LLNL-PRES-2005932

NIF
National Ignition Facility

Simulation of the Radiation Environment at the National Ignition Facility

Consultancy Meeting on the Preparation of a Major Release of the Fusion Evaluated Nuclear Data Library (FENDL)

May 13-16, 2025

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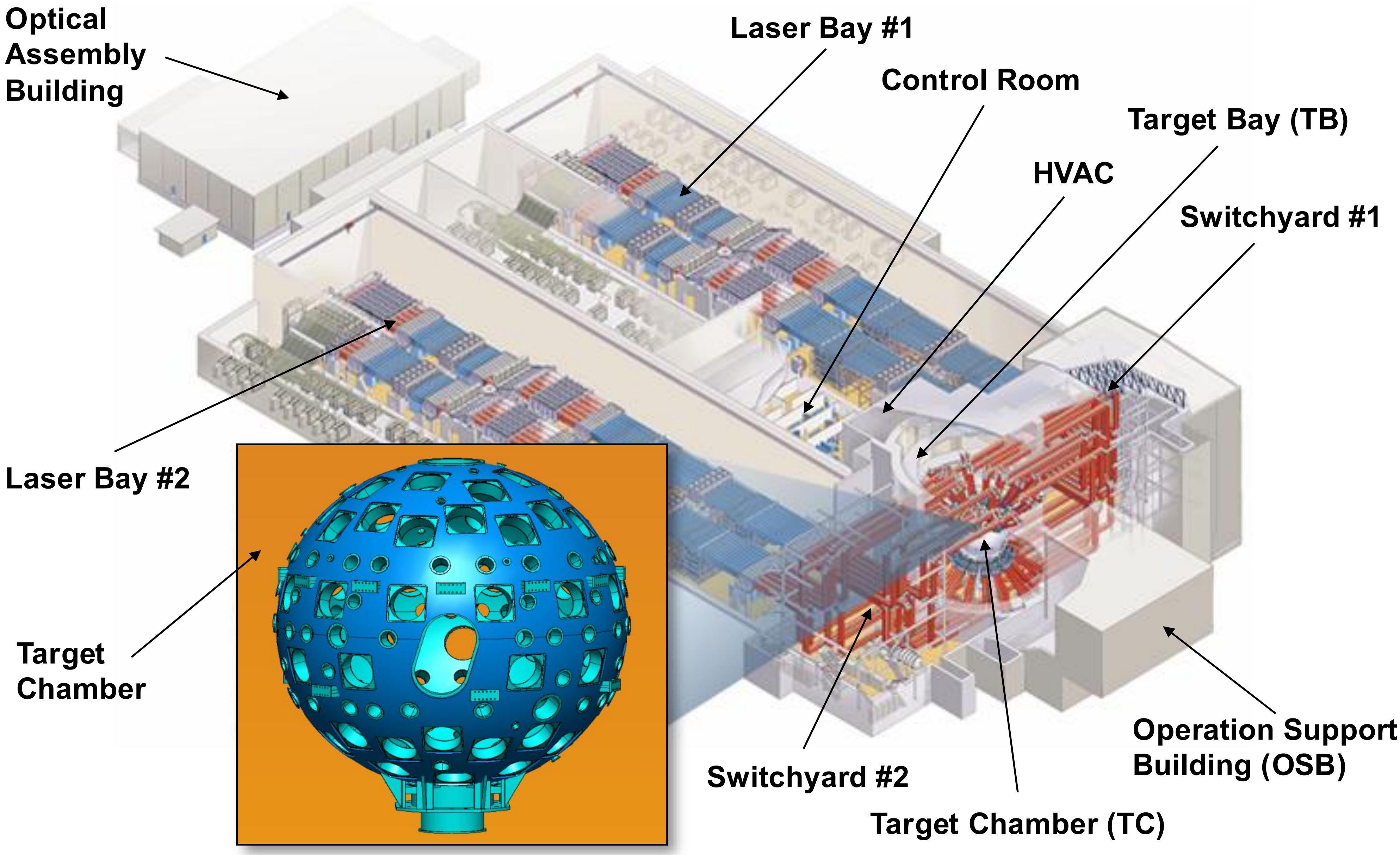
Outline

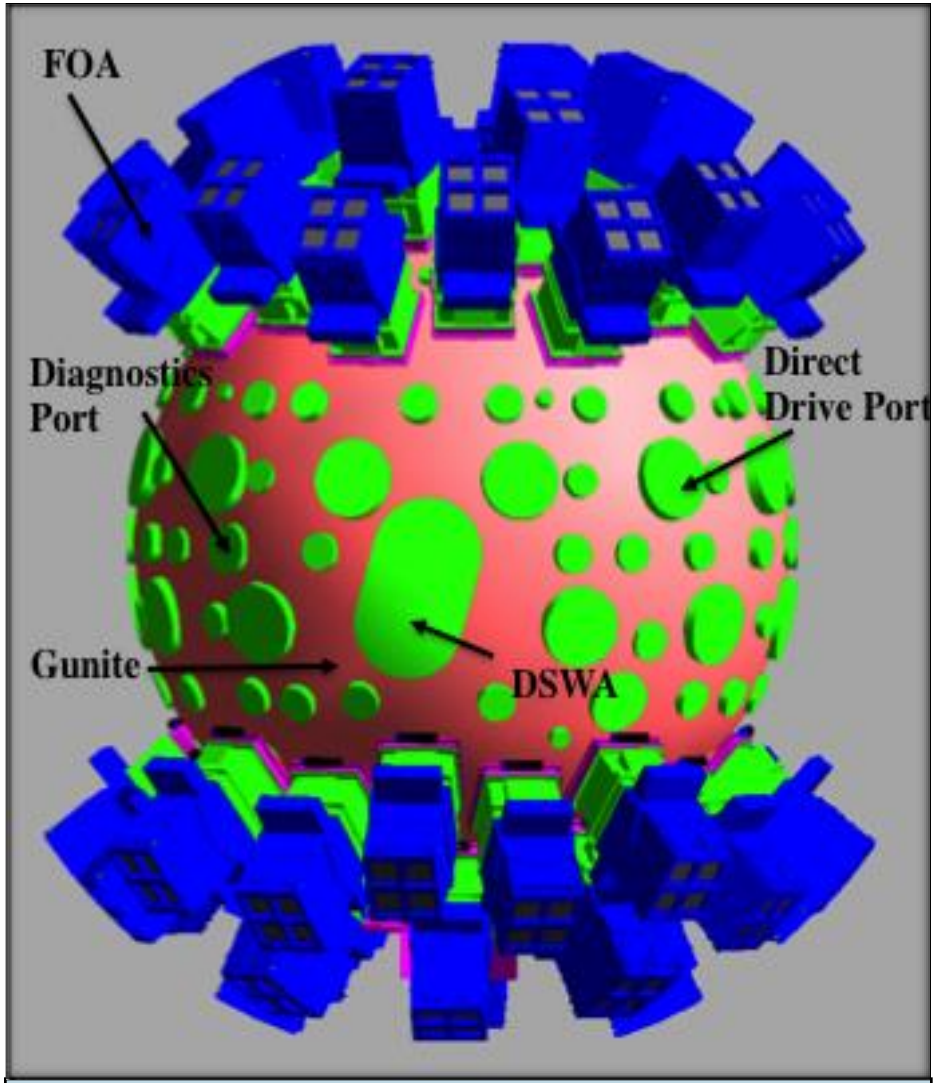
- Detailed 3-D modeling of the NIF facility is developed to accurately simulate the radiation environment at the NIF
- Prompt dose during high yield (20 MJ) shots
- Post-shot dose environment following high yield shots
- Nuclear data needs for diagnostics development

NIF Layout


Optical Assembly Building
Laser Bay #1
Control Room
Target Bay (TB)
HVAC
Switchyard #1
Laser Bay #2
Target Chamber
Switchyard #2
Operation Support Building (OSB)
Target Chamber (TC)

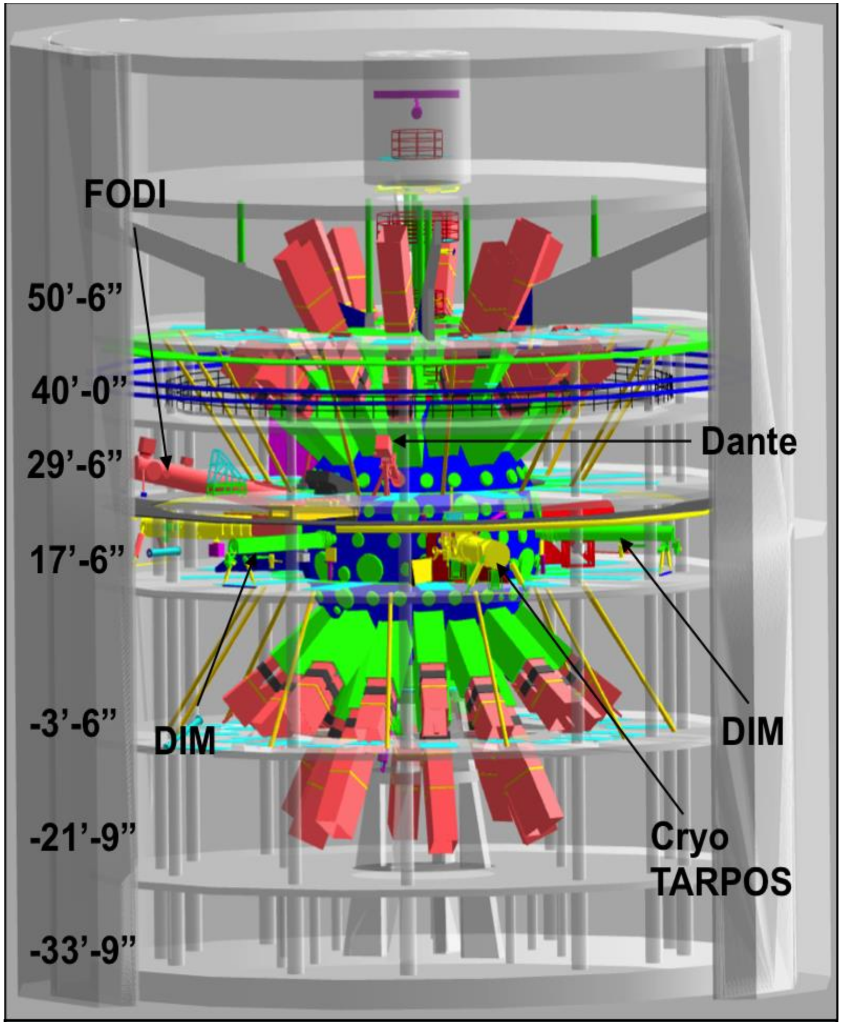
Features of the current NIF facility model

- Based on the facility as-built drawings
- 10-cm-thick Al Target Chamber (TC) wall surrounded by 40-cm of borated concrete
- 1.83-m -thick concrete Target Bay (TB) wall
- 99.1-cm-thick concrete Switchyard walls
- All Target Chamber, Target Bay and Switchyard wall penetrations are modeled
- Final Optics Assemblies (FOAs) are modeled
- All DIMs, TANDMs, positioners, and major diagnostics are modeled

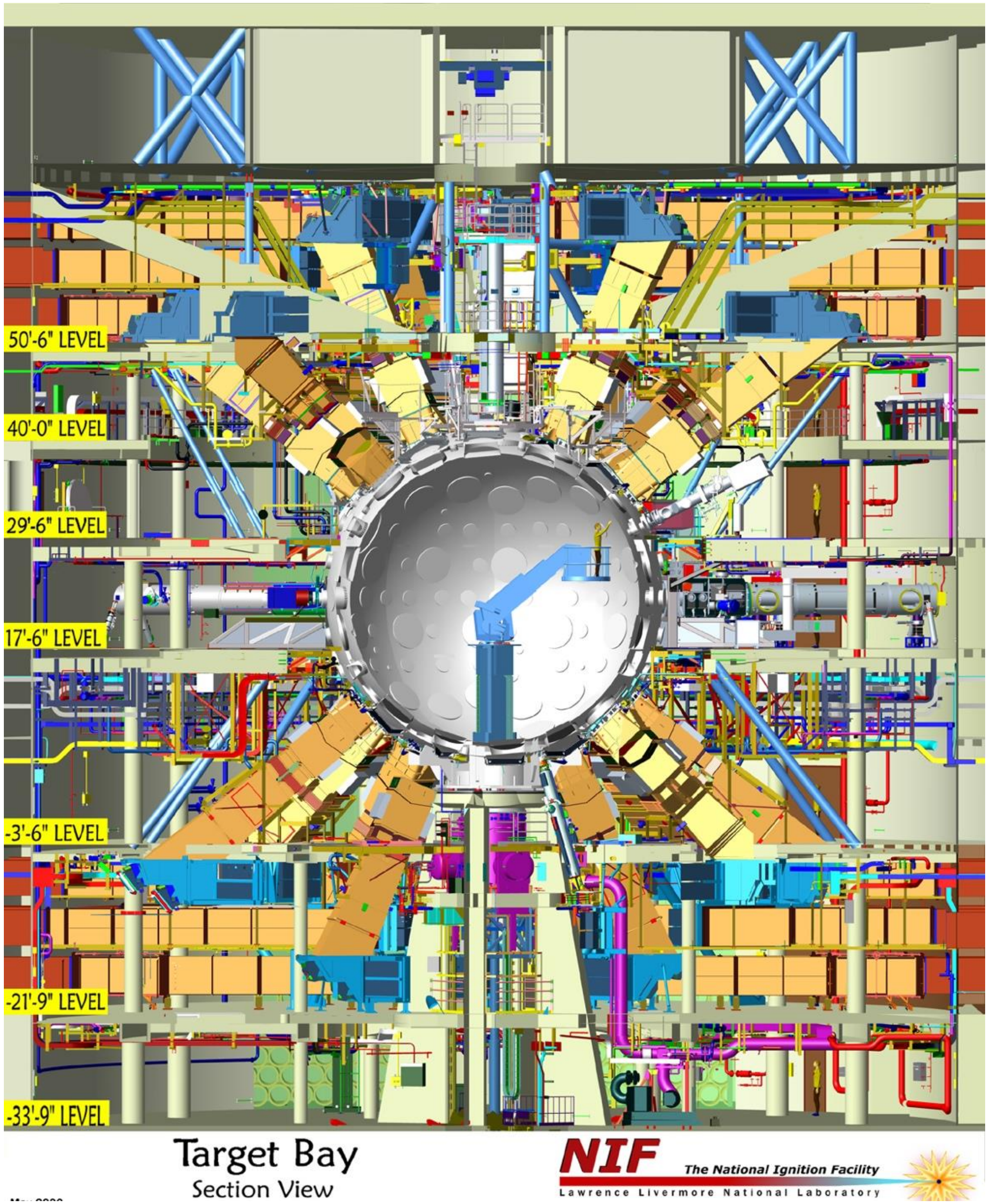


MCNP model of the Target Chamber

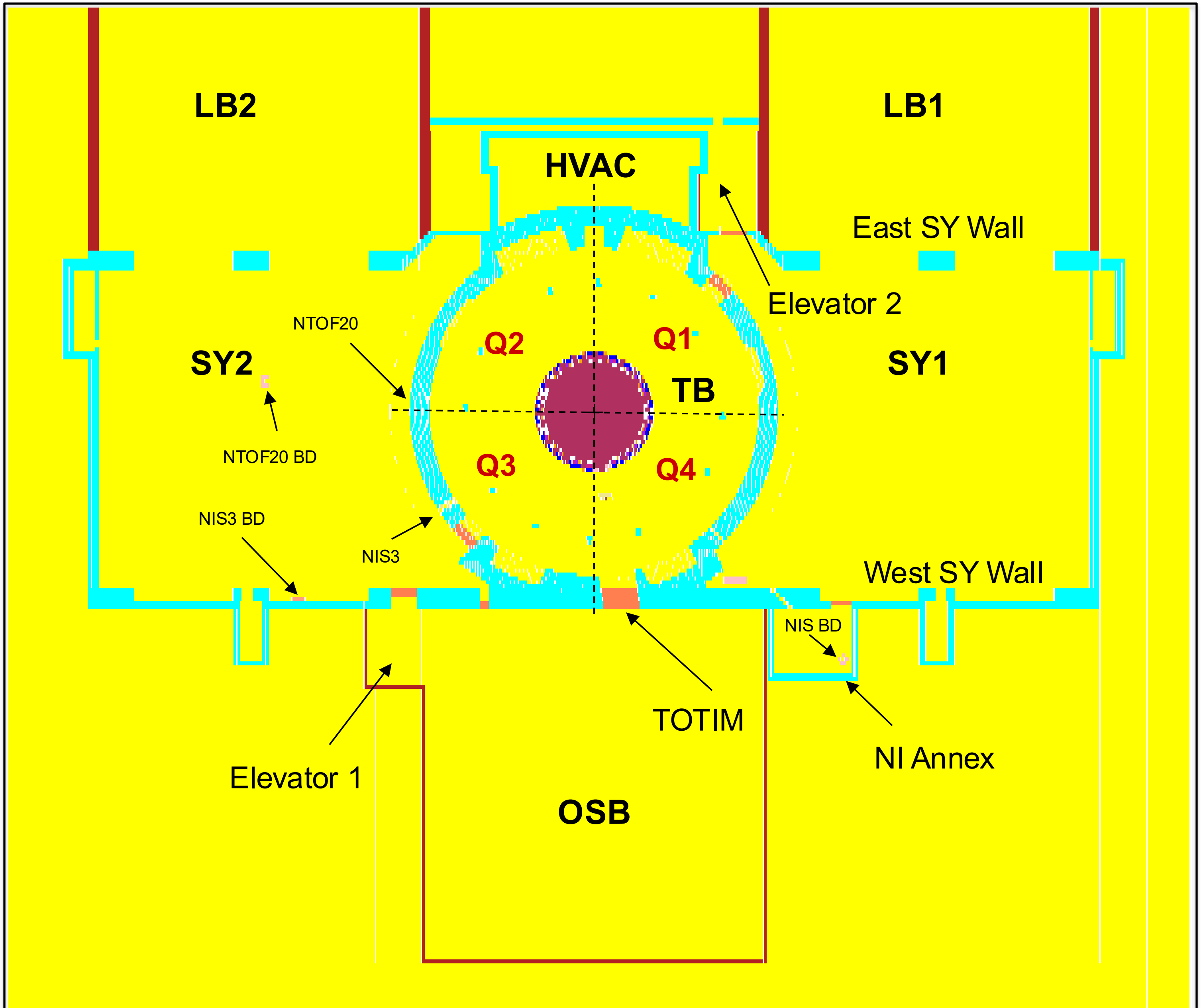
Sectional view of the Target Bay



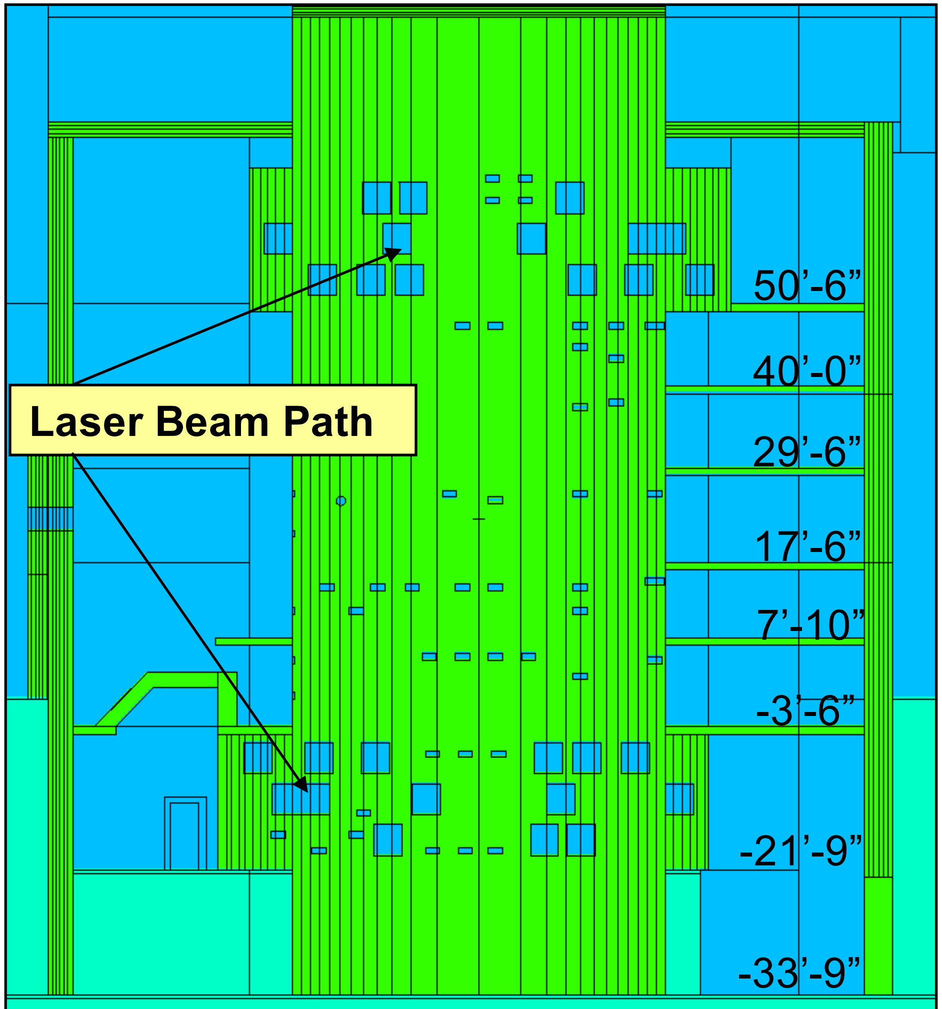
MCNP model of the Target Bay



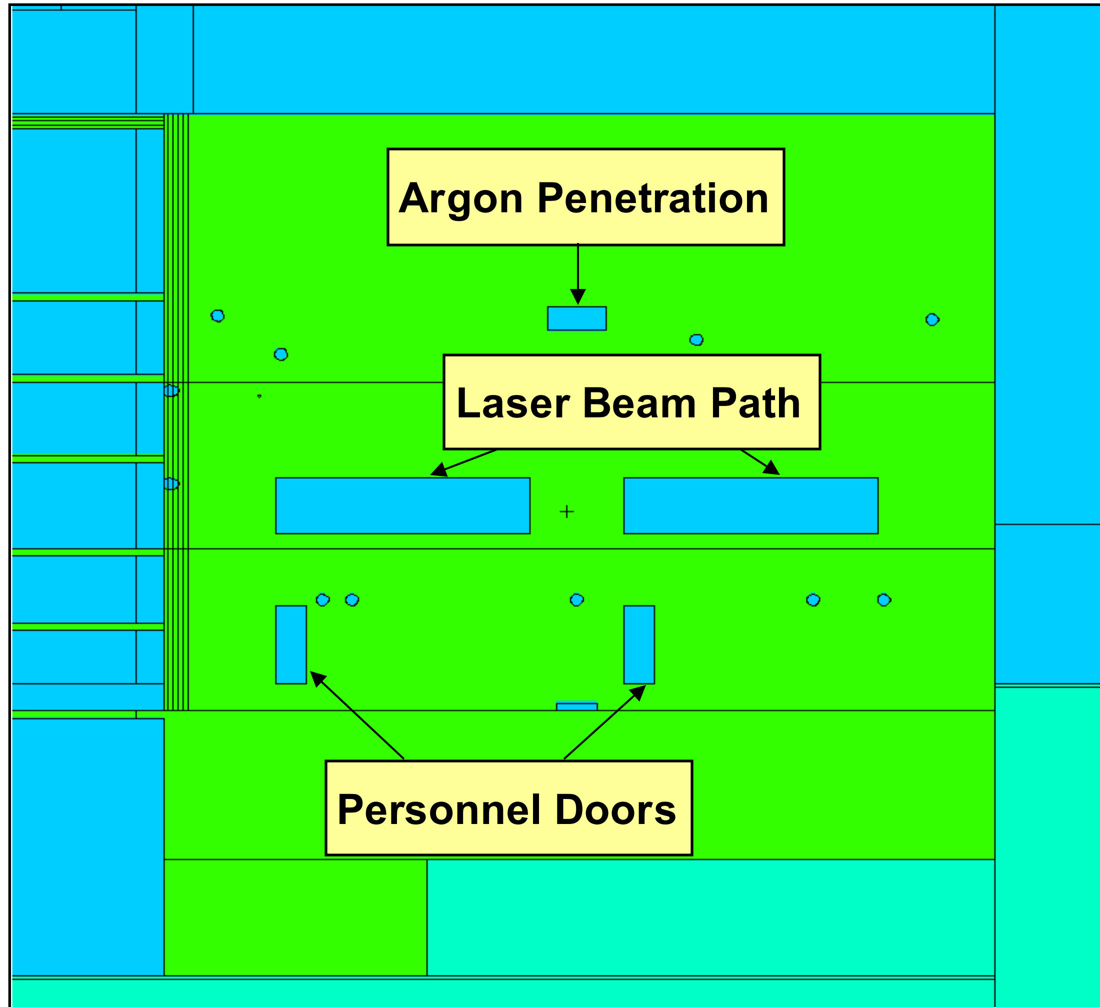
Horizontal view of TB at TCC (7 m above ground level)



Vertical views of TB and SY walls



Vertical View of Q1 and Q4 of TB Wall

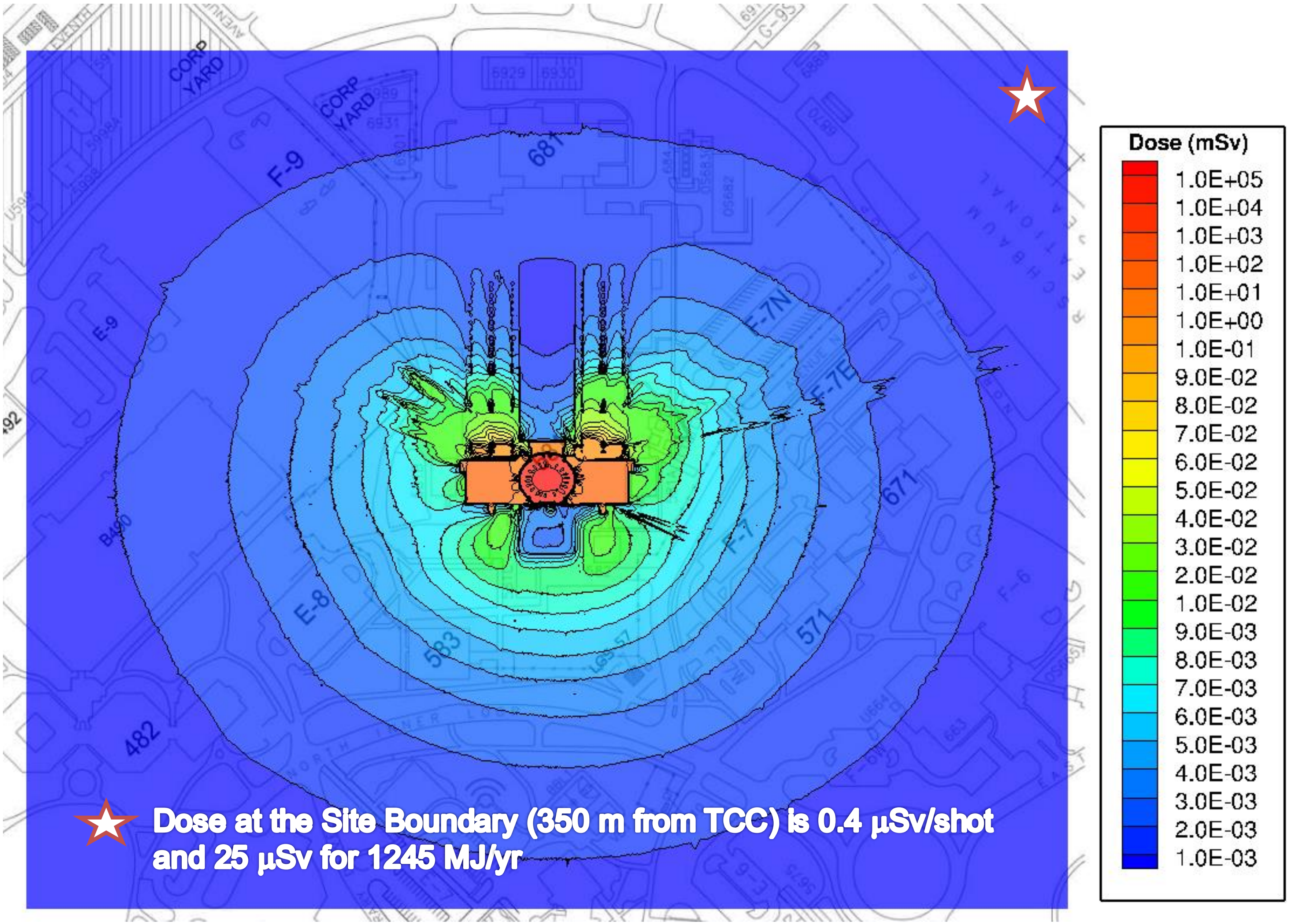


Vertical View of East Wall of SY1

Simulation approach

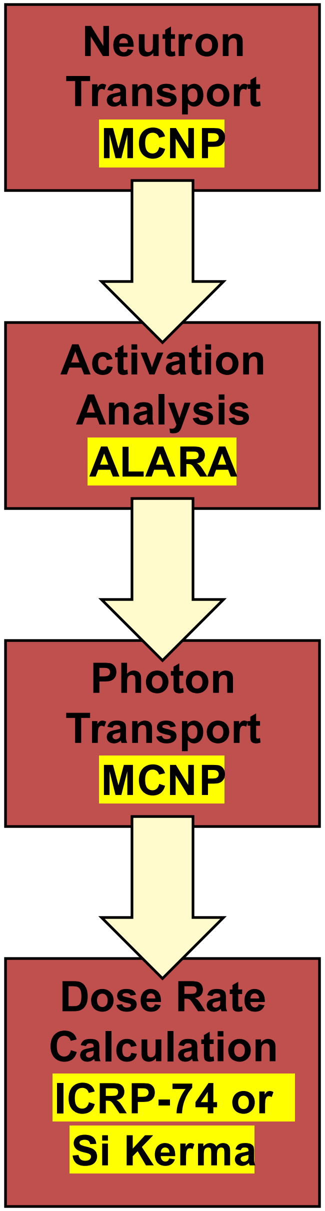
- Radiation transport simulations performed using the MCNP6.3 and the FENDL-3.2b neutron cross section library
- The Automated Variance Reduction Parameter Generator (ADVANTG) software was also used to create mesh-based weight windows (FW-CADIS method)
- Mesh tallies are used to produce prompt dose maps of the entire facility
- ICRP-74 fluence to effective dose conversion factors
- High yield shots of 20 MJ or 7.1×10^{18} neutrons per shot
- Maximum annual yield of 1200 MJ
- The NIF radiological design goal is to limit the maximum prompt dose in any occupied area to < 50 μSv per shot and < 1 mSv per year

Prompt dose map for the ground level during a 20 MJ shot

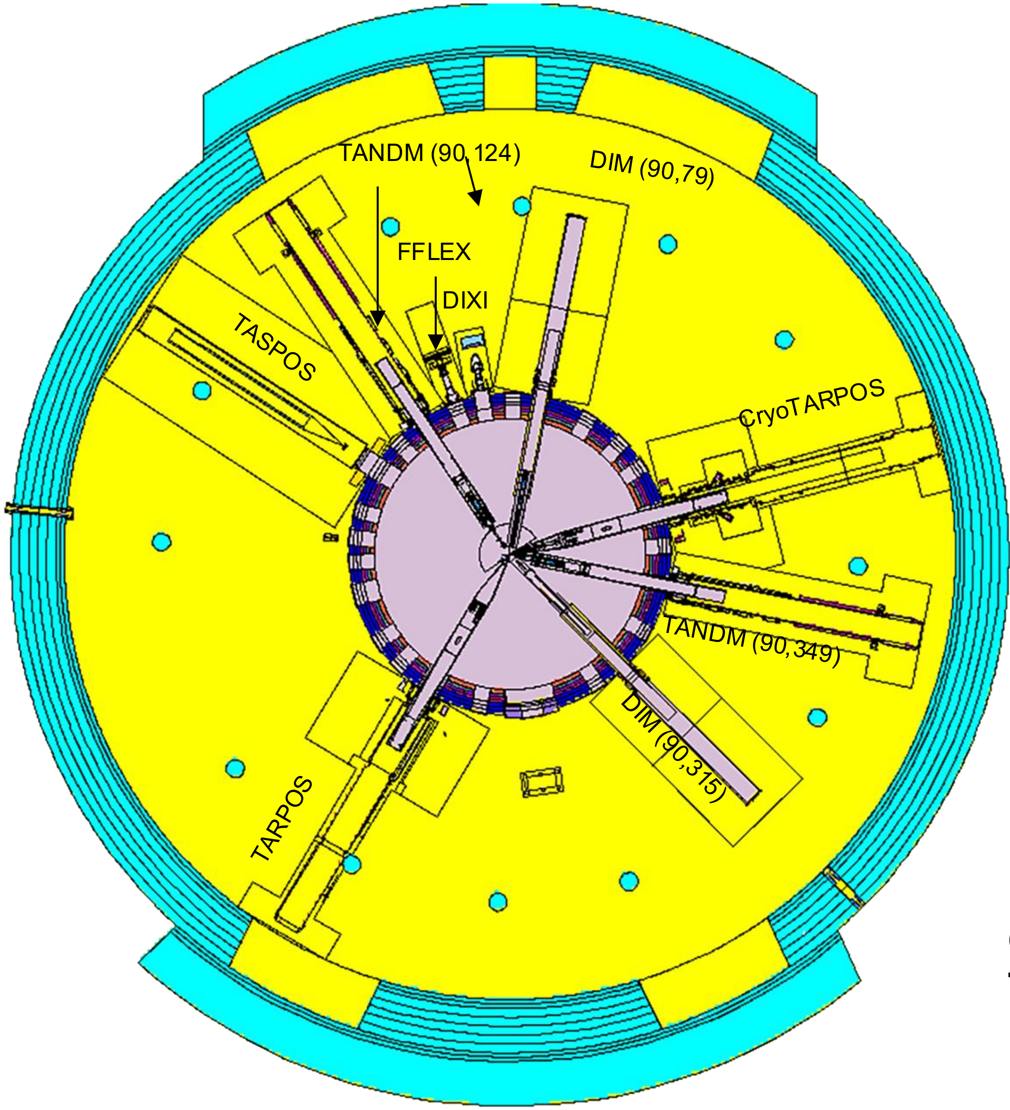


A new tool is developed to estimate post-shot dose rates

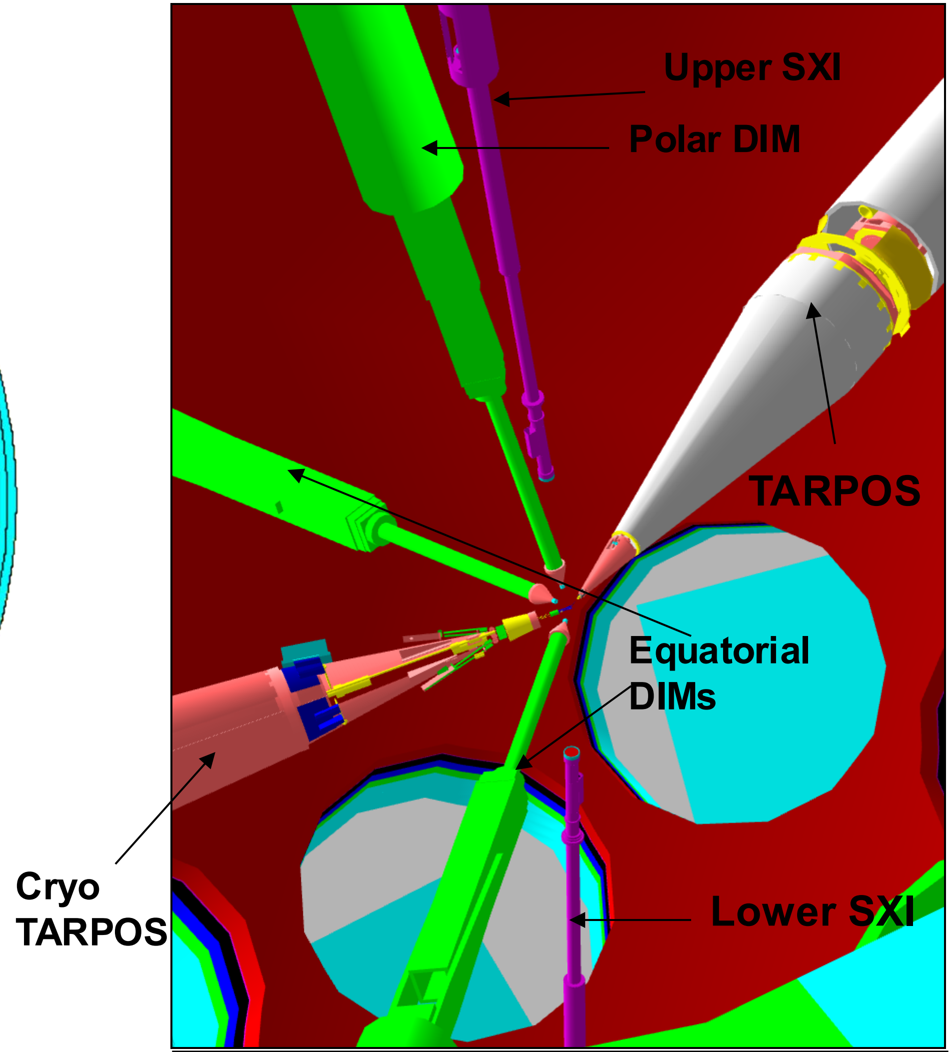
- AAMI (*Automated ALARA-MCNP Interface*) is a coupling scheme between radiation transport and neutron activation codes
  - *Step 1*: Neutron transport calculation using the MCNP 3D model to obtain 175-group flux spectra in each component of interest
  - *Step 2*: Activation analysis of components using the activation code, ALARA, to compute the γ-ray intensities and spectra for each cell and at different cooling times after a shot
  - *Step 3*: γ-rays computed in the second step are sampled and emitted from each activated component, and propagated by a transport simulation through the entire TB model
- Photon transport performed with user provided source subroutine
- Volume-based sampling used with weight adjustment to correct bias for source strength
- γ-ray fluxes are tallied using a fine 3-D grid over the entire Target Bay, and are converted into dose rates



Model of the Target Bay during a shot

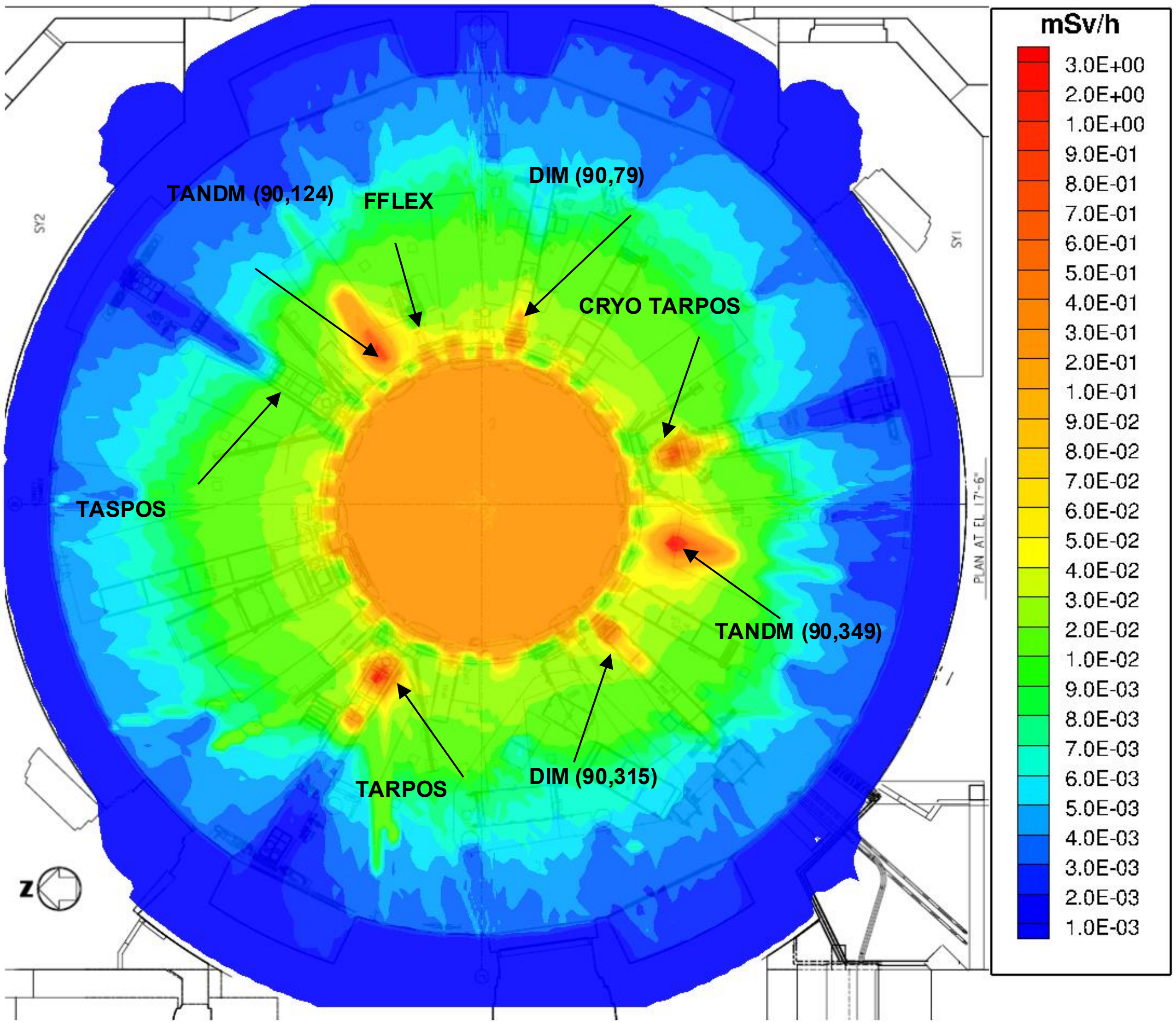


Equatorial view of the Target Bay



MCNP model of inside of the TC

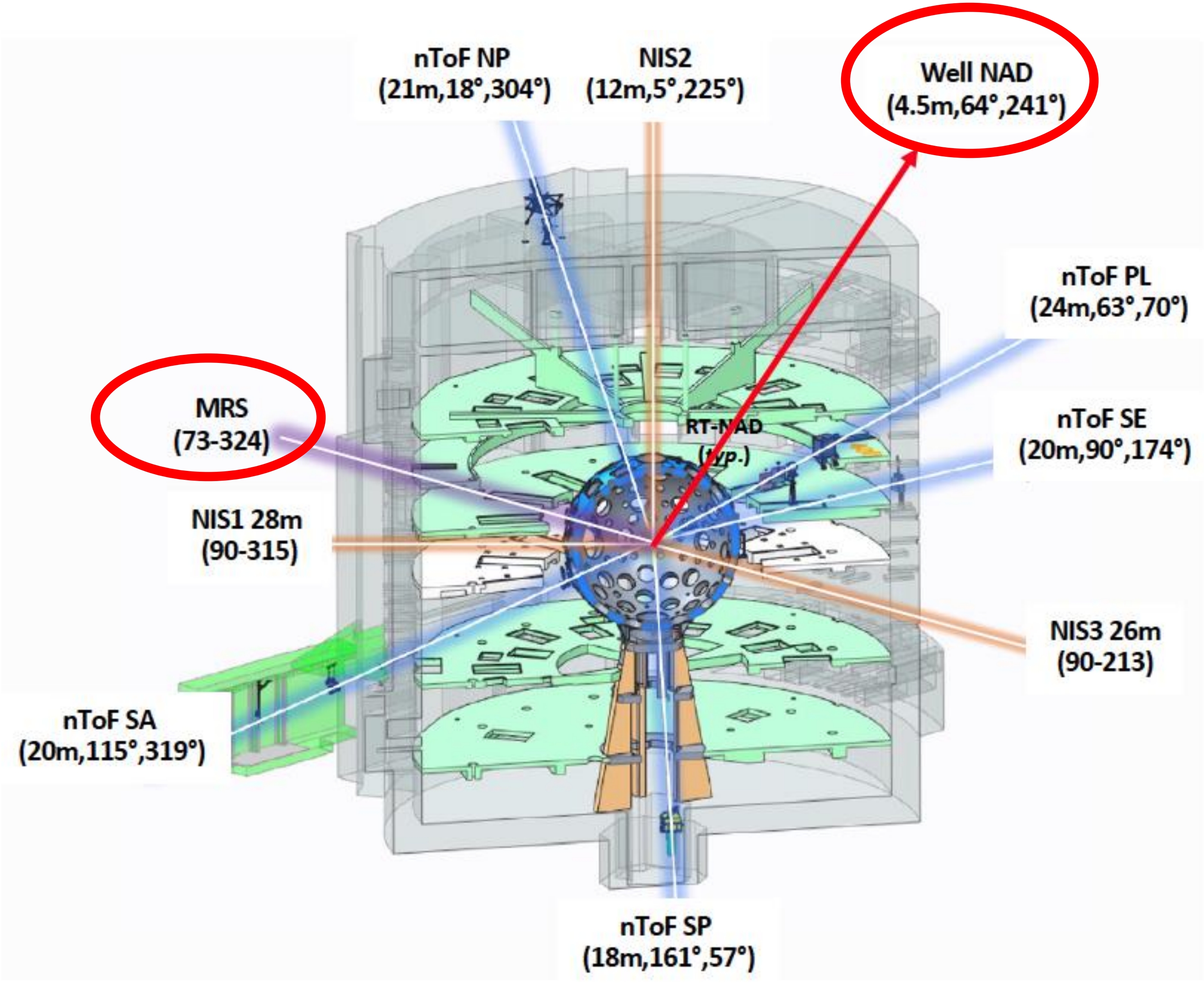
Dose rate map at Target Chamber equatorial plane following a 20 MJ shot (5 days cooling)



^{27}Al(n,α) is the dominant reaction

Dose rates are dominated by the decay of ^{24}Na ($T_{1/2}$=15 h)

Two neutron diagnostics compromise the NIF yield of record



The well neutron activation detectors

The Well Neutron Activation Detectors ("Well NADs") are Zirconium disks fielded on NIF yield experiments that are absolutely calibrated

$^{90}Zr(n,2n)^{89}Zr$
$t_{1/2} = 3.3$ d

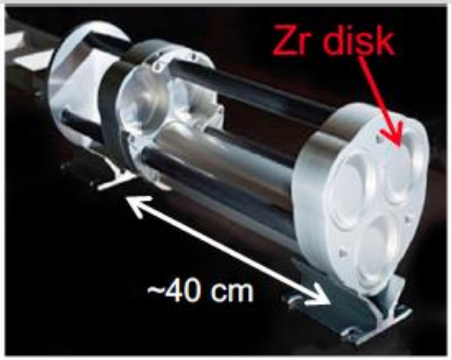
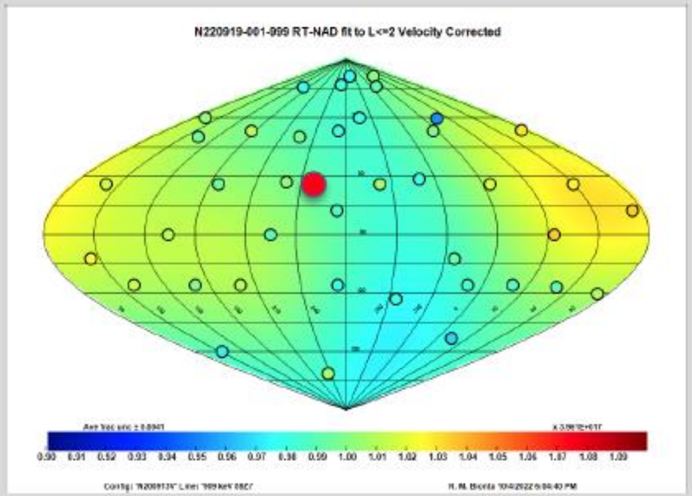
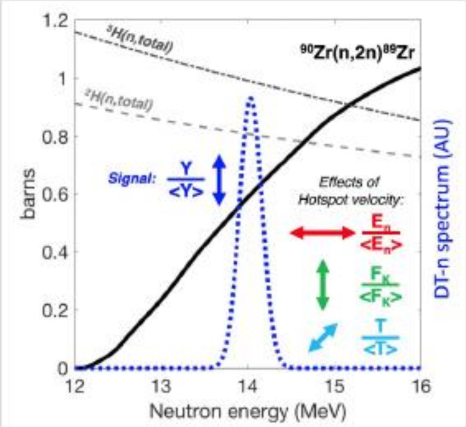
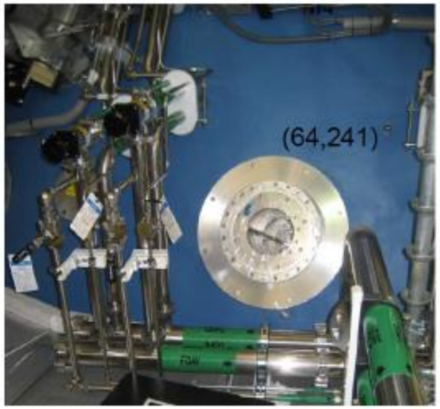


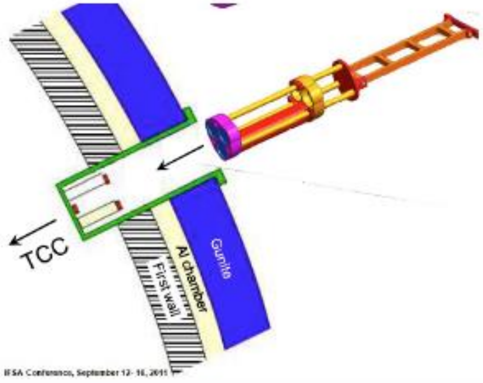
Fig. 10. The NAD in a well is designed to hold up to three zirconium samples at the front or back to measure the number of unscattered 14.1-MeV D-T neutrons.



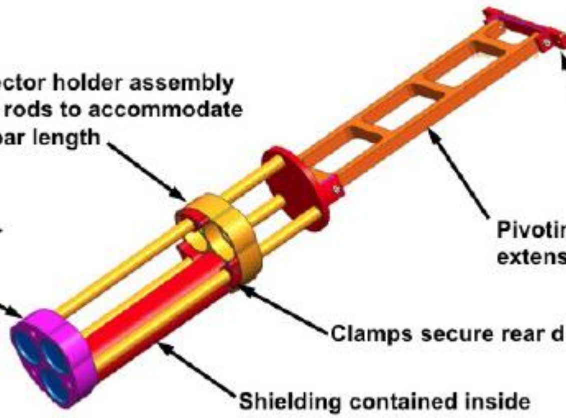
Cross-section dependencies are accounted for







Three activated Zr foils are retrieved and counted after the shot



Each sample is counted on multiple High Purity Germanium (HPGe) detectors, and at multiple source-detector distances

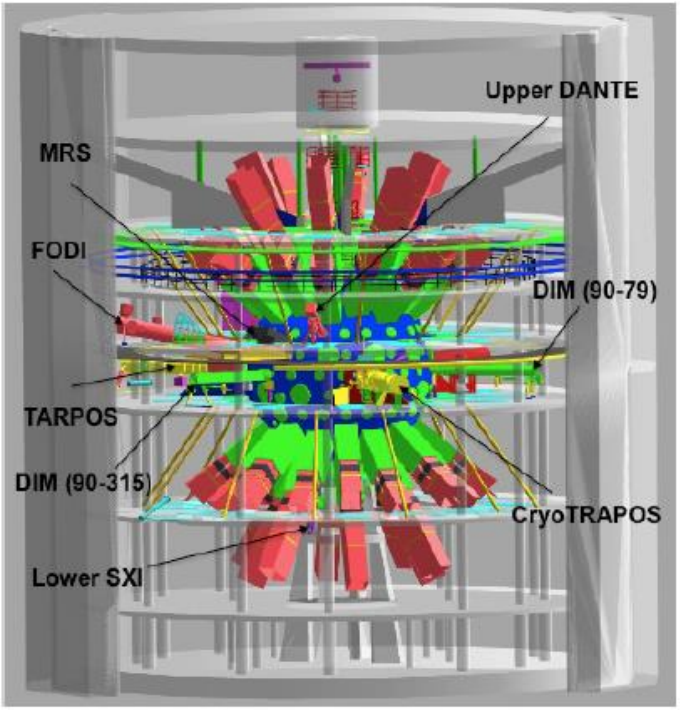
B151 low background Nuclear Counting Facility (NCF) has >40 years experience

The technique employs the ^{90}Zr(n,2n)^{89}Zr reaction

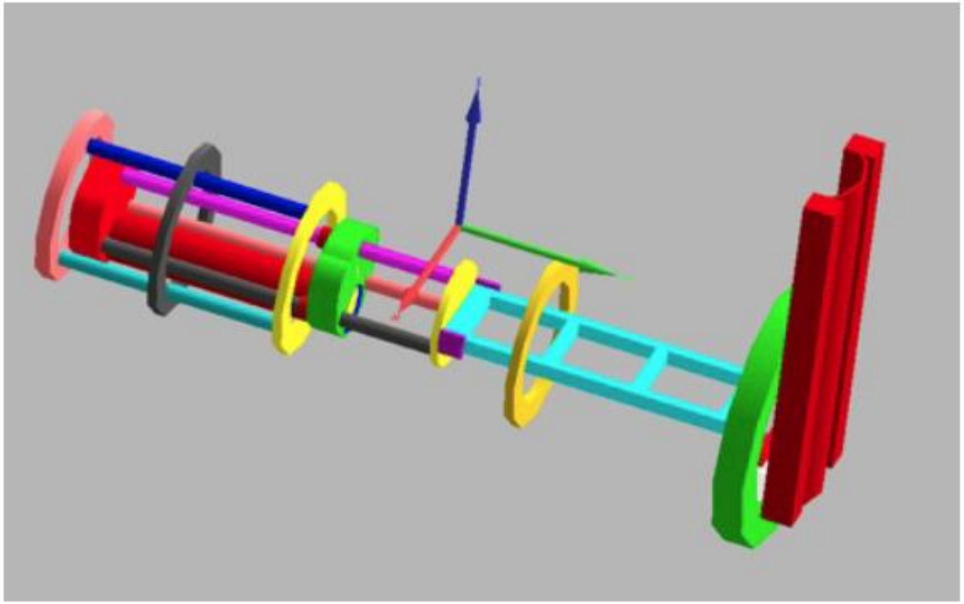
- Natural abundance of ^{90}Zr is 51.45%
- Cross Section σ(14.1 MeV) is 622.0 mb
- Half Life $T_{1/2}$ of ^{89}Zr is 3.267 days
- Reaction threshold energy E_{thres} is 12.1 MeV
- ^{89}Zr decays to ^{89m}Y meta stable state
- ^{89m}Y has a half life of 15.663 seconds and is in equilibrium with ^{89}Zr
- Branching ratio of the internal transition 909 keV gamma ray is 0.992
- A high purity Ge detector is used to count the E_γ=909 keV line

The total number of counts is converted to incident neutrons based on MCNP modeling

SUMMARY OF PEAKS WITH SIGNIFICANT NET TOTALS										
INDEX	CHANNEL	KEV	(+/-)	- PEAK -		CALC.	PROP.	PHOTONS/MIN	BKGND	PCT
				START	END	COUNTS	COUNTS		CTS/MIN	ERROR
...										
22	1817.655	909.011	0.00	1807	1823	131134	131317	1.42E+05	0.088	0.64
...										



MCNP model of the Target Bay


MCNP model of the Well NADs

Per incident neutron, $\frac{A_{0_{MCNP}}}{\lambda} = (1.36393 \pm 0.00053) \times 10^{-7} \cdot atoms$

We use nToF measurements to study different sections of the fusion neutron energy spectrum

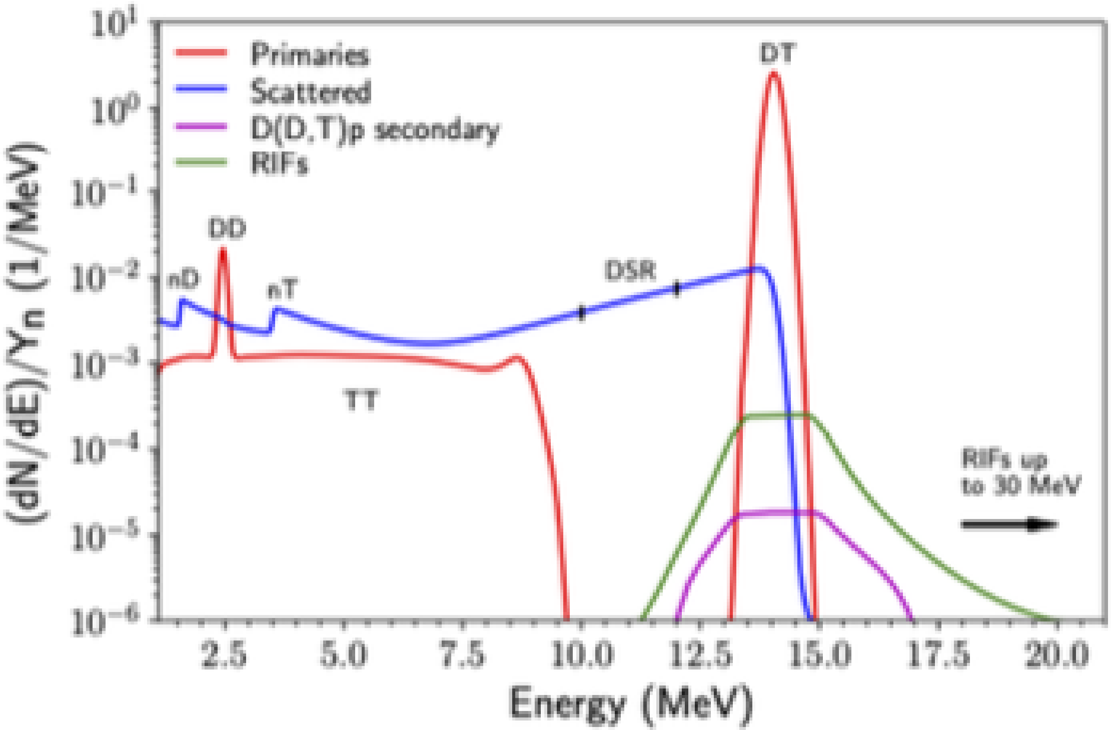
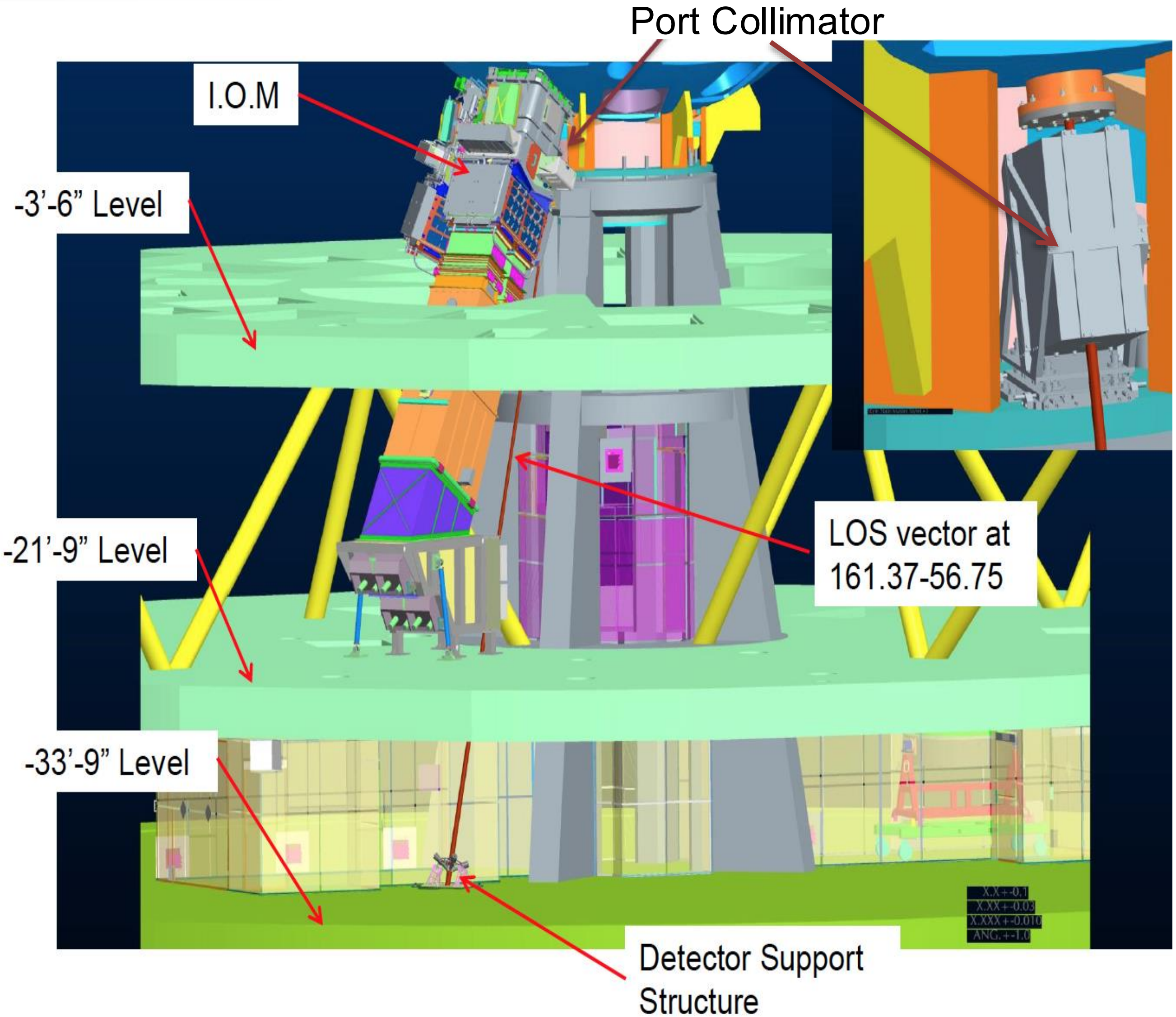


FIG. 5. An example of the components of the neutron energy spectra produced in an ICF experiment. This spectrum was produced from a simulation of a capsule with a fuel ρR = 0.25 g/cm^2. The relative intensities of the different components can vary with ρR, but the basic shapes do not change significantly. The primary reactions in Eqs. (1) and (2) are shown in red, down-scattering of neutrons as they travel through the dense fuel results in the blue spectral component. Secondary DT reactions in which the triton (<1.01 MeV) is generated by the D(D,T)p reaction is shown in purple, and NKN RIF reactions are shown in green.

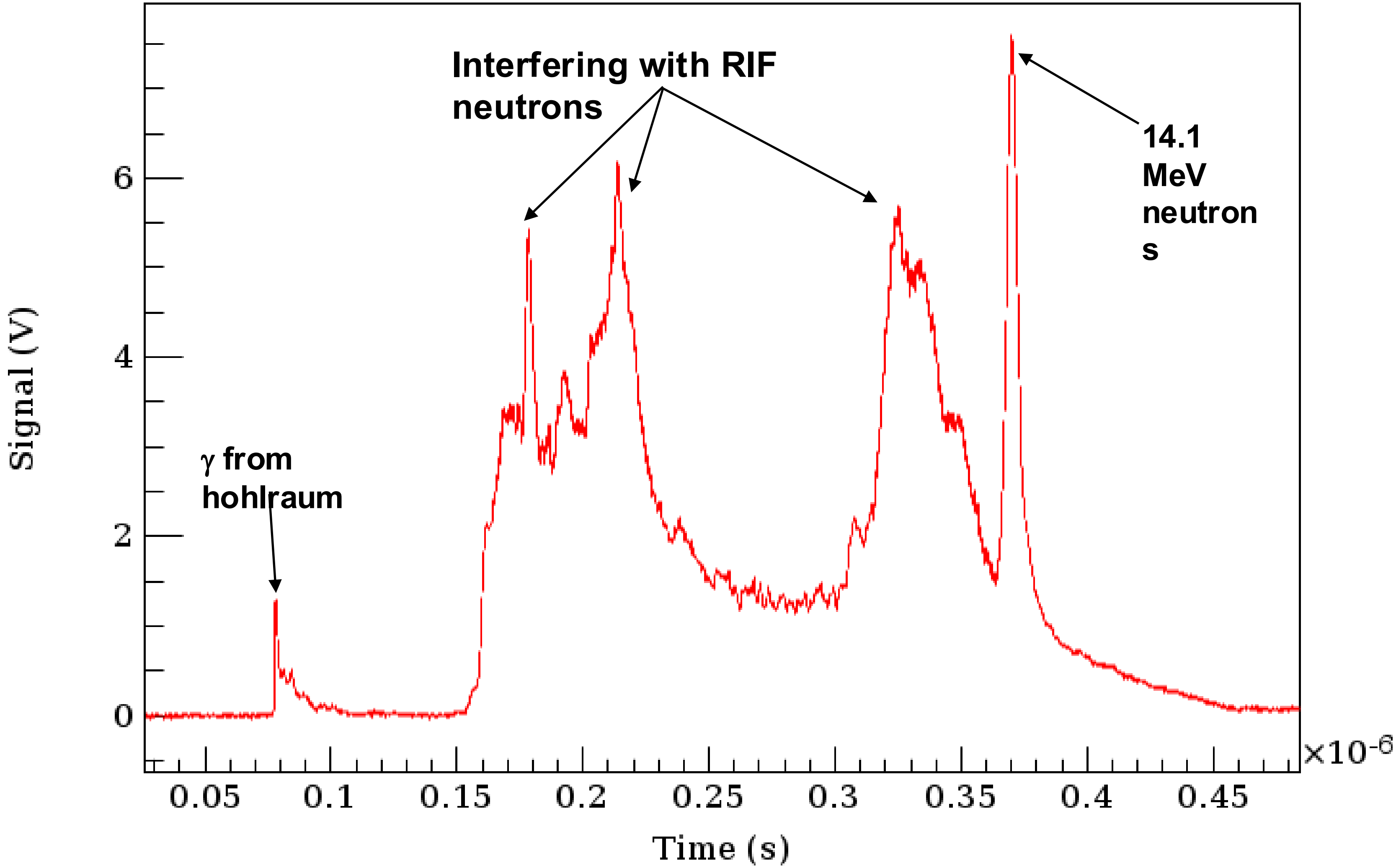
A. Moore et al., Rev. Sci. Instrum. ***94****, 061102 (2023)*

South Pole nToF LOS



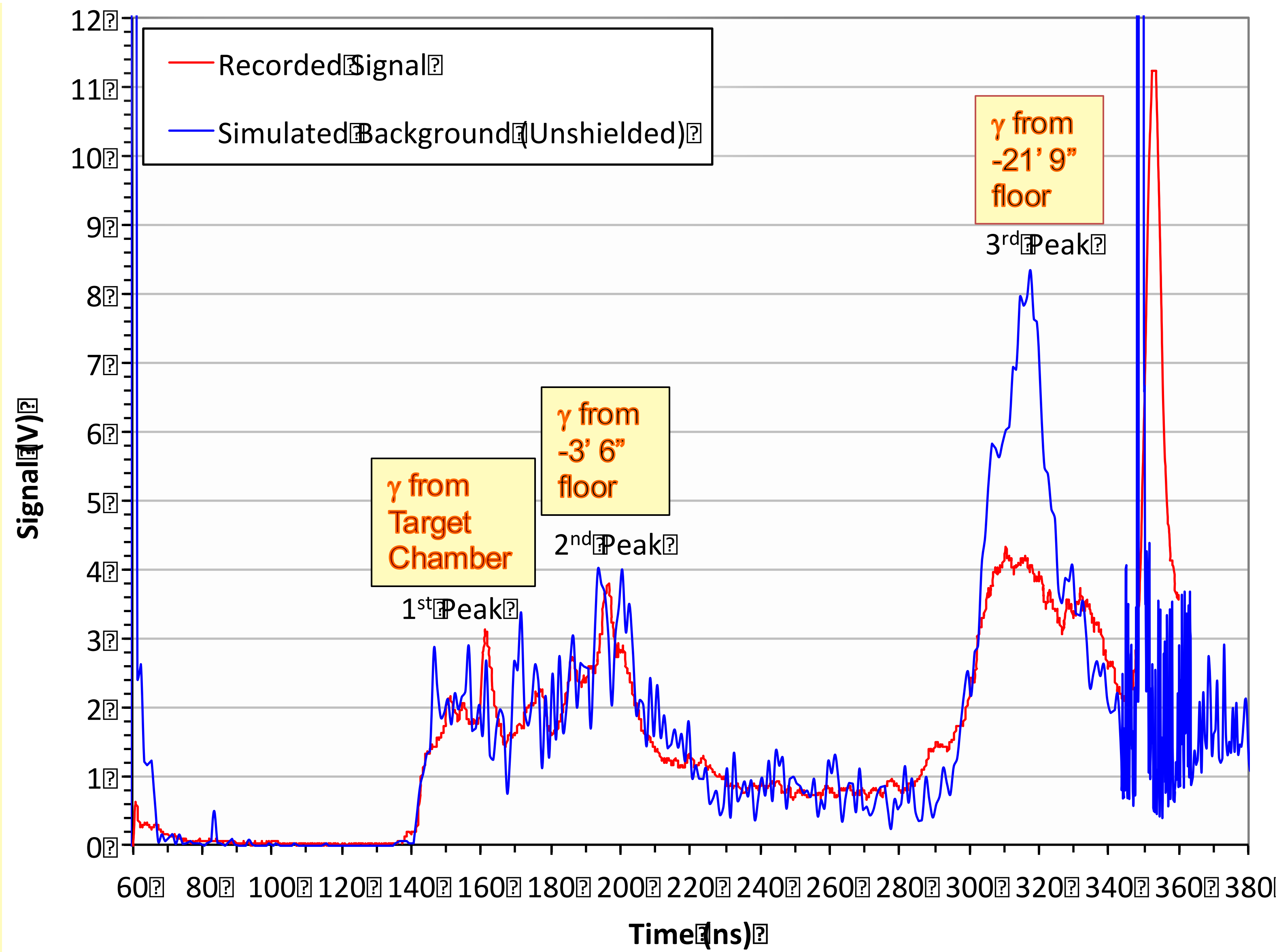
nToF detectors are fielded at the NIF to measure neutron yield, ion temperature, and downscattering in the cold fuel for D-T implosions

Recorded signal during a low yield shot (10^{16} neutrons)

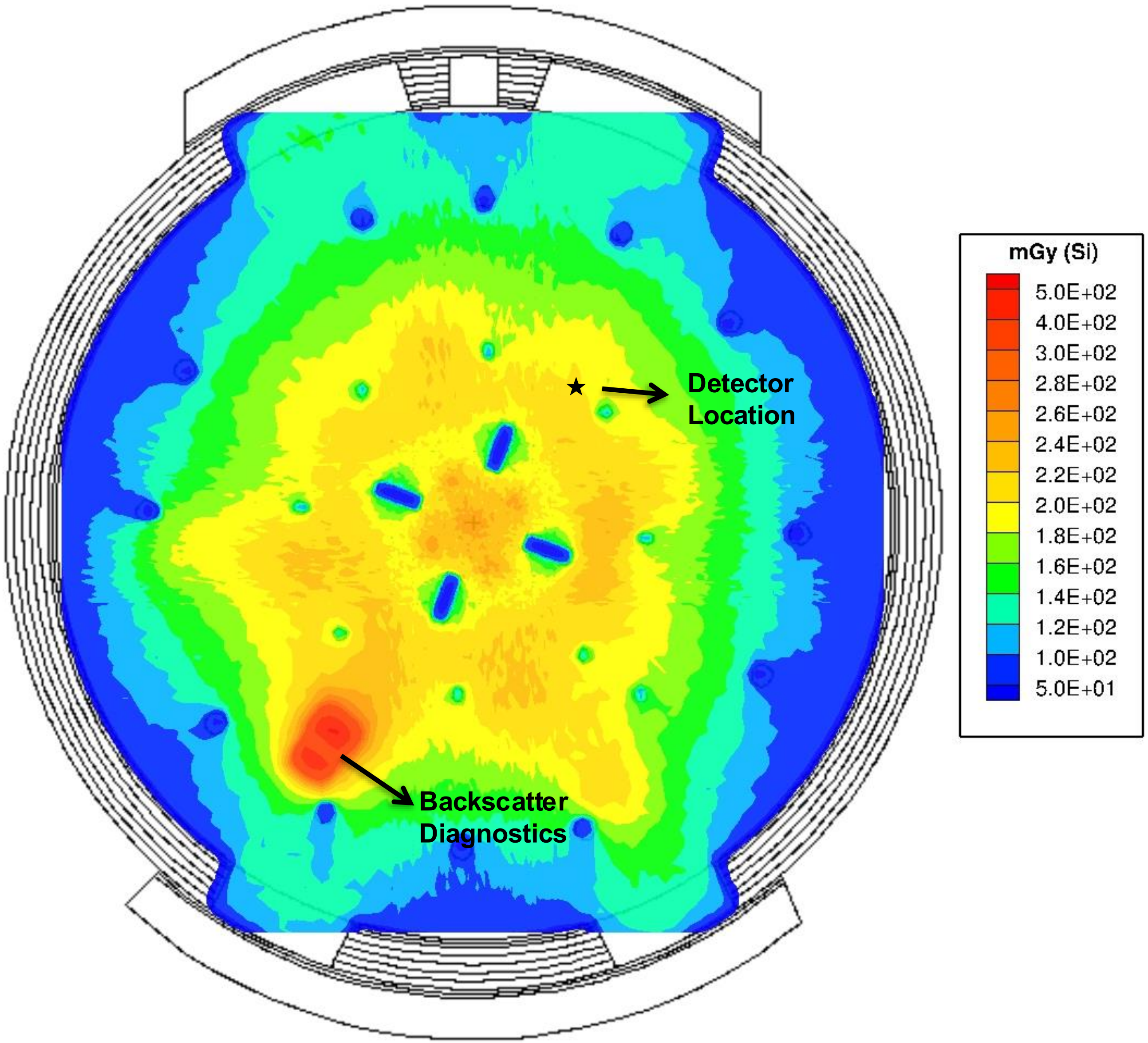


A small fraction of "reaction-in-flight" (RIF) neutrons (with energy up to ~ 30 MeV) are produced by up-scattered deuterons or tritons undergoing D-T reaction with thermal ions

Comparison between simulated background and recorded signal during a low yield shot



Photon dose at the -33' 9" floor during a 20 MJ shot

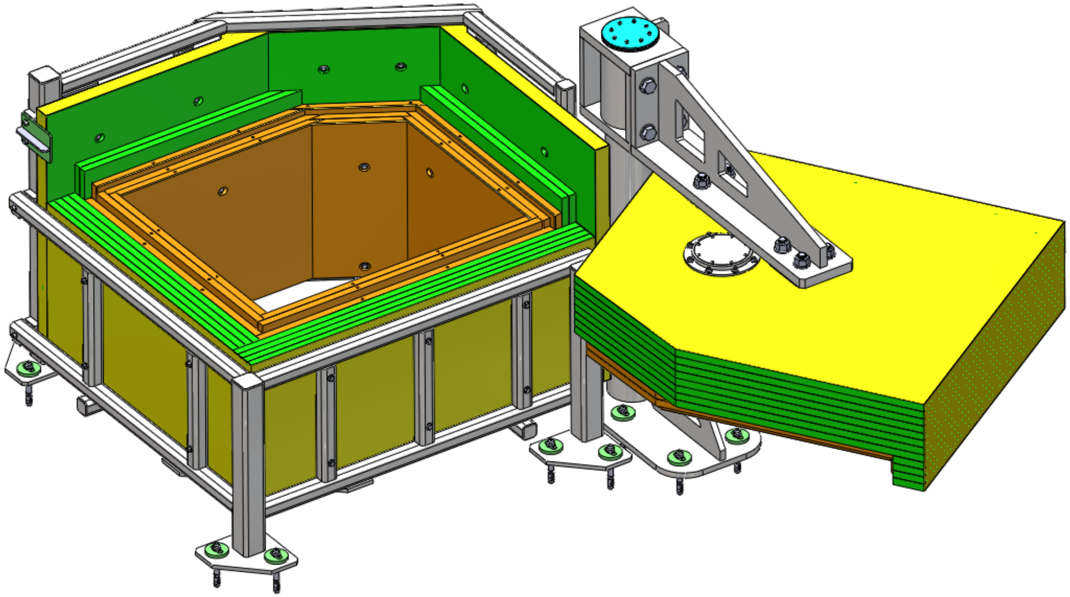


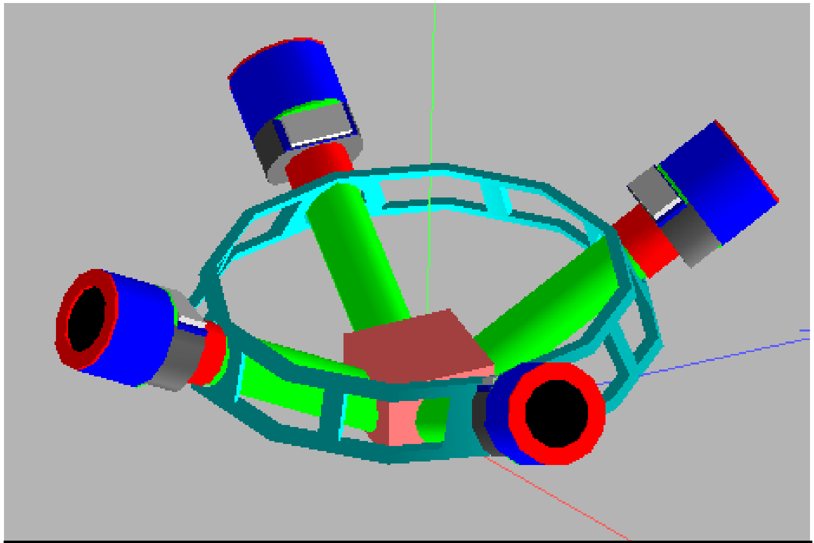
High photon dose due to streaming through the inner lower ring of beam ports

Final design of the nToF detector shielding

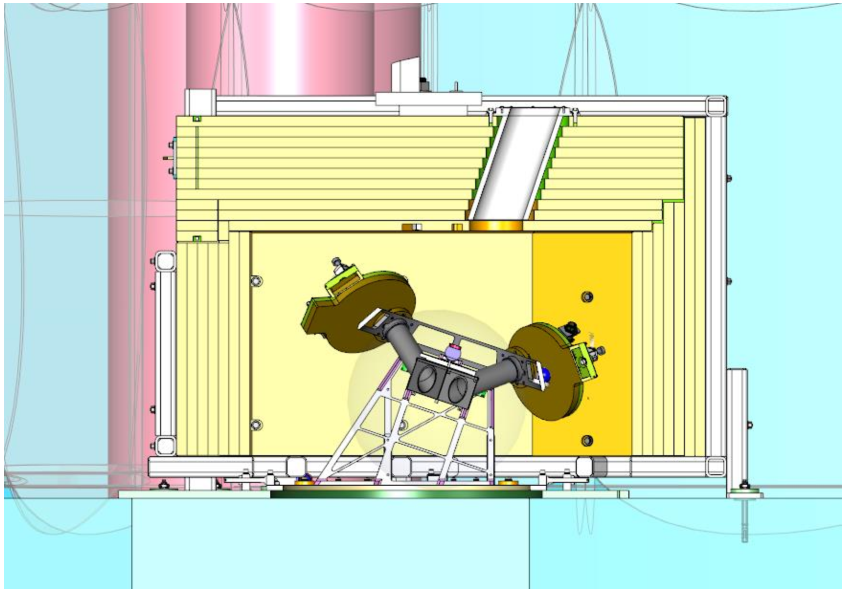
Shielding to reduce BG by factor of 10

- **Steel**
  - ✓ **7.5 cm all around**
- **Borated polyethylene**
  - ✓ **20 cm on top**
  - ✓ **12.5 cm on sides**



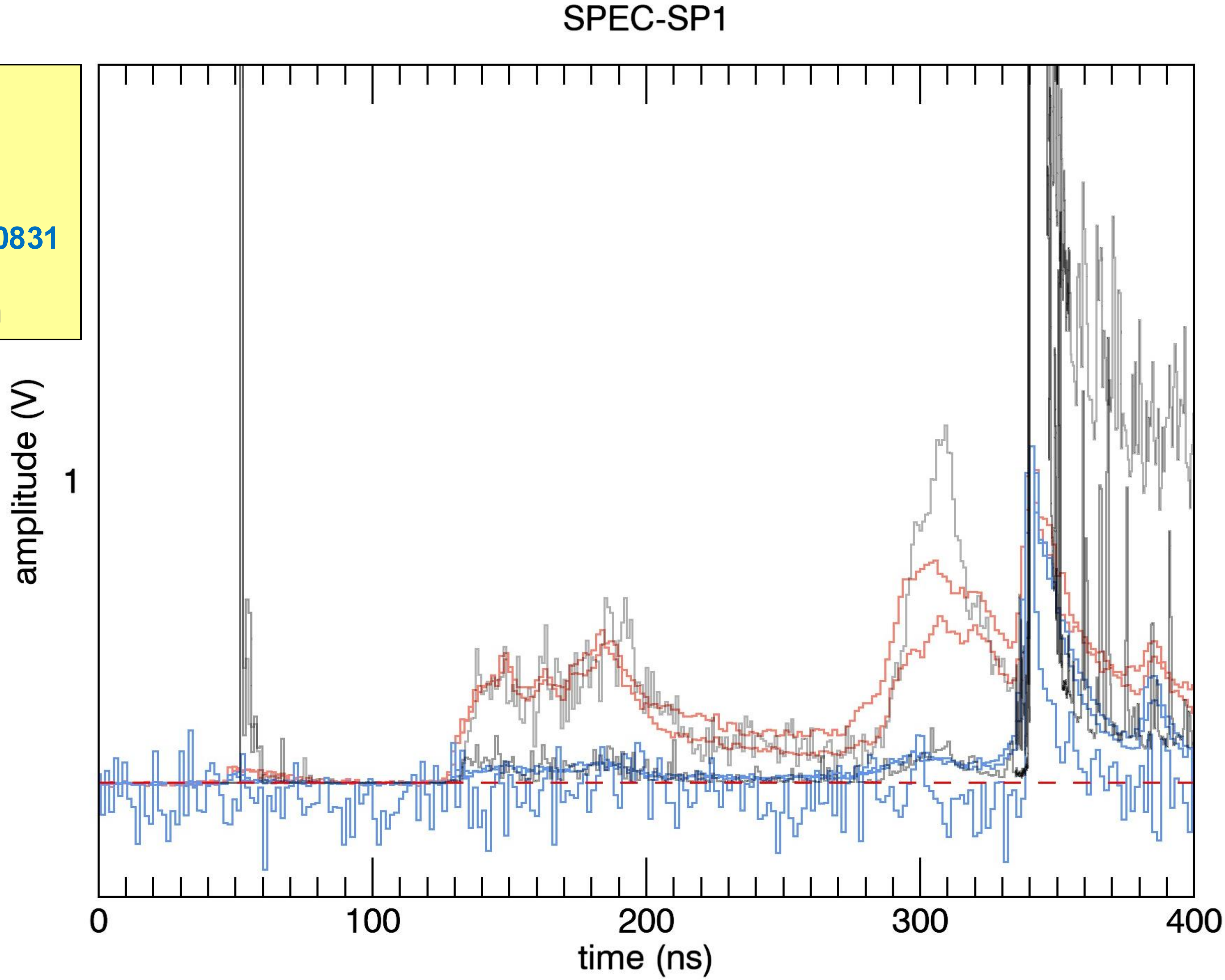


SPEC-P MCNP model



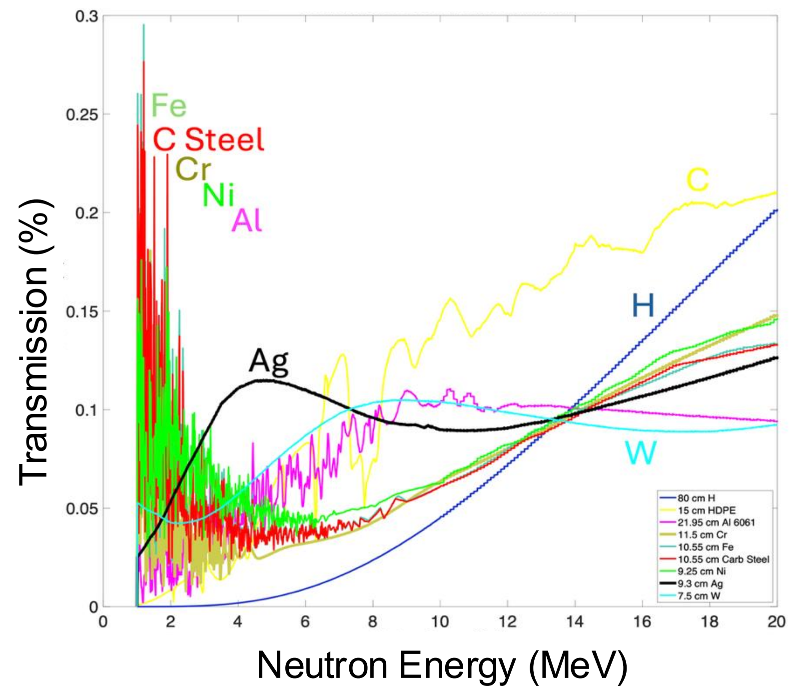
Comparing simulated photon background to measured signals with shielding in place

- ❖ **Red - without shielding N170524, N170813**
- ❖ **Blue - with shielding N170821, N170827, N170831**
- ❖ **Gray - MCNP simulation**

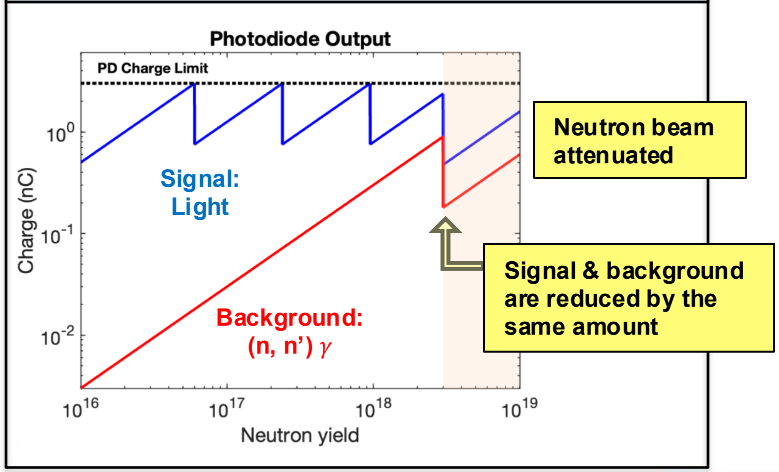


We need to extend the nTOF diagnostics to 10x higher D-T yields, and maintain linearity

- **One approach is to add physical material in the nTOF LOS's to reduce D-T neutron signals by 10x**
- **Must maintain measurements of the 4.4 MeV gammas (from target TMP) for timing/velocity inference and preserve DSR, D-D, and other measurements**
- **High-Z materials attenuate gammas and low-Z materials have "bumpy" cross-sections that impact D-D and DSR neutrons**
- **Silver appears to be a viable choice with smooth neutron cross-section, and acceptable attenuation of 1-20 neutrons, as well reasonable attenuation of the 4.4 MeV carbon gammas**
- **Better evaluation of the silver cross sections will be helpful**



Attenuating the neutron beam lowers both signal & background



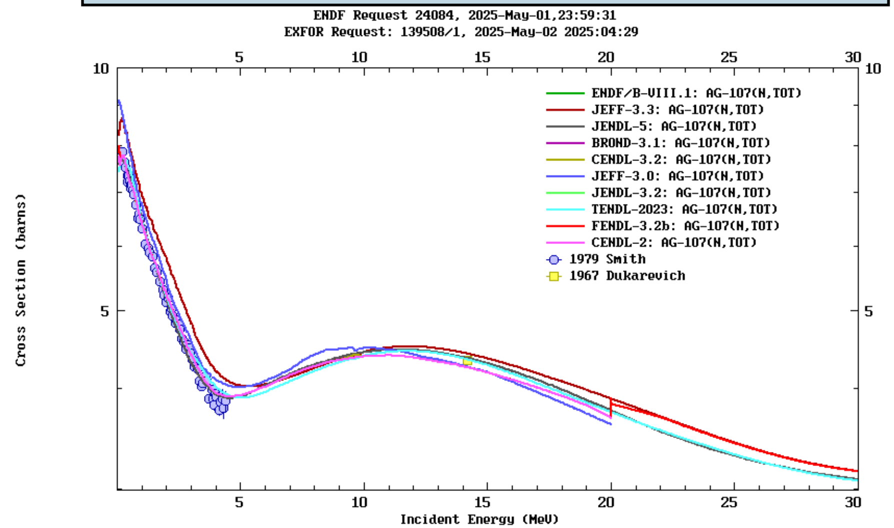
Limited experimental measurements of total neutron cross-section from 0.5-30 MeV for ^{107}Ag and ^{109}Ag

- We desire better evaluated total cross-section measurements
  - — ^{107}Ag: 4.5-30 MeV
  - — ^{109}Ag: 0.5-30 MeV

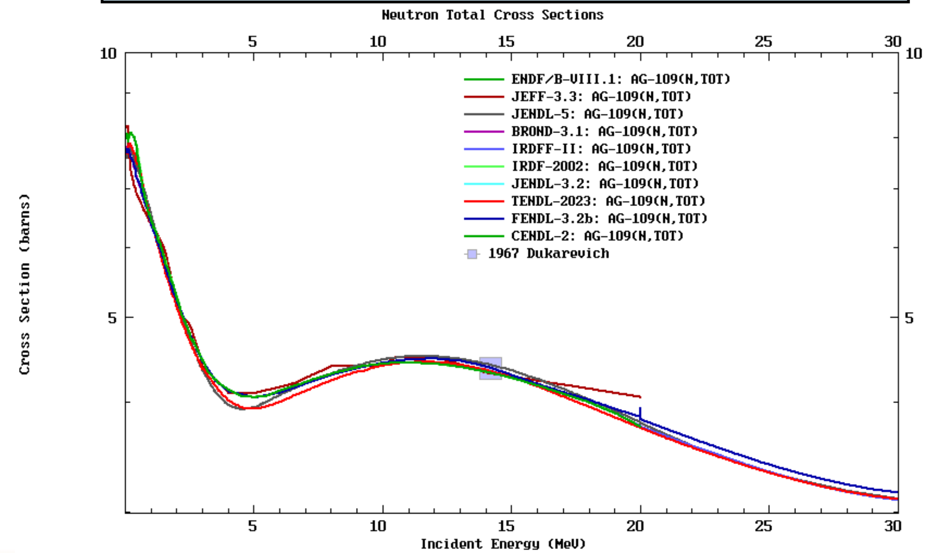
- There are subtle differences in cross sections for different evaluations

- We need to understand the relative signal differences at different energies

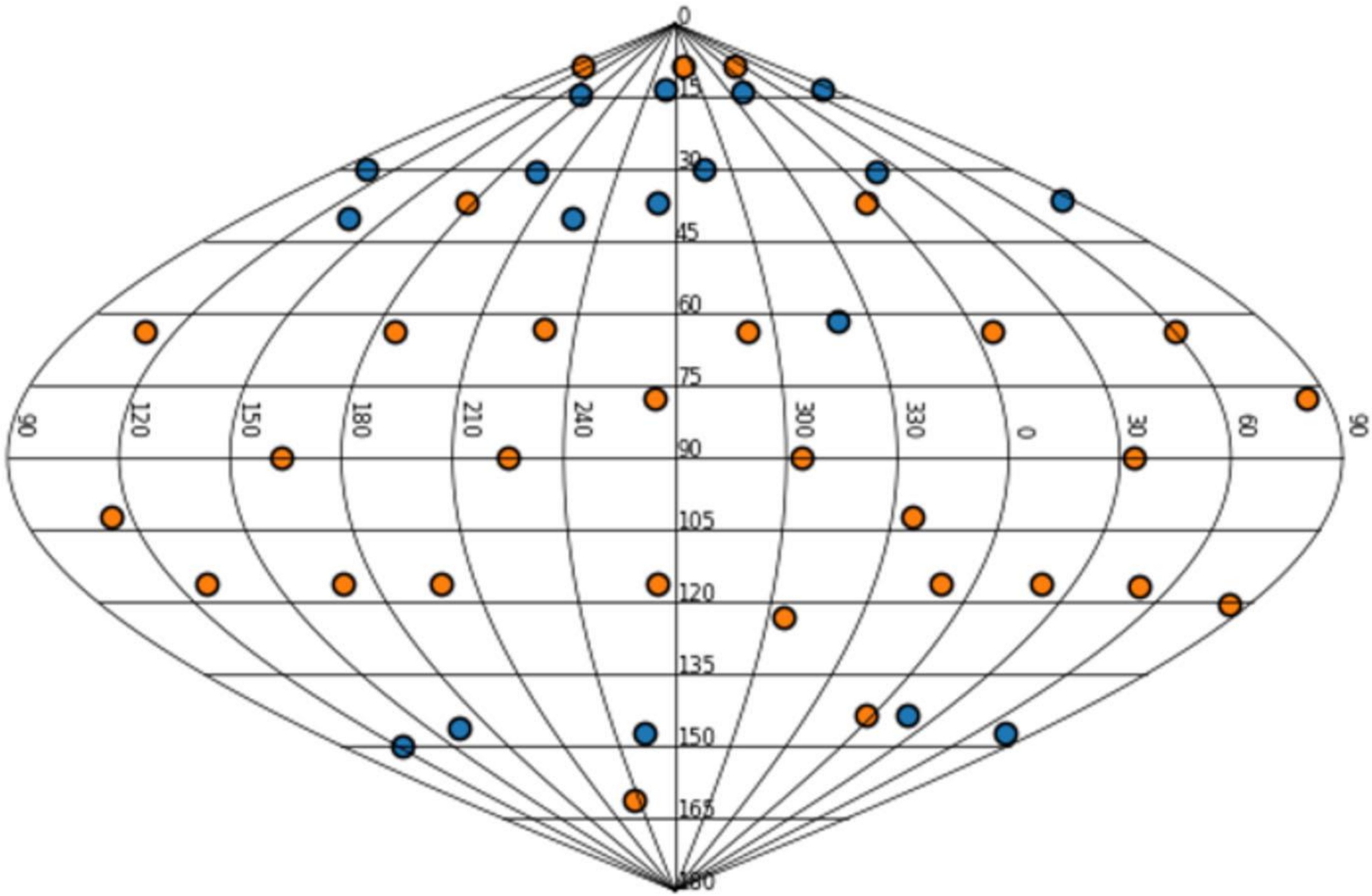
Total Neutron Cross Section: ^{107}Ag



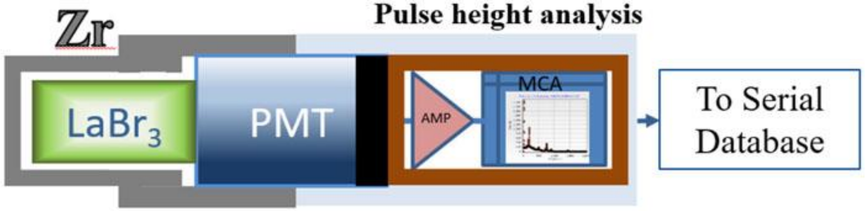
Total Neutron Cross Section: ^{109}Ag



Locations of the real-time nuclear activation detector (RTNAD) in the NIF chamber.



Using real-time nuclear activation detectors for measuring neutron yields



- The RTNADs use a Zr cap as an activation material for inferring D-T neutron yields via $^{90}Z(n,2n)^{89}Zr$

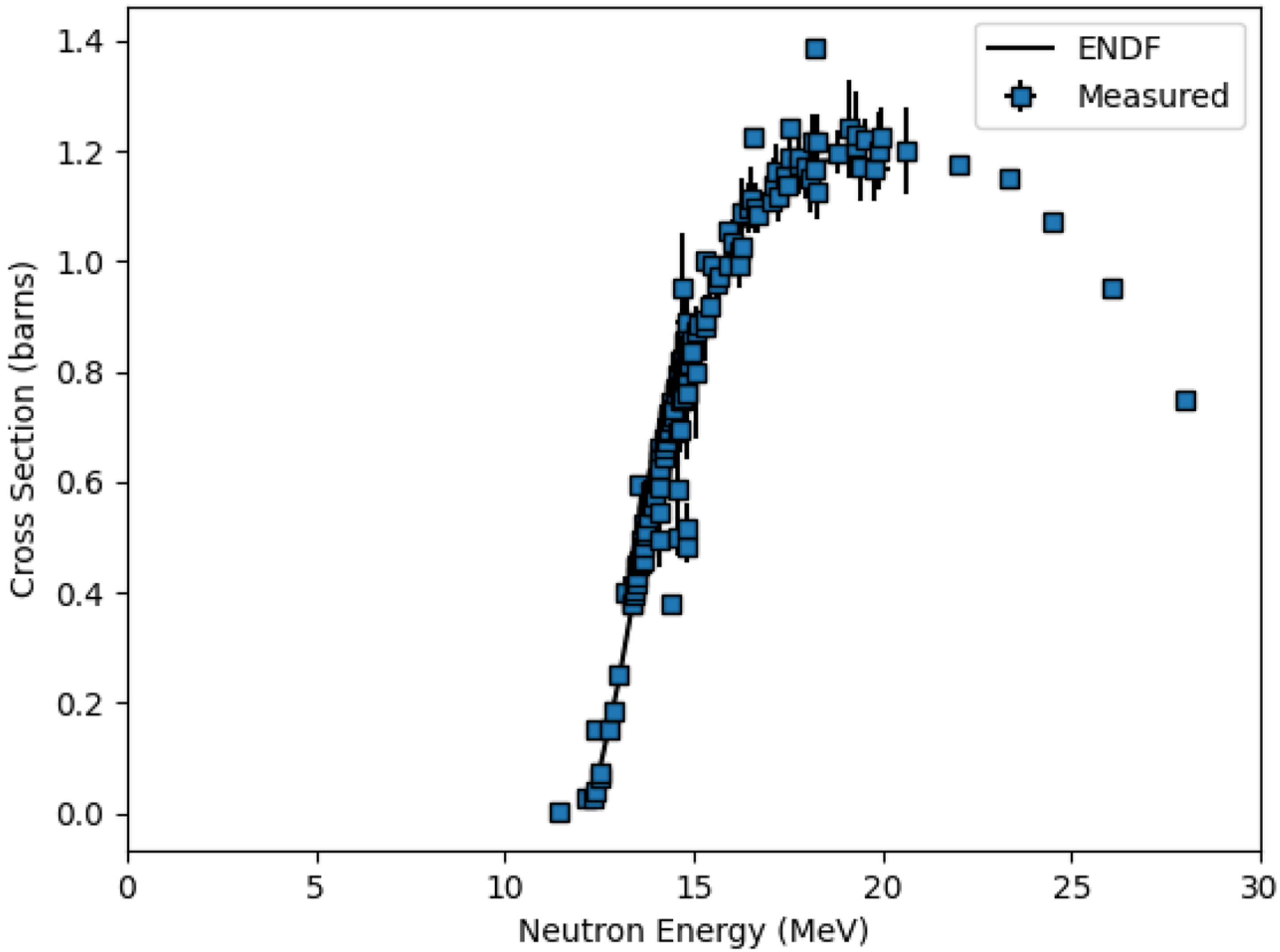
- The Zr cap surrounds a $LaBr_3$ scintillator, which is sensitive to gammas emitted from both the cap and the scintillator itself

- The $LaBr_3$ scintillators can be activated by lower energy neutrons, which is problematic for D-T neutron measurements, as it creates a source of background that can lead to high dead times immediately after the shot

- The fact that 2.5 MeV neutrons can activate the scintillator means the activation can be used to infer D-D neutron yields via the two reactions; $^{79}Br(n,n')^{79m}Br$ and $^{81}Br(n,\gamma)^{82}Br$

- More certain cross sections would enable more accurate understanding of sensitivities to the spectra

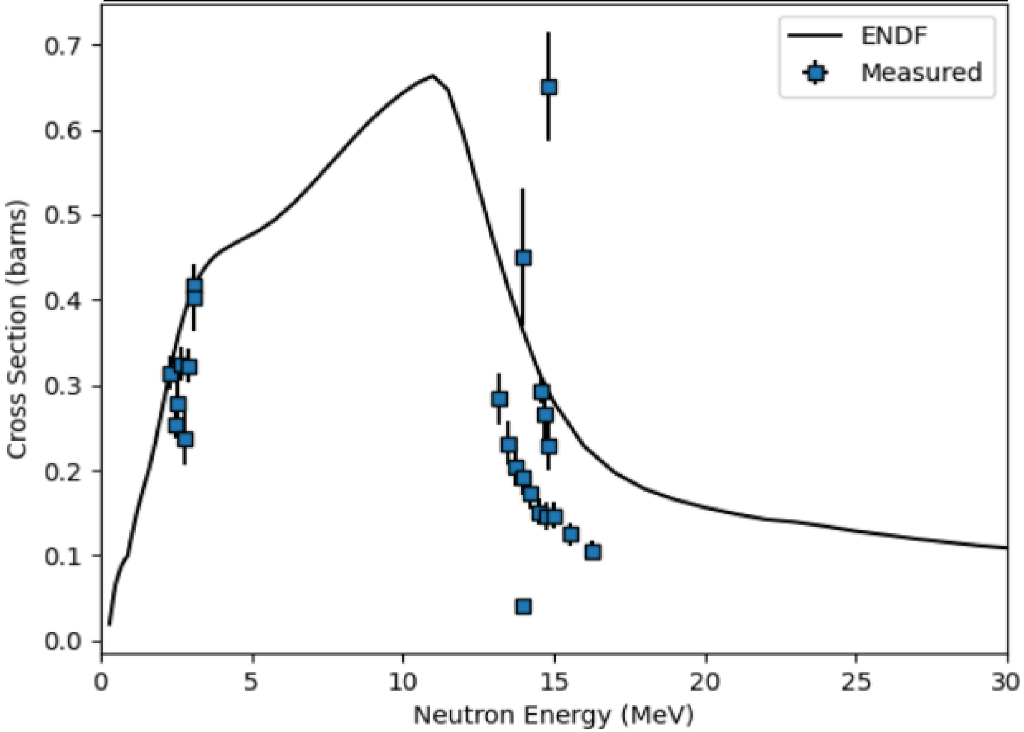
Good agreement between ENDF and measured cross sections (EXFOR) for ^{90}Zr (n,2n) reaction



Discrepancies between ENDF and measurements are observed in the ^{79}Br inelastic scattering reaction

- **Inelastic scattering reaction with ^{79}Br has a threshold-like behavior making it a good candidate for measuring D-D neutron yields**
- **The decreasing cross section with decreasing energy makes the reaction less sensitive to D-D neutrons that lose energy through scattering**
- **The low-energy threshold behavior enhances the ability of the reaction to determine the angular distribution of the 2.5 MeV neutrons from the ICF implosion**

Cross section as a function of energy for an inelastic scattering reaction with ^{79}Br

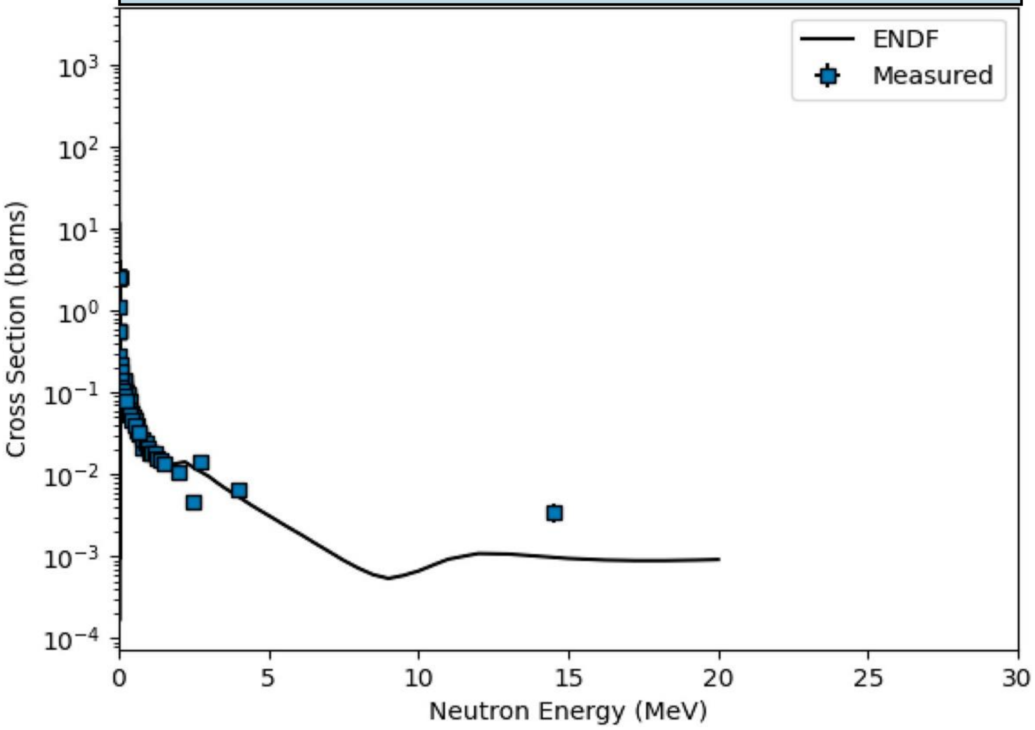


B. Lahmann, et al., Rev. Sci. Instrum. ***96****, 033506 (2025)*

Neutron reaction with ^{81}Br is not suitable for inferring D-D neutron yield

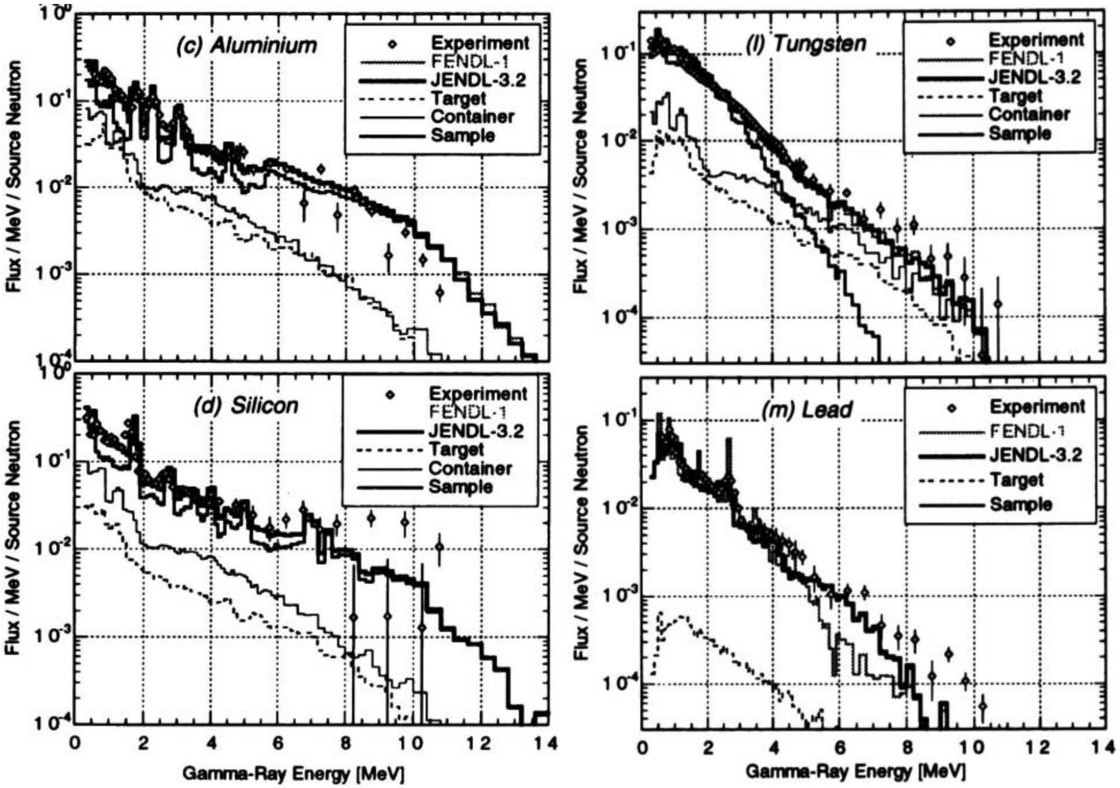
- The neutron absorption reaction with ^{81}Br rapidly increases with decreasing neutron energy
- While it is still possible to use this reaction to infer D-D neutron yield, it is a less ideal candidate as it is more sensitive to scattered neutrons and can compromise accurate determination of the neutron source distribution

Cross section as a function of energy for a neutron absorption with ^{81}Br



Inelastic scattering of neutrons (E > 6 MeV) is important for development of gamma detectors

- 14 MeV neutrons inelastically scattering on relevant elements
  - C, Al, Si, W, etc.
  - Limited experimental data available
  - How accurate are the current libraries?



F. Maekawa & Y. Oyama, Nuclear Science and Engineering ***123****, 272 (1996)*

List of reactions important for characterization of measured neutron spectrum

Foil (thickness)	Mass [g]	Reaction	Threshold [MeV] (@ 10 mb)	Primary radiation [keV] (intensity)	$t_{1/2}$
Au-1 (0.05 mm)	1.883	^{197}Au(n,2n)^{196}Au^{g+m1}	8.1 (8.3)	355.7 (0.87)	6.17 days
		^{197}Au(n,g)^{198}Au	Thermal	411.8 (0.9562)	2.69 days
Ni (0.23 mm)	4.073	^{58}Ni(n,2n)^{57}Ni	12.4 (13.3)	1378 (0.817)	35.6 h
		^{58}Ni(n,p)^{58}Co^{g+m1}	0 (1.3)	810.8 (0.9945)	70.86 days
In (0.27 mm)	3.665	^{113}In(n,n′)^{113}In^{m1}	0.4 (0.7)	391.7 (0.6494)	99.5 min
		^{115}In(n,n′)^{115}In^{m1}	0.336 (0.597)	336.24 (0.459)	4.49 h
		^{115}In(n,g)^{116}In^{m1}	Thermal	1293.56 (0.848)	54.29 min
Al (0.73 mm)	3.793	^{27}Al(n,a)^{24}Na	3.25 (6.7)	1368.63 (0.9999)	15 h
Ti (0.25 mm)	2.112	^{46}Ti (n,2n) ^{45}Ti	13.5 (14)	511.0 (1.696)	184.8 min
		^{nat}Ti(n,x)^{46}Sc	2.1 (6)	1120.5 (0.9999)	83.79 days
		^{nat}Ti(n,x)^{47}Sc	0.8 (10.5)	159.38 (0.683)	3.3492 days
		^{nat}Ti(n,x)^{48}Sc	3.3 (7.5)	1312.1 (1.001)	43.67 h
W (0.12 mm)	4.304	^{186}W(n,g)^{187}W	Thermal	685.51 (0.332)	24 h
Zr (0.27 mm)	3.083	^{90}Zr(n,2n)^{89}Zr	12.1 (12.1)	909.2 (0.9904)	78.41 h
Mg (0.09)	0.318	^{24}Mg(n,p)^{24}Na	4.9 (6.4)	1368.63 (0.9999)	15 h
Au-2 (0.05 mm)	1.884	^{197}Au(n,2n)^{196}Au^{g+m1}	8.1 (8.3)	355.7 (0.87)	6.17 days
		^{197}Au(n,g)^{198}Au	Thermal	411.8 (0.9562)	2.69 days

N. Quartemont et al., Nuclear Inst. and Methods in Phys. Research, A ***1016****, (2021)*

Reaction-in-flight (RIF) neutrons as a diagnostic for hydrodynamical mixing in double shell ICF capsules

- The neutron-induced RIF process involves a 14 MeV neutron elastically scattering a D or T ion in the plasma
- The scattered ion undergoes a D-T reaction and RIF neutrons can be produced with energies up to 30 MeV
- RIF spectra are several orders of magnitude lower than the 14 MeV neutron signal
- RIF spectra are measured at NIF by nToF or by activation of foils made of materials with energy thresholds > 14 MeV
- ^{169}Tm(n,3n)^{167}Tm (E_{th} = 15 MeV) and ^{209}Bi(n,4n)^{206}Bi (E_{th} = 22.5 MeV) reactions, are used to measure the RIF spectrum

NIF

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