SAND2011-6384C

Absolute measurement of DT neutron yield on the national ignition facility

R. J. Leeper[1], D. L. Bleuel[2], J. A. Frenje[3], M. J. Eckart[2], E. Hartouni[2], J. D. Kilkenny[4], D. T. Casey[3] , G. A. Chandler[1], G. W. Cooper[5], V. Yu. Glebov[6], C. Hagmann[2],M. Gatu Johnson[3], J. P. Knauer[6], K. M. Knittel[2], L. A. Linden-Levy[2], S. J. Padalino[7], R. D. Petrasso[3], C. L. Ruiz[1], T. C. Sangster[6], and F. H. Seguin[3]

[1] Sandia National Laboratories, Albuquerque, NM 87185 USA

[2] Lawrence Livermore National Laboratory, Livermore, CA 94550 USA

[3] Massachusetts Institute of Technology, Cambridge, MA 02139 USA

[4] General Atomics, San Diego, CA 92186 USA

[5] University of New Mexico, Albuquerque, NM 87131 USA

[6] University of Rochester, Rochester, NY 14627 USA

[7] State University of New York-Geneseo, Geneseo, NY 14454 USA

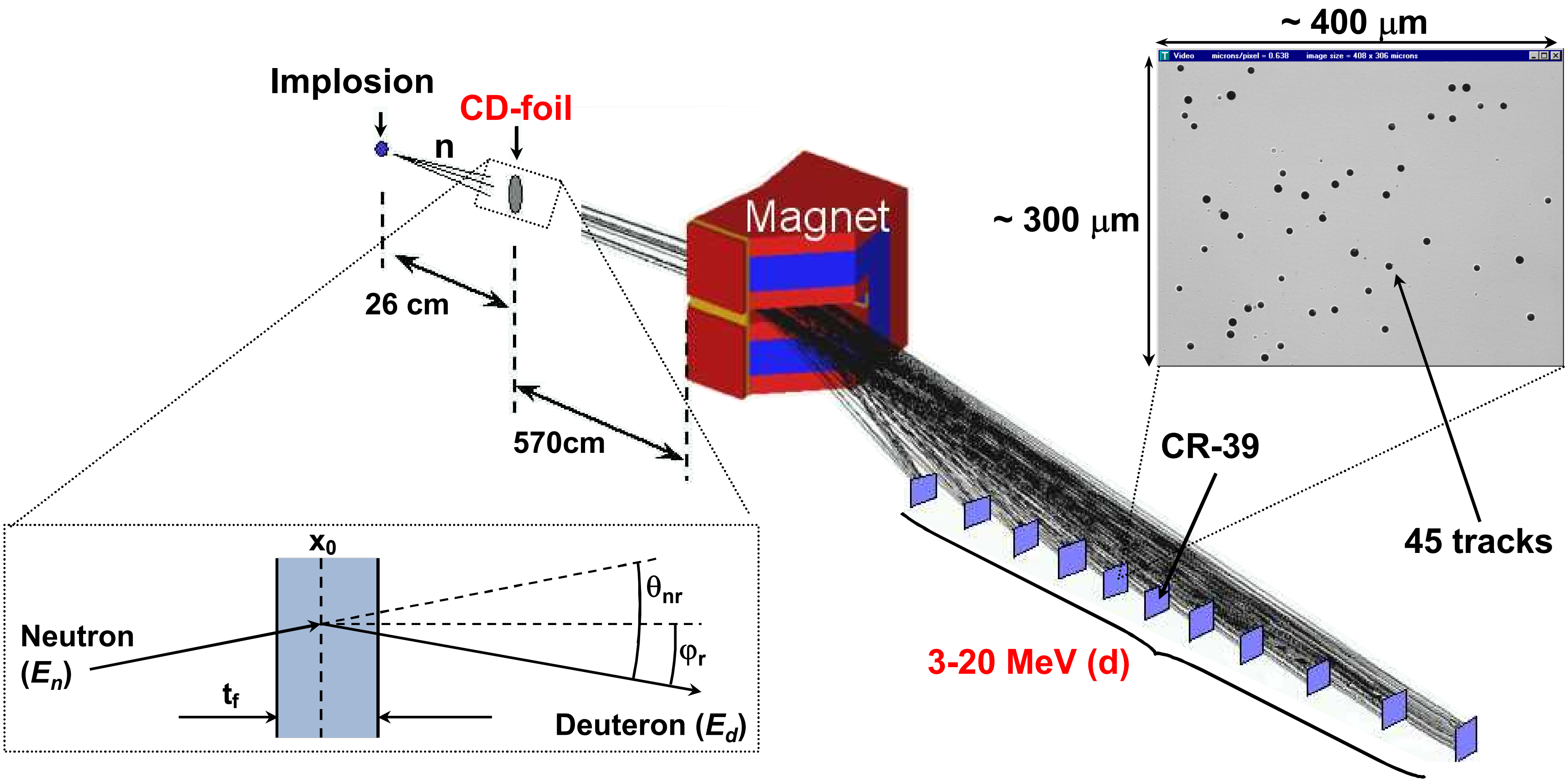
Sandia, Los Alamos, and Lawrence Livermore National Laboratories – National Ignition Campaign

This work performed under the auspices of the U.S. DOE by Sandia, Los Alamos and Lawrence Livermore National Laboratories under Contracts DE-AC04-94AL85000, DE-AC52-06NA25396 and DE-AC52-07NA27344

Abstract

Three diagnostic systems have been developed to perform measurements of the absolute total DT neutron yield on the National Ignition Facility (NIF). An accurate and precise measurement of neutron yield to ~ 5% is essential to gauge progress towards ignition on NIF but several factors, especially neutron scattering cause errors. The first diagnostic is the Magnetic Recoil Spectrometer (MRS) that magnetically analyzes recoil deuterium ions generated from neutron elastic scattering in thin CD foils. The deuterium ions scattered in the thin foil target are magnetically analyzed and detected in a CR-39 nuclear track recorder. An accurate measurement of the total neutron yield is inferred from the well-known n-d elastic scattering cross sections and from the number of tracks recorded on the CR-39. The second system is a copper activation system. This diagnostic uses the $^{63}Cu(n,2n)^{62}Cu(\beta+)$ reaction. The number of ^{62}Cu isotopes produced is measured using a positron coincidence counting system and provides a direct measurement of the total neutron yield through knowledge of the cross section for this reaction. The third diagnostic technique is a Zirconium activation system that employs the $^{90}Zr(n,2n)^{89}Zr$ reaction. The number of ^{89}Zr isotopes produced is measured using a high resolution Germanium gamma-ray spectrometer. The number of ^{89}Zr can in turn be related to the total neutron yield via the threshold cross section for this reaction. The philosophy used in developing these three yield diagnostics is to use physical processes that are independent of each other to minimize systematic errors inherent in each technique. The focus of the paper will be on identifying and estimating these systematic errors as well as addressing statistical errors as a function of total neutron yield for each of these diagnostics. Finally, the paper will discuss a standard weighted least-squares procedure of combining the measured yields and associated errors of each technique into a final yield and best-estimated error. This procedure is an adaptation of the procedure used in particle physics to combine measurements and associated errors from a number of different experiments into a best-estimated value and corresponding error.

The MRS measures the absolute neutron spectrum, using the recoil technique combined with a magnetic spectrometer



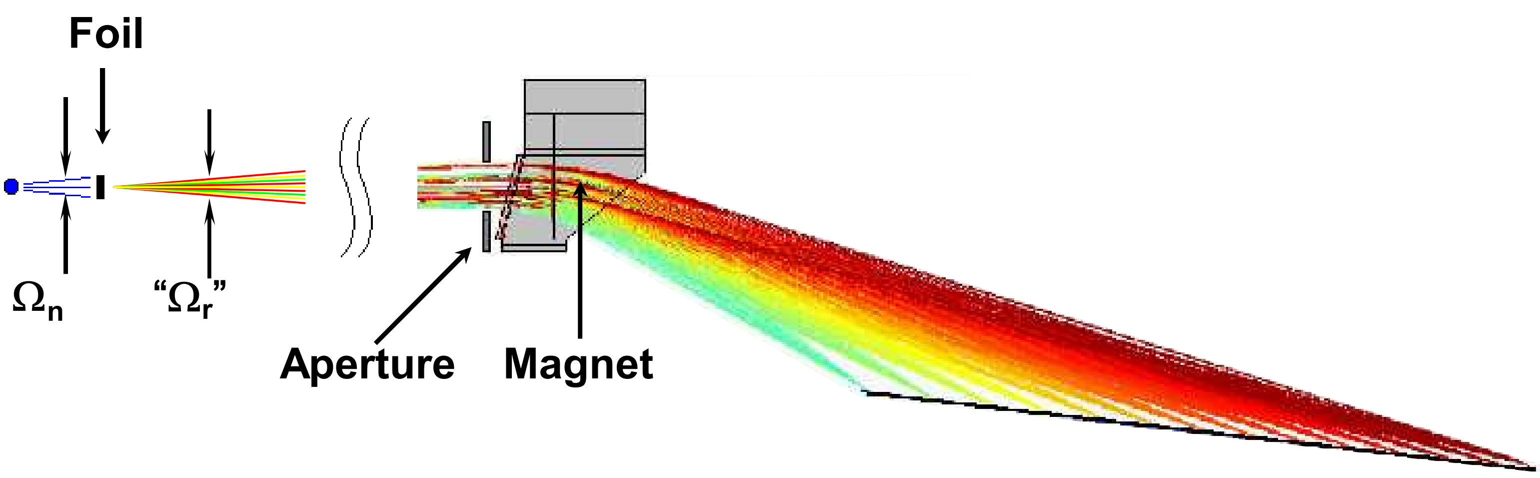
$$E_d \approx \frac{8}{9} E_n Cos^2\theta_{nd} - \frac{1}{Cos\varphi_r} \int_{x_o}^{t_f} \frac{dE(E_d)}{dx} dx$$

An absolute yield is measured with the MRS with high accuracy because all diagnostic parameters are well known

The MRS detection efficiency can be expressed as

$$\varepsilon_{MRS}(E_n) = \frac{\Omega_n}{4\pi} n_i t_f \int^{"\Omega_r"} \frac{d\sigma(E_n)}{d\Omega_{lab}} d\Omega$$

n_i : deuterium number density
t_f : foil thickness

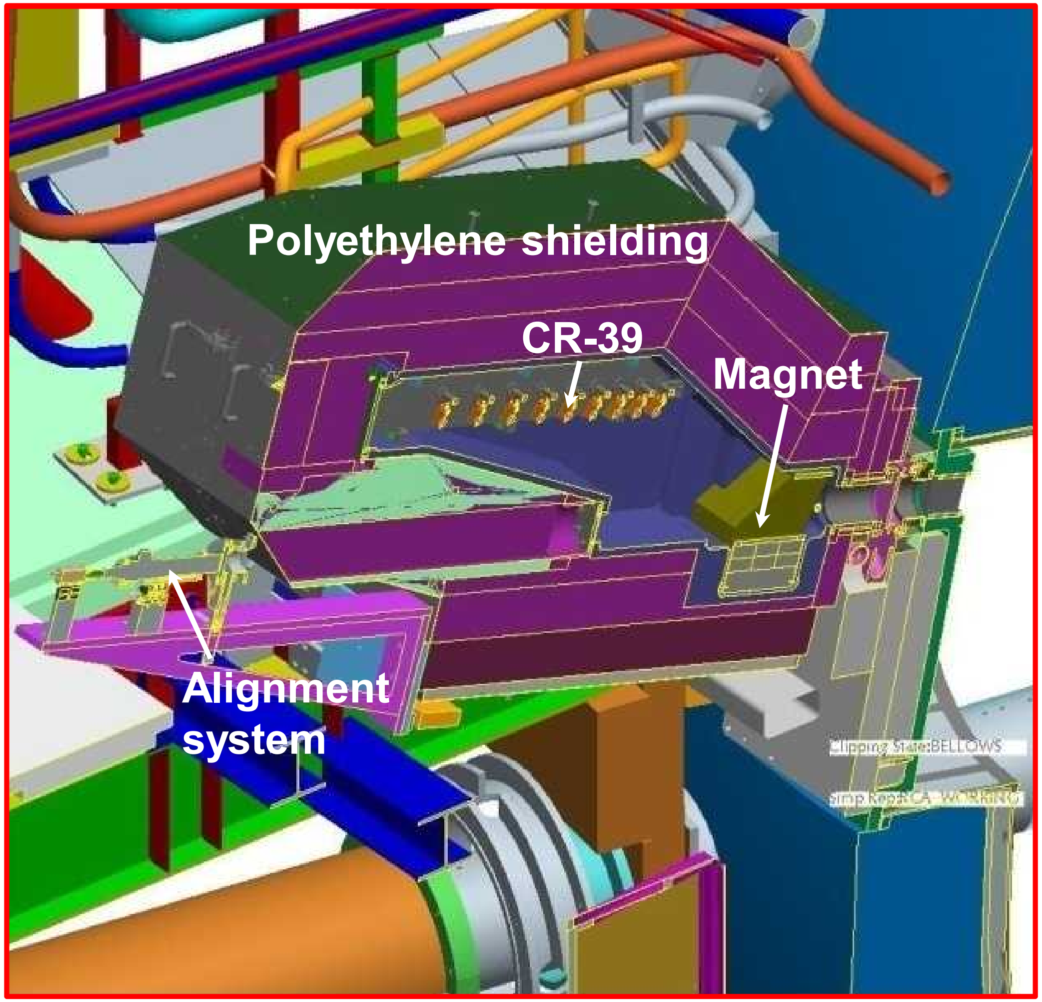


The absolute neutron yield is determined from the number of primary counts, i.e.,

$$Y_n \approx \frac{\sum S_d(E_d)}{\varepsilon_{MRS}(E_n)}$$

$S_d(E_d)$: number primary counts in MRS data

The MRS is positioned on the NIF chamber (LOS 77-324). The diagnostic is fully enclosed by 6000 pounds of polyethylene shielding for suppression of the ambient neutron background



Systematic uncertainties for the different MRS parameters and their contribution to the total systematic yield error for the MRS High-Res, Med-Res and Low-Res mode

	Absolute	High-Res [%]	Med-Res [%]	Low-Res [%]
Foil area uncertainty	±0.2 cm^2	±1.5	±1.5	±1.5
Foil distance uncertainty	±0.3 cm	±1.1	±1.1	±1.1
Number density uncertainty	±10^{21} cm^3	±1.3	±1.3	±1.3
Foil thickness uncertainty	±2.0 μm	±2.0	±0.8	±0.4
nd-cross section uncertainty (*1n*)	±12 mb/sr	±2.3	±2.3	±2.3
Magnet aperture area uncertainty	±0.2 cm^2	±1.0	±1.0	±1.0
Magnet aperture distance uncertainty	±0.1 cm	±0.02	±0.02	±0.02
Total systematic uncertainty for Y_{1n}		±4.4	±4.0	±3.9

$$\frac{\sigma_{Y_{1n}}}{Y_{1n}} \approx \sqrt{\left(\frac{\sigma_{A_f}}{A_f}\right)^2 + 4\left(\frac{\sigma_{R_f}}{R_f}\right)^2 + \left(\frac{\sigma_{n_i}}{n_i}\right)^2 + \left(\frac{\sigma_{t_f}}{t_f}\right)^2 + \left(\frac{\sigma_{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}}{\frac{d\sigma(1n,0^\circ)}{d\Omega_{lab}}}\right)^2 + \left(\frac{\sigma_{A_a}}{A_a}\right)^2 + 4\left(\frac{\sigma_{R_a}}{R_a}\right)^2}$$

The derivation of the systematic uncertainties can be found in the supplemental material.

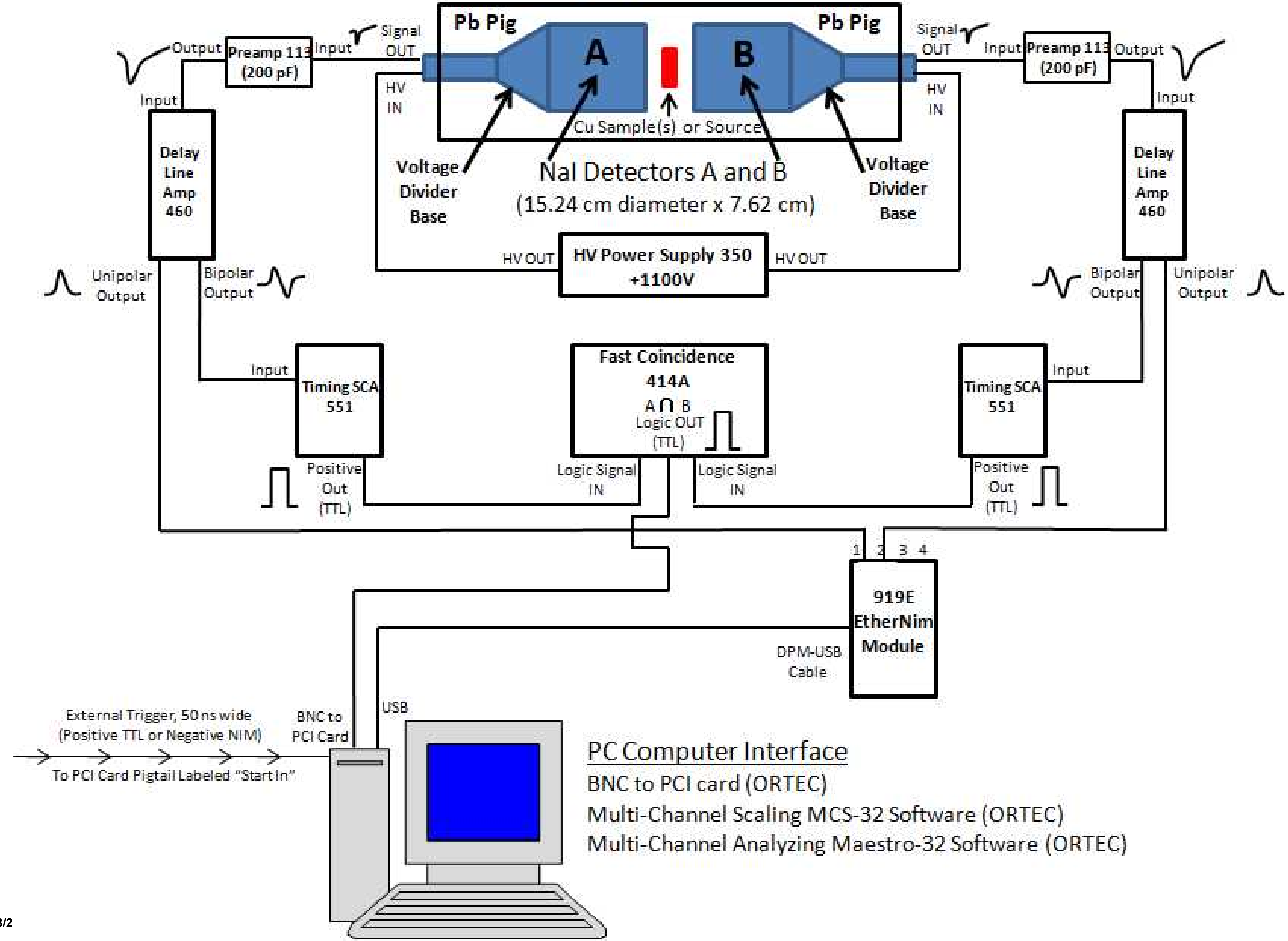
Statistical errors are < 1 % at Y_{1n} ~ 2.5 x 10^{14} when operated in Med-Res

A second measurement of the absolute DT total neutron yield on NIF is performed using a Cu Nuclear Activation Detector (CuNAD)

- The technique employs the $^{63}Cu(n,2n)^{62}Cu(\beta^+)$ reaction
  - Natural abundance of ^{63}Cu is 69.2 %
  - ^{62}Cu decay branching ratio to β^+ is 0.972
  - Cross Section σ(14.1 MeV) is 454.6 mb
  - Half Life $T_{1/2}$ of ^{62}Cu is 9.67 minutes
  - Reaction threshold energy E_{thres} is 11.0 MeV
  - ^{62}Cu β^+ endpoint energy is 2.9 MeV
  - β^+ annihilation 0.511 MeV gamma rays are counted in NaI coincidence counting system
- Two copper samples are used on NIF for this measurement
  - A thin copper sample (CuNAD19) that is 5.08 cm diameter by 0.1 cm thick located at 19.0 m from target chamber center
  - A thick copper sample (CuNAD29) that is 7.62 cm diameter by 0.95 cm thick located at 29.0 m from target chamber center
  - The thin copper sample is counted sandwiched between two copper disks that are each 5.08 cm diameter by 0.2 cm thick to insure that the β^+ annihilate in a well defined region located between the NaI scintillation detectors

NAD20

Diagram of Copper Counting System



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The copper activation sample and its mounting hardware is shown here in the NIF neutron alcove

The CuNAD counting system and Pb shield are shown mounted in the NIF neutron alcove

The CuNAD counting electronics are shown here in the NIF neutron alcove

The fundamental relationship that describes the neutron activation of any sample is given by

$$(C\text{-}B) = \phi\, \Sigma_{AB} \Sigma_{Det} \Sigma_{Br} \Sigma_{Self} M_S N_A \sigma(E)[(1 - e^{-\lambda t_o})(e^{-\lambda t_1} - e^{-\lambda t_2})]/\lambda A_S$$

where

C-B is counts minus background

ϕ is the neutron flux onto the sample

ε_{AB} is the natural abundance of the target nuclide

ε_{Det} is the detector's counting efficiency

ε_{Br} is the branching ratio of the emitted radiation

ε_{Self} is a factor that accounts for self-attenuation within the sample and counting geometry

M_S is the mass of the activation sample

N_A is Avogadro's number

σ (E) is the energy dependent activation cross section

λ is the radionuclide's decay constant

t_0 is the sample irradiation time

t_1 is the start time of the sample's counting referenced to the end of sample irradiation

t_2 is the stop time of the sample's counting referenced to the end of sample irradiation

A_S is the atomic weight of the activation sample

For an isotropic point source that emits S neutrons per second the neutron flux in terms of the yield Y is given by

$$\varphi = S/(4\pi d^2) = Y/(t_0 4\pi d^2)$$

where

d is the source to detector distance

If substitute this expression for φ in the above relationship we have

$$(C\text{-}B) = Y/(t_0 4\pi d^2) \Sigma_{AB} \Sigma_{Det} \Sigma_{Br} \Sigma_{Self} M_S N_A \sigma(E)[(1 - e^{-\lambda t_o})(e^{-\lambda t_1} - e^{-\lambda t_2})]/\lambda A_S$$

If we irradiate the sample with a pulsed source, the term $(1 - e^{-\lambda t_o})$ becomes simply λt_0 and we have

$$(C\text{-}B) = Y/(4\pi d^2) \Sigma_{AB} \Sigma_{Det} \Sigma_{Br} \Sigma_{Self} M_S N_A \sigma(E)(e^{-\lambda t_1} - e^{-\lambda t_2})/A_S$$

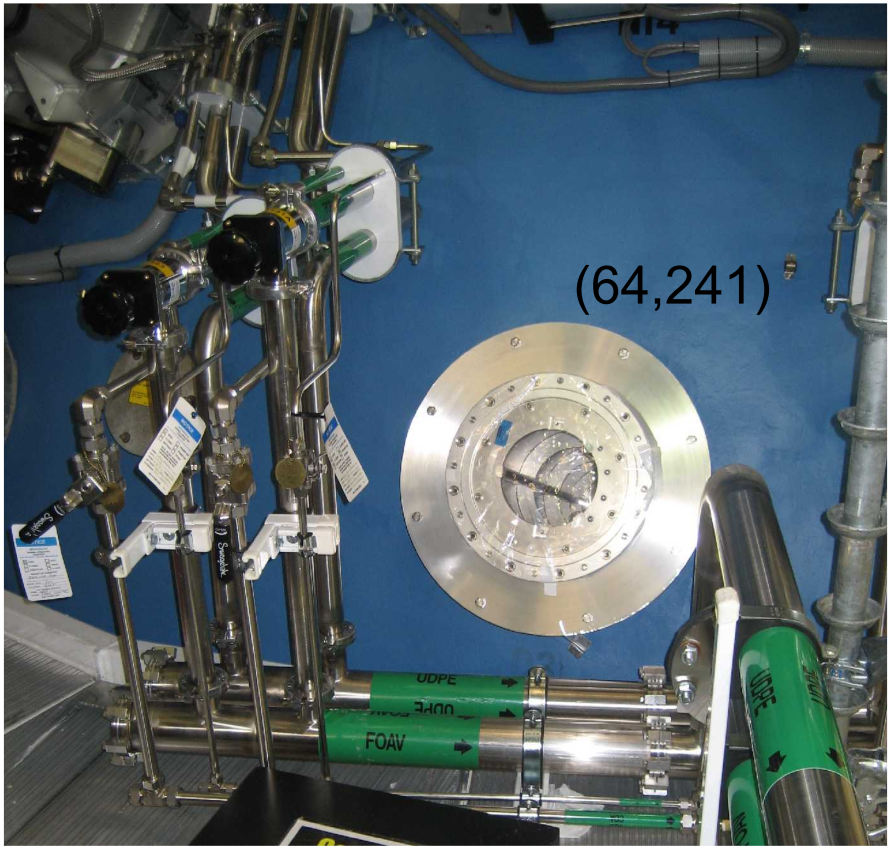
Typical systematic and statistical errors for the NIF Cu NAD are shown here

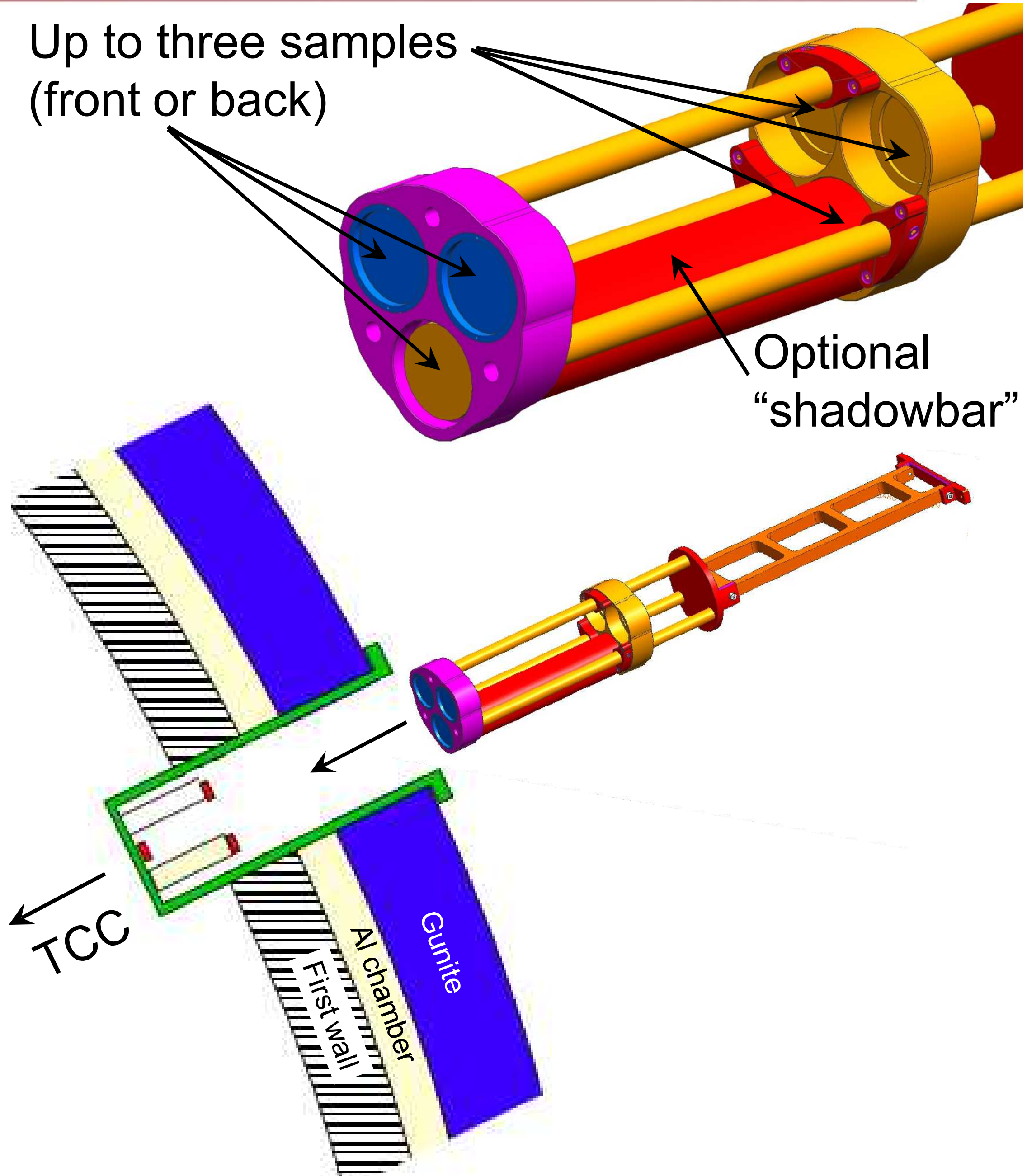
Quantity	Value	Relative Error	Relative Error (%)
Cu^{63} Natural Abundance	0.6917	0.0003	0.04
Cu^{62} Decay Branching Ratio	0.9743	0.0002	0.02
Detector Counting Efficiency	0.1445	0.0044795	3.10
Self Attenuation for 511 keV Photons	0.95	0.0475	5.00
Cross Section at 14.1 MeV (cm^2)	4.5459E-25	5.86421E-27	1.29
Cu^{62} Decay Half-life (min)	9.673	0.008	0.08
Cu^{62} Mean Half-life (min)	13.95518913	0.01154156	0.08
Sample Distance (cm)	1900.5	1.9005	0.10
Attenutation Factor	1.965	0.0786	4.00
Total Systematic Error			7.25
Typical Statistical Error			1.00

A third measurement of the absolute DT total neutron yield on NIF is performed using a Zr "Well NAD" technique

- The technique employs the $^{90}Zr(n,2n)^{89}Zr$ reaction
  - Natural abundance of ^{90}Zr is 54.45 %
  - 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 $E\gamma$=909 keV line

$^{90}Zr(n,2n)^{89}Zr$ activation geometry on NIF is shown here





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

$^{90}Zr(n,2n)^{89}Zr$ Activation for D-T Yield Anisotropy Uncertainties (Accuracy/Precision)

NIC

Effect	Effect on Activity (8.65cm Zr)	Well-mounted "Accuracy" (Zirconium)	Anisotropy "Precision" (Zirconium)
Detector efficiency		2-5%	<2%
Gamma-ray self-shielding	(-15%)*	*	--
Neutron "depletion" in zirconium	-3.1%	0.6%**	--
Self-shielding differential from neutron depletion		2%	--
Cross section uncertainty		1%	--
Position uncertainty		1.1%	<1%
Scatter/absorption off Al shield/well	-5.7%	1.1%**	--
Chamber/wall scatter		<1%	--
Scatter off nearby materials		<1%	--
Downscattered/non-primary neutrons		2%	<2%
Drift velocity/temperature peak shift (<100keV)		2%	2%
Ion Temperature peak broadening		<1%	--
Sample purity (98.7%)	-1.35%	0.2%	0.2%
Sample weight/oxidation/contamination		<1%	<1%
TOTAL SYSTEMATIC		6%	3%
Statistical		1%***	2%***

(WELL) (FLANGE)

***Yield > 10^{14}

**20% of effect

*included in detector efficiency/analysis

On each NIF shot, a standard weighted least-squares technique is used to determine a final "authorized" neutron yield and associated best estimated error

NIC

- This procedure is an adaptation of the procedure used in particle physics to combine measurements and associated errors from a number of different experiments into a best estimated value and corresponding error (See K. Nakmura et al. (Particle Data Group), Phys. G 37, 075021 (2010)
- To average the data, the technique uses a standard weighted least squares procedure

$$\bar{x} \pm \delta\bar{x} = \frac{\sum_i w_i x_i}{\sum_i w_i} \pm \left(\sum_i w_i\right)^{-1/2}$$

where

$$w_i = 1/(\delta\bar{x}_i)^2$$

- Here x_i and δx_i are the value and error reported by the ith experiment and the sums run over N experiments. Next $\chi^2 = \sum w_i(\bar{x} - x_i)$ is calculated and compared with N-1, which is the expectation value of χ^2 if the experiments are from Gaussian distributions
- If χ^2/(N-1) is less than or equal to 1, and there are no known problems with the data, the results are accepted
- If χ^2/(N-1) is very large, the data may not be averaged at all
- If χ^2/(N-1) is greater than 1, but not greatly so, the data is still averaged but the error bars on all the measurements are increased by a scale factor S defined as

$$S = \left[\chi^2/(N-1)\right]^{1/2}$$

This table shows a comparison of yield values obtained via Cu NADs, Zr NADs, and MRS along with the NIF authorized value for a represenitive number of NIF shots

NIC

NIF Shot Number	Thin Cu Yield	Thick Cu Yield	Zr Yield	MRS Yield	Authorized NIF Value
101030 Exploding Pusher	2.12×10^{14} ± 9.0 %	2.17×10^{14} ± 7.6 %	2.33×10^{14} ± 7.3 %	2.22×10^{14} ± 5.1 %	2.36×10^{14} ± 6.4 %
110121 Layered THD	2.21×10^{13} ± 10.0 %	2.01×10^{13} ± 10.9 %	2.08×10^{13} ± 7.2 %	2.10×10^{13} ± 5.0 %	2.12×10^{13} ± 3.0 %
110201 Layered THD	1.31×10^{14} ± 7.8 %	1.11×10^{14} ± 7.9 %	1.08×10^{14} ± 7.1 %	1.10×10^{14} ± 4.5 %	1.11×10^{14} ± 3.6 %
110217 Exploding Pusher	1.88×10^{14} ± 8.2 %	1.95×10^{14} ± 7.7 %	1.94×10^{14} ± 7.1 %	1.98×10^{14} ± 5.0 %	1.95×10^{14} ± 3.2 %
110603-2 Exploding Pusher	2.18×10^{14} ± 7.5 %	2.09×10^{14} ± 7.5 %	2.14×10^{14} ± 7.4 %	2.21×10^{14} ± 4.4 %	2.31×10^{14} ± 2.2 %
110212 Layered THD	1.27×10^{14} ± 7.9 %	1.23×10^{14} ± 7.7 %	1.18×10^{14} ± 7.7 %	1.23×10^{14} ± 4.5 %	1.26×10^{14} ± 2.9 %
100923 Exploding Pusher	Not Fielded	5.09×10^{13} ± 7.7 %	4.66×10^{13} ± 7.3 %	5.41×10^{13} ± 5.3 %	5.05×10^{13} ± 3.4 %
100929 Layered THD	Not Fielded	8.51×10^{12} ± 12.4 %	7.43×10^{12} ± 7.4 %	8.6×10^{12} ± 14.4 %	7.54×10^{12} ± 7.5 %
101212 Exploding Pusher	Not Fielded	1.38×10^{14} ± 8.0 %	1.52×10^{14} ± 6.5 %	1.45×10^{14} ± 6.0 %	1.49×10^{14} ± 2.2 %
110618 Exploding Pusher	2.30×10^{14} ± 7.5 %	2.23×10^{14} ± 7.5 %	2.37×10^{14} ± 7.7 %	Not Fielded	2.48×10^{14} ± 2.7 %
100917 Exploding Pusher	Not Fielded	1.12×10^{13} ± 10.1 %	1.14×10^{13} ± 7.7 %	Failed N-P Foil	1.19×10^{13} ± 6.8 %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