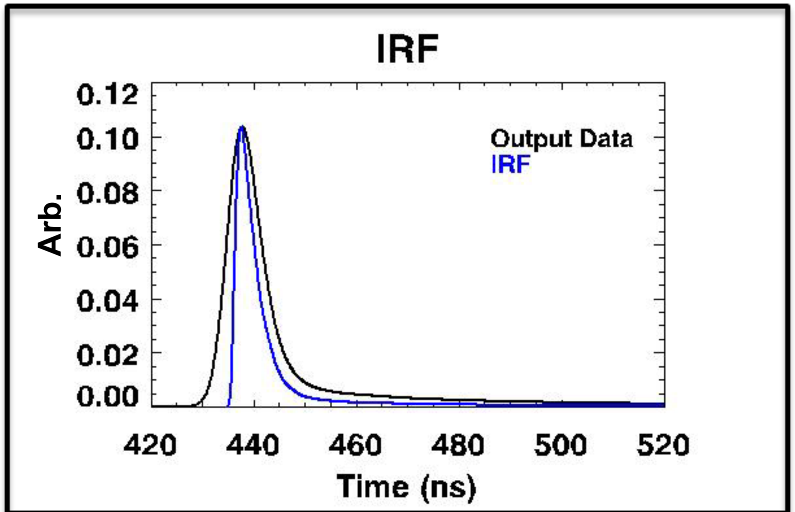
	Calculation	Description
Neutron Yield	$\sum_{E=13}^{15} N_S(E)$	**Number of primary neutrons (13-15 MeV)**
Ion Temperature	$\propto \text{FWHM}$	**Temperature of compressed hot spot**
Time of Arrival	T_0	**Emission time of 14 MeV neutrons**
Downscattered Ratio (DSR)	$\sum_{E=10}^{12} N_S(E) \Big/ \sum_{E=13}^{15} N_S(E)$	**Proportional to areal density (g/cm^2) of the hot fuel**

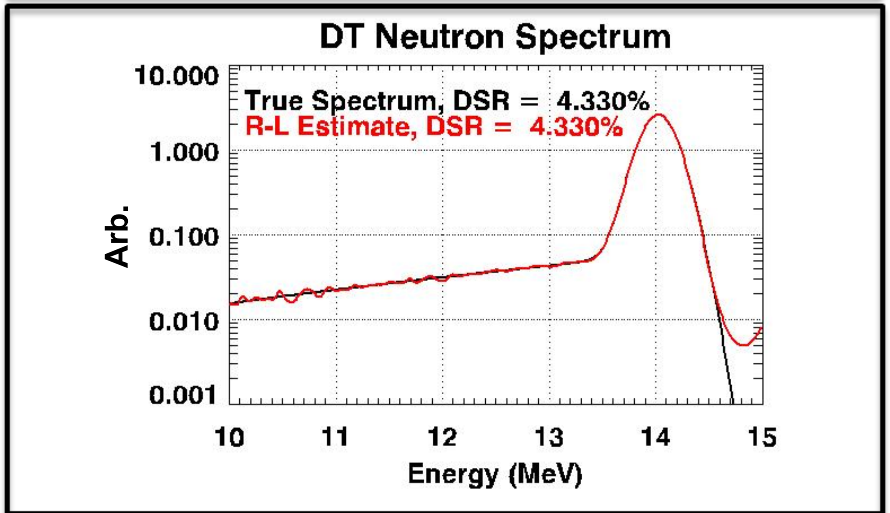
Evaluation of deconvolution technique using noisy synthetic data (scenario 1)

- **Known neutron spectrum**
  - — Tion = 4 keV
  - — Areal density ≈ 1.0 g/cm^2
  - — Distance = 20 m
- **Test signal**
  - — Neutron signal convolved with a known IRF
  - — Additive digitizer noise with peak-to-noise ratio of 30 dB

- **Result**
  - — Convergence in 120 iterations for a 0.5% diff in chi square
  - — Percent difference in DSR is 0%

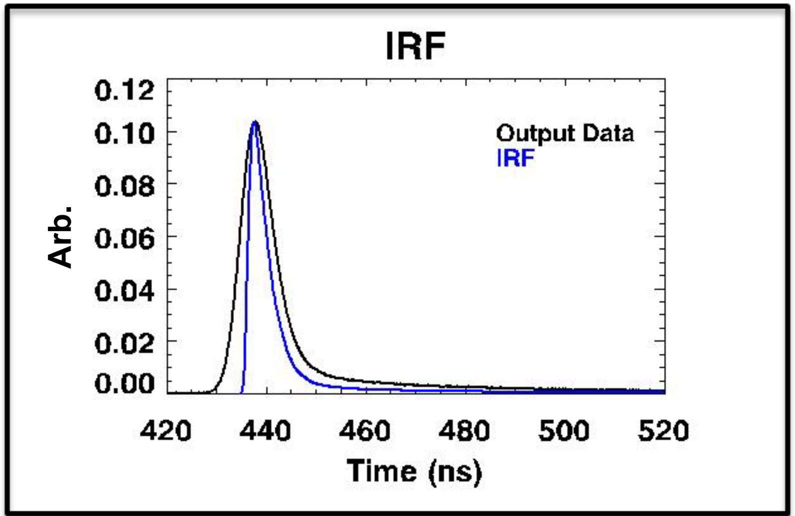




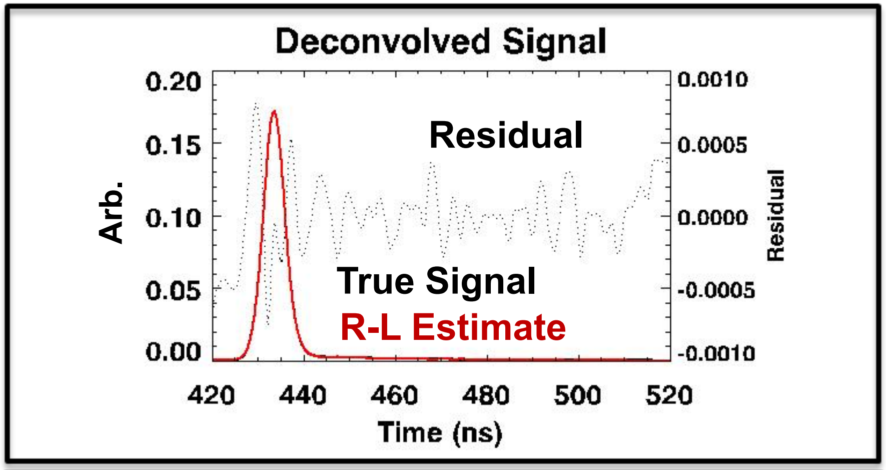


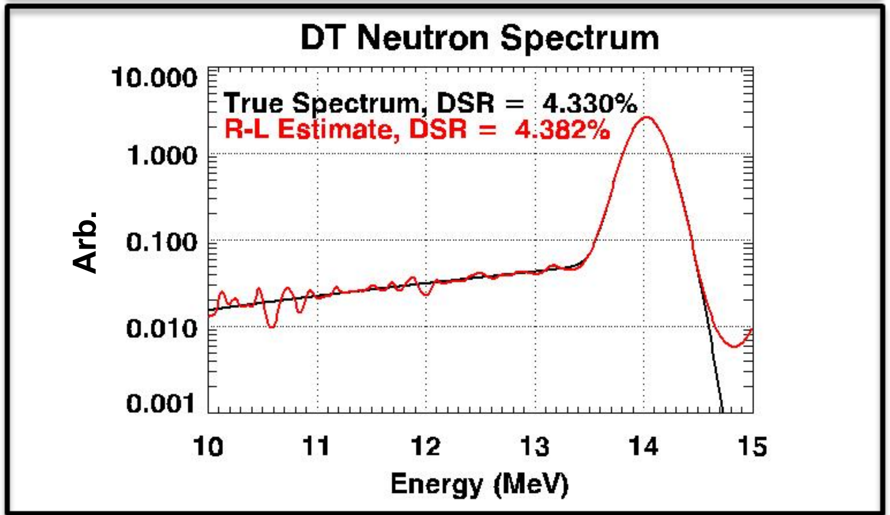
Evaluation of deconvolution technique using noisy synthetic data (scenario 2)

- Known neutron spectrum
  - — Tion = 4 keV
  - — Areal density ≈ 1.0 g/cm^2
  - — Distance = 20 m
- Test signal
  - — Neutron signal convolved with a known IRF
  - — Additive digitizer noise with peak-to-noise ratio of 20 dB



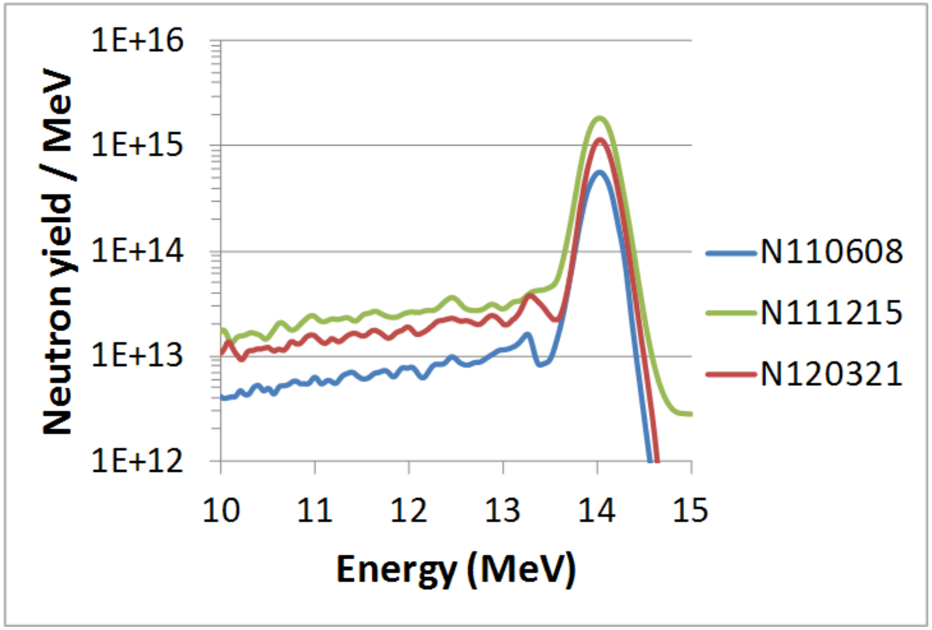
- Result
  - — Convergence in 48 iterations for a 0.5% diff in chi square
  - — Percent difference in DSR is 1.2%





Example neutron spectra deconvolved from experimental data

- nTOF SPEC-A (116-316 location) deconvolved neutron spectra for three DT experiments with approximately the same ion temperature



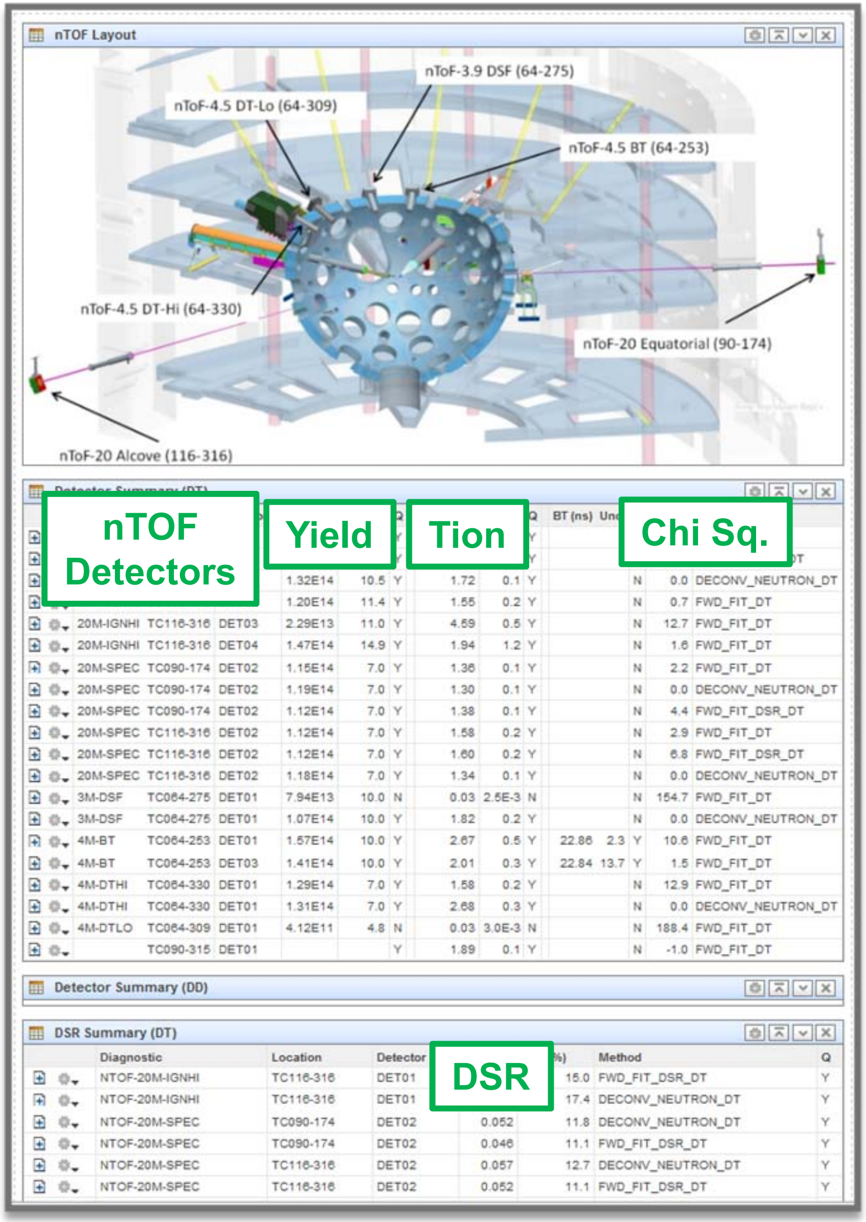
nTOF SPEC-A (116-316) Results

Shot ID	Yield (neutrons)	DSR	Tion (keV)
N110608	1.9e14	0.042	3.2
N111215	7.5e14	0.052	3.5
N120321	4.0e14	0.070	3.3

Note:
- yield relative uncertainty: 0.07
- DSR relative uncertainty: 0.10
- Tion absolute uncertainty: 0.15 keV

Concluding Remarks

- **A method for estimating the neutron spectrum using Richardson-Lucy deconvolution has been presented**
- **The spectral estimate allows for key nuclear metrics to be readily computed including the neutron yield and downscatter ratio**
- **This analysis is quality-controlled software that is *automatically* launched within minutes after an experiment occurs on data from 14 nTOF detectors**
  - **— Results displayed on a NIF web page (see typical example on right)**



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