National Ignition Facility Neutron Sources

Hardened Electronics and Radiation Technology

C.5

Charles B. Yeamans and Brent E. Blue

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Lawrence Livermore National Laboratory

National Ignition Facility Neutron Sources

outline

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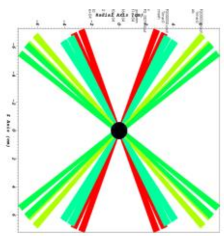
Abstract

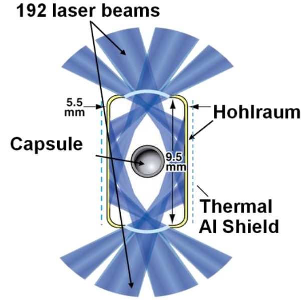
Neutron experiments conducted at the National Ignition Facility can utilize high neutron fluences delivered in very short pulses. By adapting inertial confinement fusion laser pulses and targets, fluences of up to 10^{15} n/cm^2 can be achieved on small experimental volumes, and prospectively up to 10^{16} n/cm^2 onto capsule materials under development. Neutron pulse lengths are less than 1 ns. Large experimental volumes from 150 cm^3 to 20 L can access fluences of 10^8-10^{12} n/cm^2. Experimental platforms may contain encapsulated hazardous materials, active electronics connected to sophisticated prompt read-out equipment, and large assemblies up to 200 kg. Sources are designed to maximize total yield, total experimental fluence, or maximum fluence per user-day allocated as required.

National Ignition Facility Neutron Sources
outline

The National Ignition Facility is the world's largest laser-driven neutron source.

Overview: Using the NIF as a neutron source





	Direct drive	Indirect drive
Capsule material	CH, SiO_2	CH, C, Be, other
Hohlraum material	n/a	Au, Au/DU
Fielding temperature	293 K	293 K, 18-120 K
DT yield	4×10^{15}	1.7×10^{16}
Burn duration (ps)	250	150-200
Neutron thermal temperature (keV)	8-15	2-5
Maximum fluence available (n/cm^2)		
Destructive	3×10^{14}	3×10^{15}
nondestructive	6×10^{12}	1.6×10^{13}
DT neutrons per NIF optics log growth	74	9

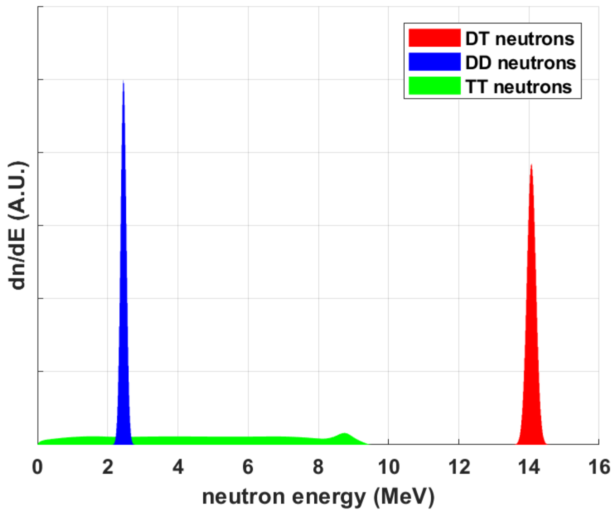
- Experiments enter through the NIF User Office or specific programs.
- Based on user needs, individual experiments are fielded on an available NIF neutron yield shot.
- Experiments are designed into a diagnostic instrument manipulator (DIM) or Target and Diagnostic Manipulator (TANDM), with design based on fluence an volume requirements.

Overview: Practical considerations for a NIF user

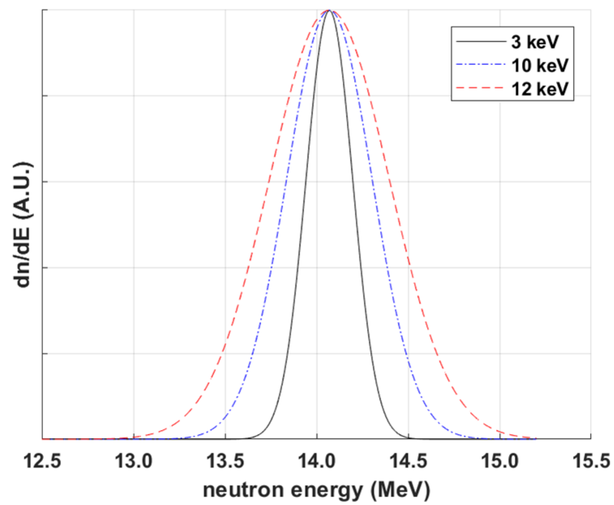
- Experiments allocated through accepted program proposals (JNSAC/NSA, HED and ICF councils, Discovery Science) can select their experimental configuration to best use the allocation.
- Ride-along: Any NIF DT yield shot (29 in FY17, 26 in FY16) may support additional experiments through coordination with the campaign experimental team. This includes NIF facility neutron calibration shots as well as programmatic.
- Optics Use: NIF is a rare laser facility operating above the optics damage threshold. A computational laser performance model helps determine the "optics use" per proposed laser shot in units of damage log growth.
- Shot cycle length: Allocation is usually made in "user days." Neutron yield shots have lengthy neutron mitigation procedures. Typical planning is one yield shot per user day.
- Debris and Shrapnel: The experimental planning process at NIF focuses on machine safety and maintaining experimental throughput.

Overview: Fusion spectra available at NIF

- All neutron sources have designs for 14 MeV deuterium-tritium (DT), 0-10 MeV pure tritium (TT), pure deuterium (DD), and He-3 and He-4 for charged particle sources.



Energy spectrum per source neutron for different gas fills

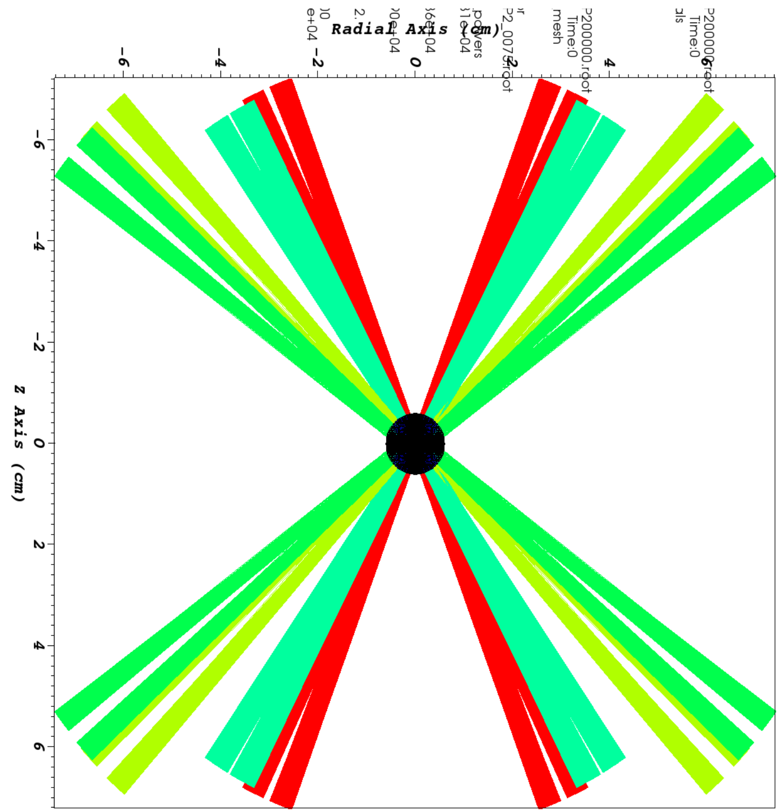


Energy spectrum per source DT neutron for different burn temperatures

Source yields for TT and DD are typically 1% of those for DT due to the difference in fusion reactivity of the respective species.

National Ignition Facility Neutron Sources
outline

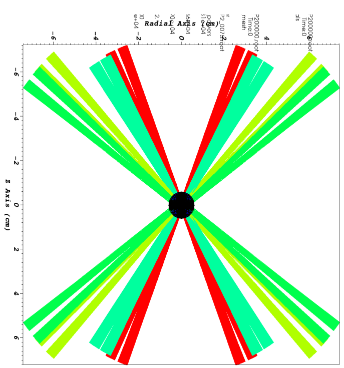
NIF Neutron Sources: Direct Drive



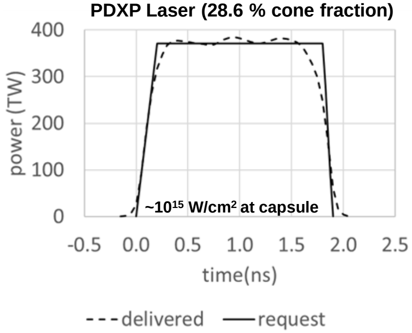
- Because the NIF beam geometry supports experiments with z-oriented hohlraums, experiments utilizing laser energy depositions directly on the imploding surface are configured in a pole-hot geometry.
- Subsequent fundamental physics work has refined the PDD technique to produce reliable high neutron yields using a simple, low-mass target assembly.
- The low-mass target assembly reduced the debris wind load substantially, allowing neutron experiments using PDD sources to reduce their source standoff.

NIF Neutron Sources: Polar direct drive exploding pusher (PDXP)

		PDXP
Inputs	Fill gas DT	65:35
	capsule pressure (torr)	6080
	Target temperature (K)	room
	Laser energy (MJ)	0.62
	optics log growth per shot	0.005
	shot cycle time (h)	9
Outputs	expected yield (DT)	3.7×10^{15}
	$\check{T}_{ion}$ (keV)	12
	burn width (ps)	250-300
	neutron volume (mm^3)	0.05
	output spectrum	pure DT
	minimum sample standoff (cm)	1
	minimum DLP standoff (cm)	5
Metrics	10^{15} neutrons/optics log growth	740
	doping capsule/fill	y/y
	max fluence: destructive (n/cm^2)	2.9×10^{14}
	max fluence: non-destructive (n/cm^2)	1.2×10^{13}

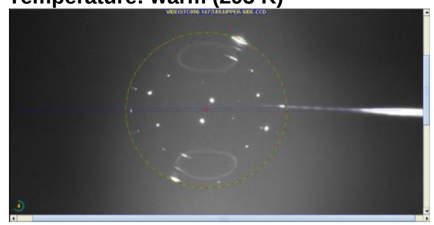


PDXP Laser (28.6 % cone fraction)

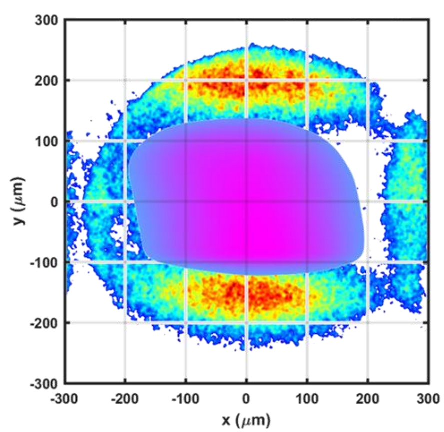


Target

Material: CH (GDP)
Outer diameter: 2.9 mm
Thickness: 18 microns
Gas fill: 65:35 DT, 8 atm (1.6 mg/cc)
Temperature: warm (293 K)

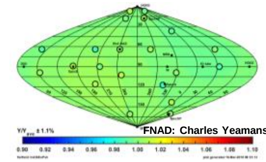


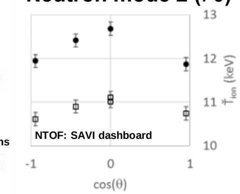
N170913-001 PDXP source



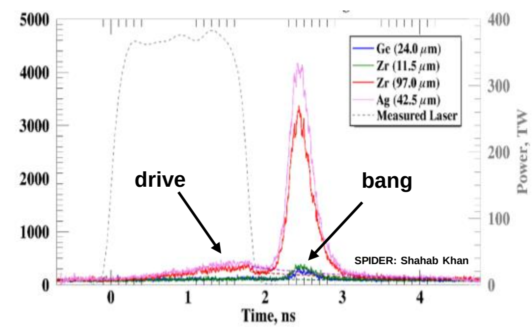
CNXI 90-315 x-ray (MATLAB jet) with primary neutron image (purple-blue cool) overlaid.

Neutron mode 1 (=0) **Neutron mode 2 (≠0)**





Time-resolved spatially-integrated x-ray emission

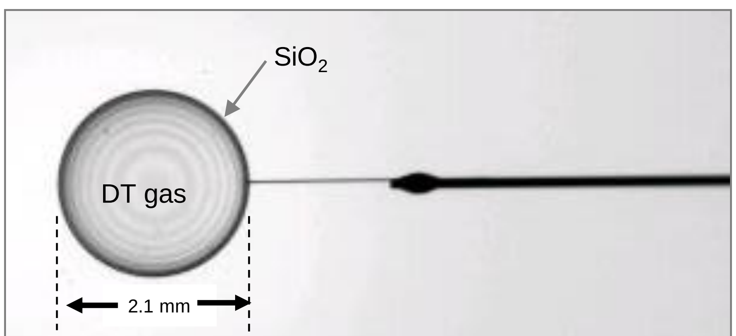


As N_Sdev_ExPsh moves to improved capsules, x-ray yield is expected to increase 5x.

- PDXP source is a pure 14 MeV DT fusion output from a nearly massless system.
- Target downscatter is minimized and required experimental standoff is less than for cooled targets.
- allows 5 cm source standoff
- Targets are relatively easy to field, possible to execute 2 shots in one user shot/day.

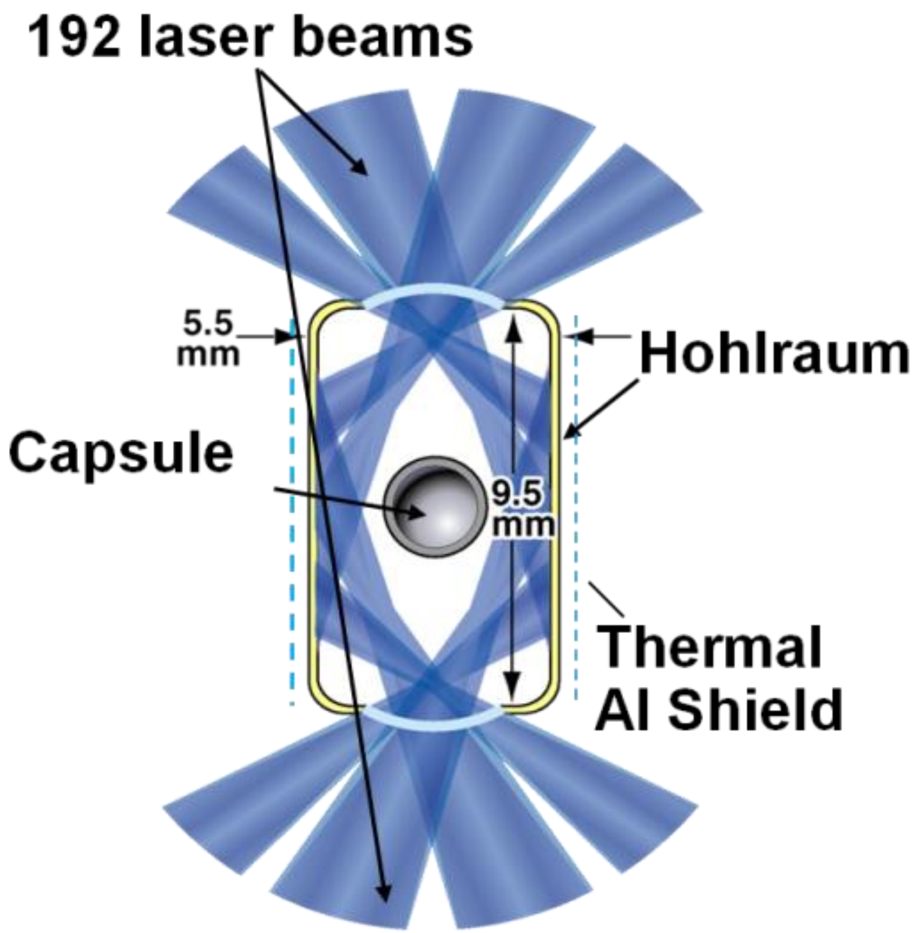
NIF Neutron Sources: glass direct drive exploding pusher (DDEP)

		DDEP
Inputs	Fill gas DT	50:50
	capsule pressure (torr)	7600
	Target temperature (K)	room
	Laser energy (MJ)	0.82
	optics log growth per shot	0.01
	shot cycle time (h)	9
Outputs	expected yield (DT)	8×10^{14}
	$\check{T}_{ion}$ (keV)	7
	burn width (ps)	250-300
	neutron volume (mm^3)	0.05
	output spectrum	pure DT
	minimum sample standoff (cm)	4
	minimum DLP standoff (cm)	5
Metrics	10^{15} neutrons/optics log growth	80
	doping capsule/fill	n/y
	max fluence: destructive (n/cm^2)	4.0×10^{12}
	max fluence: non-destructive (n/cm^2)	2.5×10^{12}



- diffusion-filled SiO_2 capsule up to 2.1 mm in diameter
- The diffusion filling process allows for precisely-tuned gas fills that may not be practically adapted to the NIF shot-time gas fill system
- Max fuel pressure is limited only by capsule burst and not NIF gas delivery rating
- ability to suppress DT yield using high-Z noble gas fill dopants.

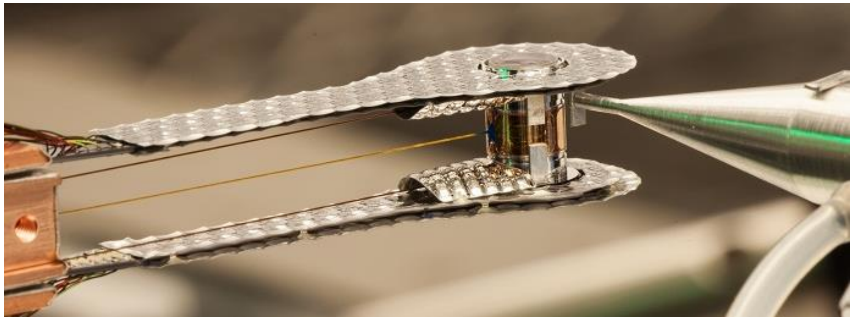
NIF Neutron Sources: Indirect Drive



- indirect drive smooths the radiation profile impinging on the ablating surface substantially.
- has been the choice of the NIF ICF ignition science program.
- Indirect drive neutron sources have been developed and tested over a wide range of neutron yield and output spectrum parameters.
- The target assemblies are relatively massive, therefore limiting the minimum source-experiment standoff.

NIF Neutron Sources: indirect drive exploding pusher (IDEP)

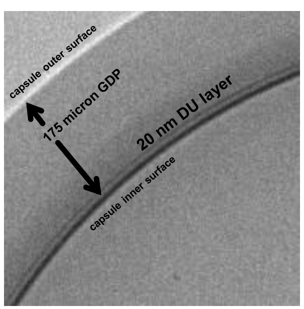
		IDEP
Inputs	Fill gas DT	50:50
	capsule pressure (torr)	2487
	Target temperature (K)	32
	Laser energy (MJ)	0.71
	optics log growth per shot	0.027
	shot cycle time (h)	16
Outputs	expected yield (DT)	5.5×10^{14}
	$\check{T}_{ion}$ (keV)	5
	burn width (ps)	250-300
	neutron volume (mm^3)	0.05
	output spectrum	pure DT
	minimum sample standoff (cm)	0.5
	minimum DLP standoff (cm)	10
Metrics	10^{15} neutrons/optics log growth	20
	doping capsule/fill	y/y
	max fluence: destructive (n/cm^2)	1.7×10^{14}
	max fluence: non-destructive (n/cm^2)	4.4×10^{11}



- By designing the capsule and laser around a minimum of ablator mass remining, a neutron source with negligible capsule or room return scatter can be created.
- Because the target assembly relies on a hohlraum, experimenters have been successful using the hohlraum thermomechanical package as a mounting surface to conduct neutron experiments on small samples of materials, which are collected as debris postshot using standard nuclear forensic techniques.

NIF Neutron Sources: DT gas-filled Symcap

		CH Sym	HDC Sym
Inputs	Fill gas DT	50:50	50:50
	capsule pressure (torr)	2892	1478
	Target temperature (K)	32	32
	Laser energy (MJ)	0.91	1.3
	optics log growth per shot	0.025	0.11
	shot cycle time (h)	16	18
Outputs	expected yield (DT)	8 x 10^{14}	4.5 x 10^{15}
	$\check{T}_{ion}$ (keV)	2.8	3.8
	burn width (ps)	200-250	175-225
	neutron volume (mm^3)	0.0009	0.0009
	output spectrum	DT + 1% downscatter	DT + 0.5% downscatter
	minimum sample standoff (cm)	0.5	0.5
	minimum DLP standoff (cm)	10	10
Metrics	10^{15} neutrons/optics log growth	32	41
	doping capsule/fill	y/y	n/y
	max fluence: destructive (n/cm^2)	2.5 x 10^{14}	1.4 x 10^{15}
	max fluence: non-destructive (n/cm^2)	6.3 x 10^{11}	3.6 x 10^{12}



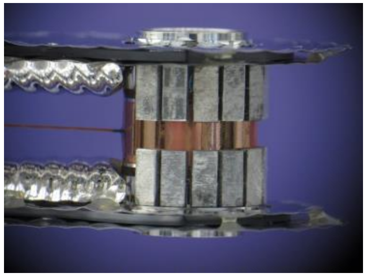

SymCDT target with mass-tamped hohlraum

- cold capsule fill gas (32-128 K) allows fuel gas density up to 9 mg/cc
- less complicated target operations and faster shot cycles than the layered platform.
- HDC ablators may have DT yields up to 4.3 x 10^{15}
- GDP plastic ablators have yielded up to 8 x 10^{14}, and may be doped with:
  - a wide variety of materials through ion implantation or deposition during the capsule growth
  - sub-microgram quantities of dopants for separated isotope cross section experiments

NIF Neutron Sources: DT cryogenic layered

		layered
Inputs	Fill gas DT	50:50
	capsule pressure (torr)	68
	Target temperature (K)	18.6
	Laser energy (MJ)	1.8
	optics log growth per shot	0.18
	shot cycle time (h)	24
Outputs	expected yield (DT)	1.8×10^{16}
	$\check{T}_{ion}$ (keV)	3-5.5
	burn width (ps)	175-225
	neutron volume (mm^3)	0.0001
	output spectrum	DT + 1-5% downscatter
	minimum sample standoff (cm)	0.5
	minimum DLP standoff (cm)	10
Metrics	10^{15} neutrons/optics log growth	100
	doping capsule/fill	y/n
	max fluence: destructive (n/cm^2)	5.7×10^{15}
	max fluence: non-destructive (n/cm^2)	1.4×10^{13}

A "shroud" is necessary to maintain temperature stability prior to shot. Clearance for shroud opening limits volume remaining for the neutron experiment.



- Cryogenic DT ice layers are driven to convergence ratios of 20-35 to produce the highest NIF DT yields.
- Capsules of different materials can be uses to select yield, spectrum properties, and dopant capability.
- Experimental volume limited by shroud clearance.
- High optics and facility time use: "expensive" shots.

NIF Neutron Sources: Summary table

		PDXP	DDEP	IDEP	CH Sym	HDC Sym	layered
Inputs	Fill gas DT	65:35	50:50	50:50	50:50	50:50	50:50
	capsule pressure (torr)	6080	7600	2487	2892	1478	68
	Target temperature (K)	room	room	32	32	32	18.6
	Laser energy (MJ)	0.62	0.82	0.71	0.91	1.3	1.8
	optics log growth per shot	0.005	0.01	0.027	0.025	0.11	0.18
	shot cycle time (h)	9	9	16	16	18	24
Outputs	expected yield (DT)	3.7×10^{15}	8×10^{14}	5.5×10^{14}	8×10^{14}	4.5×10^{15}	1.8×10^{16}
	$\check{T}_{ion}$ (keV)	12	7	5	2.8	3.8	3-5.5
	burn width (ps)	250-300	250-300	250-300	200-250	175-225	175-225
	neutron volume (mm^3)	0.05	0.05	0.05	0.0009	0.0009	0.0001
	output spectrum	pure DT	pure DT	pure DT	DT + 1% downscatter	DT + 0.5% downscatter	DT + 1-5% downscatter
	minimum sample standoff (cm)	1	4	0.5	0.5	0.5	0.5
	minimum DLP standoff (cm)	5	5	10	10	10	10
Metrics	10^{15} neutrons/optics log growth	740	80	20	32	41	100
	doping capsule/fill	y/y	n/y	y/y	y/y	n/y	y/n
	max fluence: destructive (n/cm^2)	2.9×10^{14}	4.0×10^{12}	1.7×10^{14}	2.5×10^{14}	1.4×10^{15}	5.7×10^{15}
	max fluence: non-destructive (n/cm^2)	1.2×10^{13}	2.5×10^{12}	4.4×10^{11}	6.3×10^{11}	3.6×10^{12}	1.4×10^{13}

National Ignition Facility Neutron Sources
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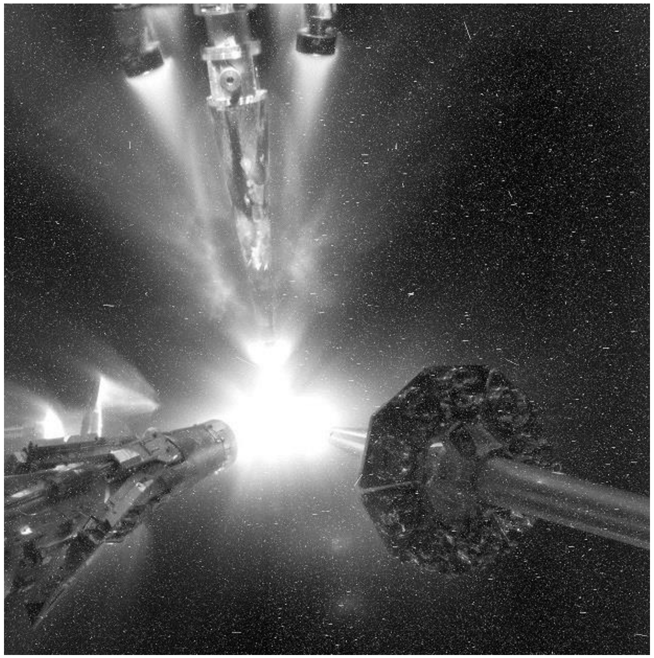
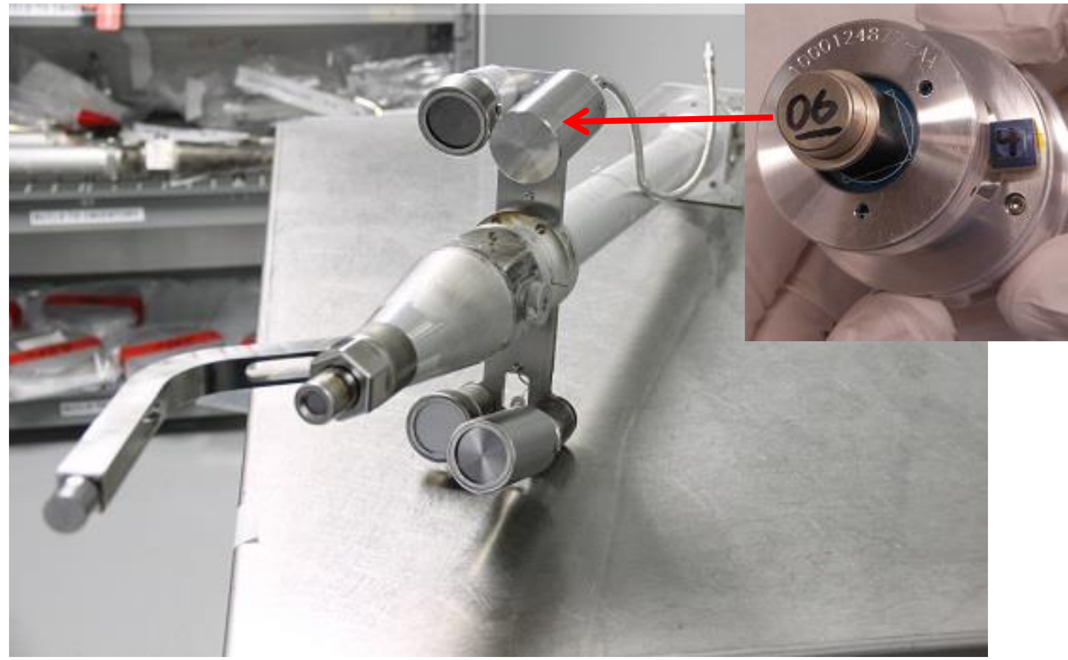
Many neutron experiments are assembled onto a single NIF shot.



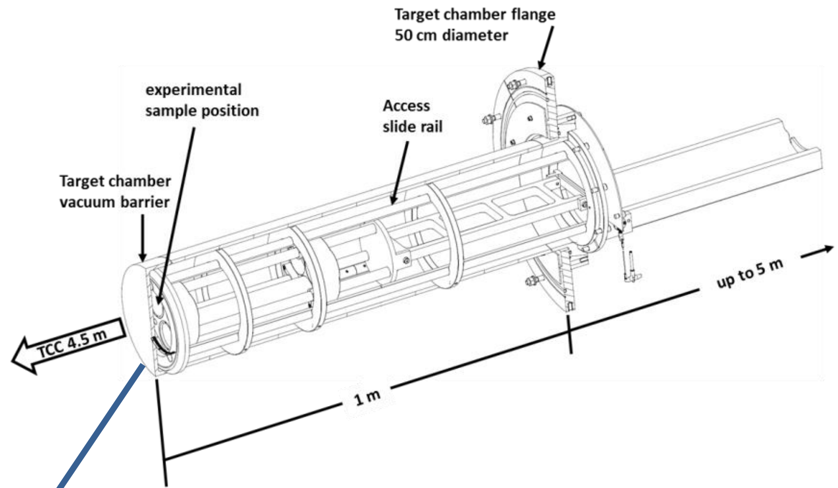


	capsule	hohlraum	support ring	DLP	Treefrog	HTOAD	SRC Toad	Snout-NAD	test well sample	reentrant well	port flange
distance from TCC (cm)	0.1	0.5	1	5	7	45	50	50	350	375	550
sample area (cm^2)		0.05	3	90	0.5	20	4.9	20	37	1250	1250
sample depth (cm)		0.05	0.5	20	0.14	8	0.1	1	1	1000	20
solid angle (msr)		200	3000	3600	10	10	2.0	8.0	0.3	8.9	4.1
Volume (cm^3)		0.0025	1.5	1800	0.07	160	0.5	20	37	1.25×10^6	25,000
max DT neutron yield	4.0×10^{14}	1.7×10^{16}	3.7×10^{15}	3.7×10^{15}	3.7×10^{15}	1.7×10^{16}	1.7×10^{16}	1.7×10^{16}	1.7×10^{16}	1.7×10^{16}	1.7×10^{16}
max fluence (n/cm^2)	3.2×10^{15}	5.4×10^{15}	2.9×10^{15}	1.2×10^{13}	6.0×10^{12}	6.7×10^{11}	5.4×10^{11}	5.4×10^{11}	1.1×10^{10}	1.1×10^{10}	4.5×10^{9}

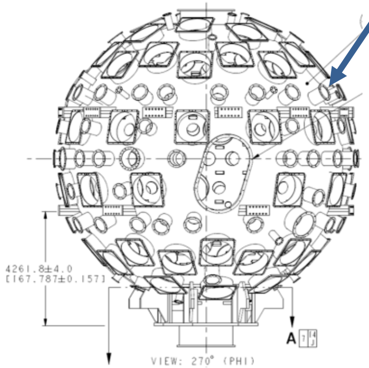
NIF Neutron Experimental Platforms: exterior flange-mounted and reentrant well

- A test well may be outfitted with a large-volume neutron experiment seeing up to 10^{10} n/cm^2. Test volume is connected to target bay atmosphere.

- Additional experiments may be positioned directly on exterior port flanges. (ex: “nuclear forensic signatures of common cellular telephones”)

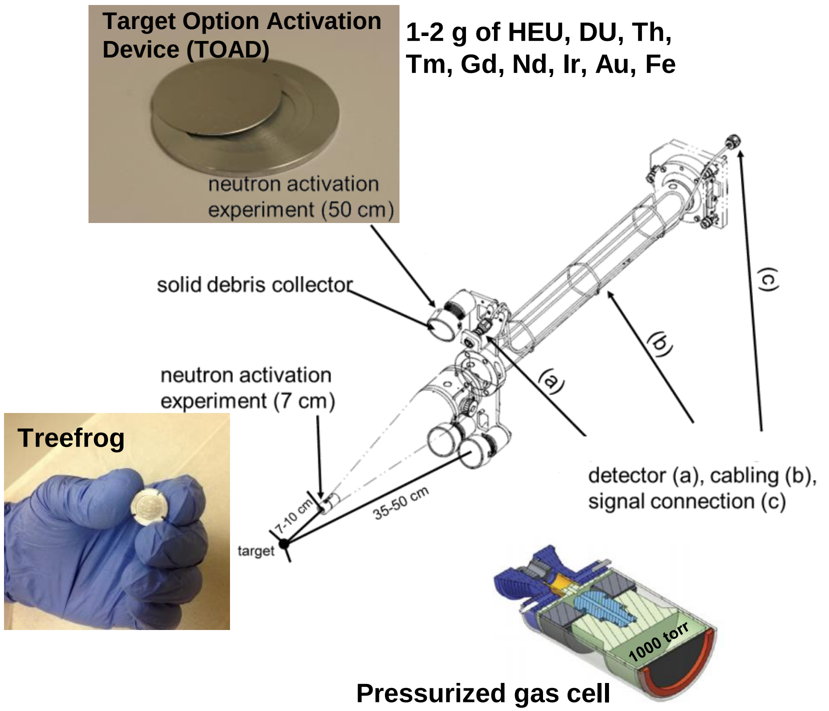


Test well configuration for camera tests, with spatially-resolved neutron dosimetry.



	test well sample	reentrant well	port flange
distance from TCC (cm)	350	375	550
sample area (cm^2)	37	1250	1250
sample depth	1	1000	20
solid angle (msr)	0.3	8.9	4.1
volume	37	1.25×10^6	25,000
max DT neutron yield	1.7×10^{16}	1.7×10^{16}	1.7×10^{16}
max fluence (n/cm^2)	1.1×10^{10}	1.1×10^{10}	4.5×10^9

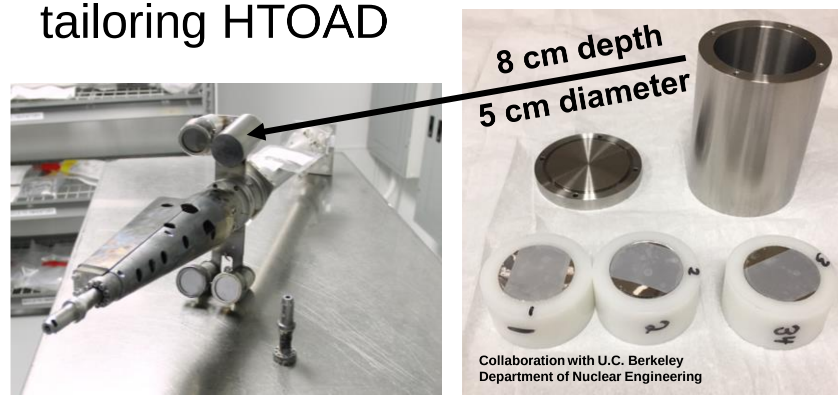
NIF Neutron Experimental Platforms: Snout-mounted auxiliary experiments (passive)



NIF diagnostic manipulators are used to carry ride-along experiments on neutron-yielding shots. This capability is readily accessible to collaborating groups.

	Treefrog	HTOAD	SRC Toad	Snout-NAD
distance from TCC (cm)	7	45	50	50
sample area (cm^2)	0.5	20	4.9	20
sample depth	0.14	8	0.1	1
solid angle (msr)	10	10	2.0	8.0
volume	0.07	160	0.5	20
max DT neutron yield	3.7×10^{15}	1.7×10^{16}	1.7×10^{16}	1.7×10^{16}
max fluence (n/cm^2)	6.0×10^{12}	6.7×10^{11}	5.4×10^{11}	5.4×10^{11}

Neutron spectrum tailoring HTOAD



This is the experimental compliment to a MCNP design study in spectrum tailoring.

NIF Neutron Experimental Platforms: User-designed dynamic load packages

	DLP
distance from TCC (cm)	5
sample area (cm^2)	90
sample depth	20
solid angle (msr)	3600
volume	1800
max DT neutron yield	3.7×10^{15}
max fluence (n/cm^2)	1.2×10^{13}

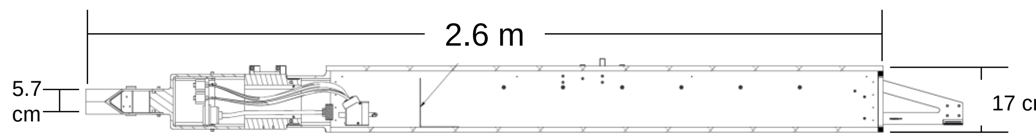
*** Example based on Sandia TANDM ENP**

Technicians install a National Security Applications ENP (Energetic Neutron Platform, Sandia Natl. Lab) in DIM 90-78 for a data collection shot awarded to the Sandia PI (W. J. Martin) through the NIF User Office.

The experimenter designs to fit within the available TANDM space.

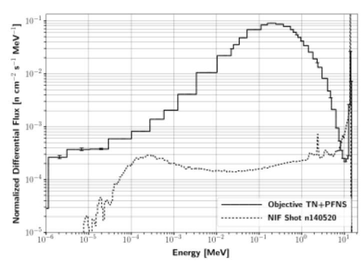
Energetic Neutron Platform (ENP)

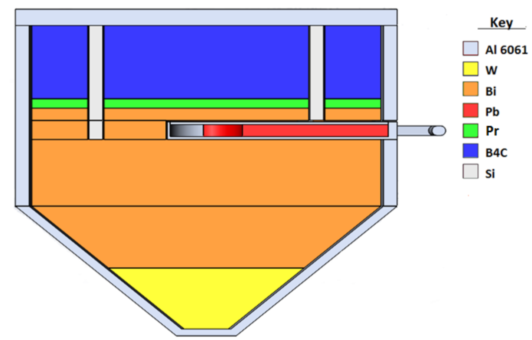
SNL PI: William J. Martin



Energy Tuning Assembly (ETA)

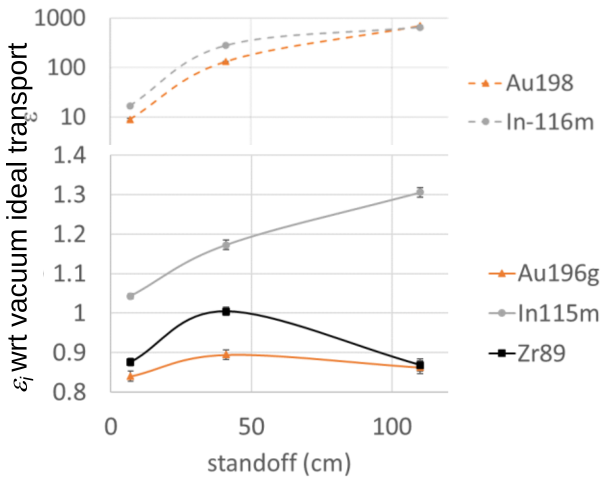
AFIT: Capt. James Bevins
UCB: Racheal Slaybaugh, Lee Bernstein, Bethany Goldblum
LLNL: William Dunlop, Dawn Shaughnessy, Charles Yeamans, Eugene Henry

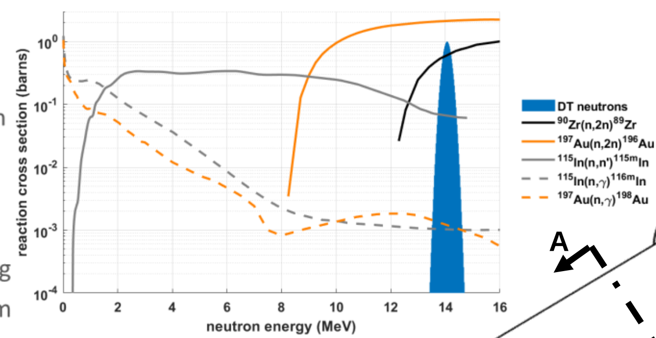


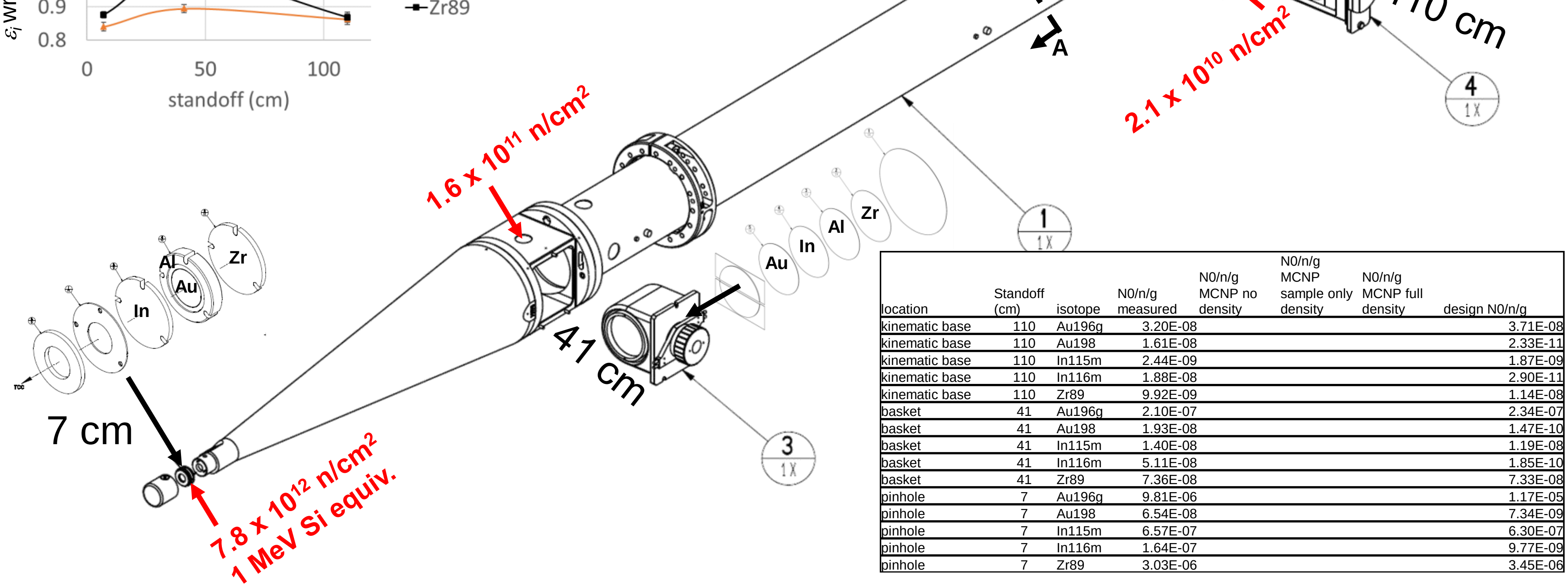


The UCB/AFIT ETA is designed to transform a NIF neutron source into the objective TN+PFNS neutron spectrum.

NIF Neutron Experimental Platforms: Passive snout neutron spectrum tuning







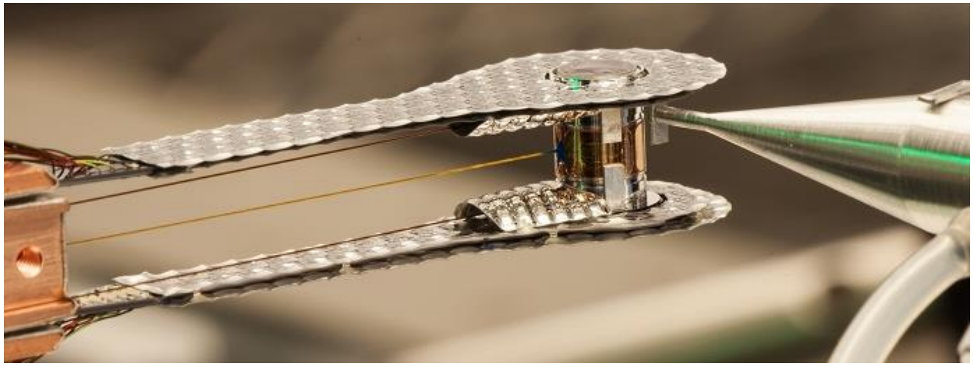
location	Standoff (cm)	isotope	N0/n/g measured	N0/n/g MCNP no density	N0/n/g MCNP sample only density	N0/n/g MCNP full density	design N0/n/g
kinematic base	110	Au196g	3.20E-08				3.71E-08
kinematic base	110	Au198	1.61E-08				2.33E-11
kinematic base	110	In115m	2.44E-09				1.87E-09
kinematic base	110	In116m	1.88E-08				2.90E-11
kinematic base	110	Zr89	9.92E-09				1.14E-08
basket	41	Au196g	2.10E-07				2.34E-07
basket	41	Au198	1.93E-08				1.47E-10
basket	41	In115m	1.40E-08				1.19E-08
basket	41	In116m	5.11E-08				1.85E-10
basket	41	Zr89	7.36E-08				7.33E-08
pinhole	7	Au196g	9.81E-06				1.17E-05
pinhole	7	Au198	6.54E-08				7.34E-09
pinhole	7	In115m	6.57E-07				6.30E-07
pinhole	7	In116m	1.64E-07				9.77E-09
pinhole	7	Zr89	3.03E-06				3.45E-06

NIF Neutron Experimental Platforms: hohlraum-mounted materials experiments

NIF Nuclear cross sections: PI – Dawn Shaughnessy
Experimental group: Narek Gharibyan, Sherry Faye, John Despotopulos, Pat Grant, Ken Moody, Charles Yeamans

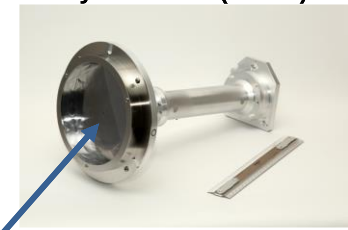
Primary objective: measuring 14 MeV neutron reaction cross sections relevant to post-detonation nuclear forensics

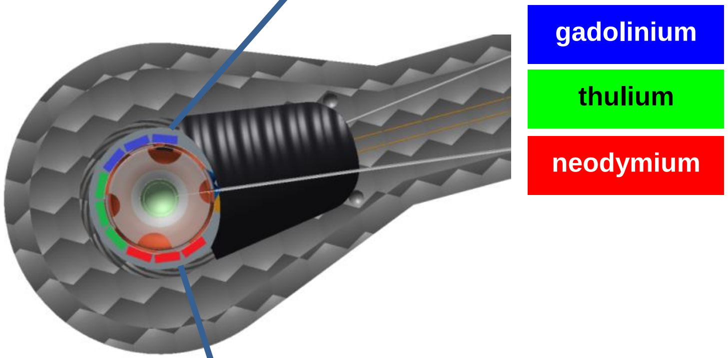
Results:
1) **Debris emission from the target assembly is mostly outwardly radial as expected.**
2) **The added foil mass substantially changes the target disassembly dynamics.**

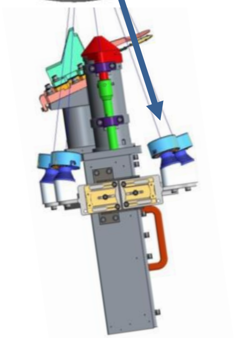


NIF target fabrication: Brian Yoxall

Large Area Solid Radiochemistry collector (LASR)







Solid Radiochemistry Collector (SRC)

Solid collection efficiency is 8% of the total target mass in the line of sight to collector.

NIF Neutron Experimental Platforms: high-Z dopant layer in the ablator

NIF Nuclear Forensics: PI – Dawn Shaughnessy
Experimental group: Narek Gharibyan, John Despotopulos, Ken Moody, Pat Grant, Carol Velsko, Bill Cassata, Sherry Faye, Charles Yeamans, Ellen Edwards

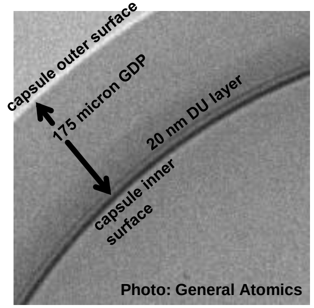
Results:

1) Successful capsule debris collection. Completed experimental series using depleted uranium and conventional capsule fabrication. Development of experimental platform to study fission yield and neutron reaction cross sections under conditions relevant to the nuclear forensic program
2) Development of advanced doping techniques using micro/nanogram quantities of material.

	Laser energy	DU recess	Fission yield[1]	Collection efficiency[2]
N170130-003	0.9 MJ	10 um	6.56	1.53
N160210-001	0.9 MJ	21 um	4.54	0.07
N150907-003	1.3 MJ	10 um	8.70	0.12
DU hohlraum	1.5 MJ	n/a	1.00	1.00

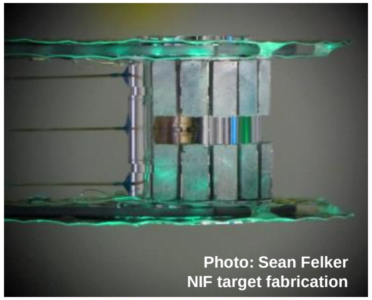
1. Normalized $^{137,138,139}Xe$ and $^{87,88}Kr$ per 10^{15} neutrons
2. Normalized ^{97}Zr (90-315) atoms/cm^2 per 10^{15} neutrons

Uranium-doped CH capsule



CH plastic capsule, 175 micron thickness with 10^{16} atoms of depleted uranium.

Mass-tamped hohlraum



SymCDT target with mass-tamped hohlraum

	capsule	hohlraum
distance from TCC (cm)	0.1	0.5
sample area (cm^2)		0.05
sample depth		0.05
solid angle (msr)		200
volume		0.0025
max DT neutron yield	4.0×10^{14}	1.7×10^{16}
max fluence (n/cm^2)	3.2×10^{15}	5.4×10^{15}

Capsule and hohlraum debris has been collected successfully on many shots.

National Ignition Facility Neutron Sources

outline

1. Abstract

2. NIF overview
   - A. Using the NIF as a neutron source
   - B. Practical consideration for the user
   - C. Fusion spectra available

3. NIF neutron sources
   - A. Polar direct drive
     - i. CH PDXP
     - ii. SiO_2 DDEP
   - B. Indirect drive
     - i. ICF cryogenic layered
     - ii. DT gas Symcaps
     - iii. IDEP
   - C. Summary table

4. Experimental Platforms
   - A. Exterior flange mounted and reentrant well
   - B. Snout-mounted auxiliary positions
   - C. Dynamic load packages
   - D. Hohlraum
   - E. Capsule

5. Neutron Source and Experimental Platform Development
   - A. Capsule microinjection doping
   - B. Neutron source development: yield enhancements
   - C. Experimental support ring and reduced source standoff

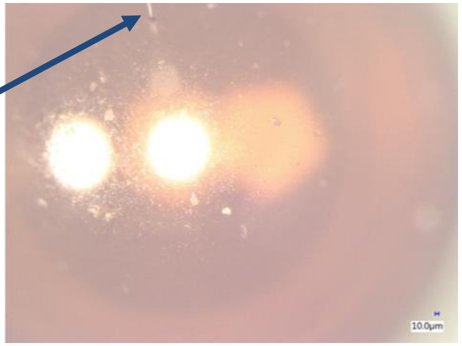
6. Reference table

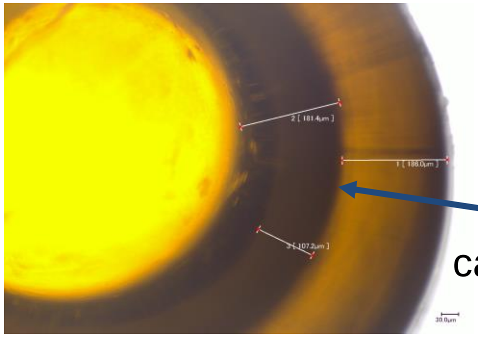
Developmental Platforms: Capsule Microinjection Doping

- **Goal: Add 10^{16} radioactive atoms to the inner surface of a capsule**
  - **More efficient and faster than sputtering or ion implantation; allows the use of radionuclides as dopant atoms**
  - **Prevents issues related to outer surface roughness**

- **Investigating direct surface coating with metal oxide aerogels (analogous to established foam doping methods)**

Micro injector adding material through fill tube hole

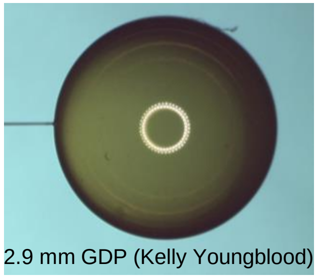




Aerogel layer inside capsule (before drying)

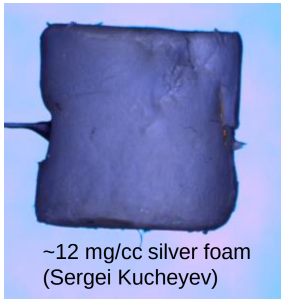
John Despotopulos

Neutron Source development: HYDRA calculates the combined environment target is a better source of both neutrons and x-rays than a bare capsule.



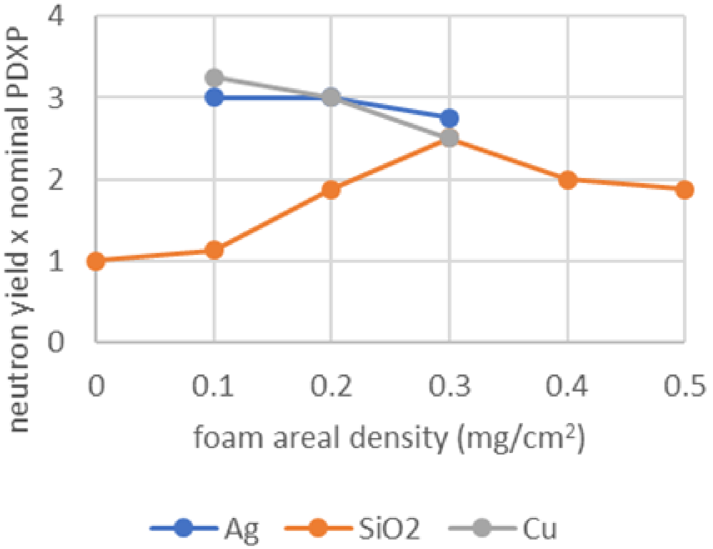
2.9 mm GDP (Kelly Youngblood)

+



~12 mg/cc silver foam
(Sergei Kucheyev)

- As a neutron source, a spherical metal foam shell on a capsule driven by a 2 ns square pulse is calculated to better than a bare capsule.
- This combines two well-established target fabrication techniques.

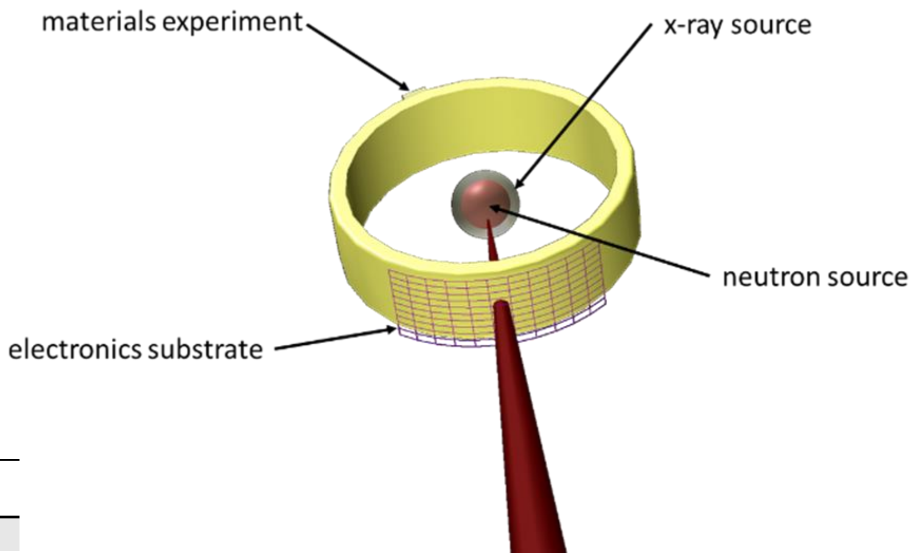


Addition of a metal foam layer, as is currently fabricated for x-ray source targets, is predicted to increase neutron yield 2-3x.

Energy range (keV)	XRCE (%)		Foam/bare XRCE
	with foam	bare capsule	
0-1.5	9.5	7.5	1.3
1.5-3	3.9	2.7	1.4
3-7	9.2	0.95	9.7
7-10	0.27	0.09	3.0
10-250	0.93	0.05	18.6
0-250	**24.4**	**11.6**	**2.1**

Advanced Experimental Capability: Get the user experiments closer to the neutron source.

- A support ring added to the target assembly decreases standoff substantially.
- Experiments positioned on the ring see 14 MeV neutron fluences 100x greater than can be achieved at any other facility.
- An articulated sample positioner would bring the nondestructive testing capability within the cryogenic shroud clearance to within 2 cm of a layered cryogenic neutron source.



	support ring	support ring with improved source	articulated positioner
distance from TCC (cm)	1	1	2
sample area (cm^2)	3	3	0.5
sample depth	0.5	0.5	3
solid angle (msr)	3000	3000	125
volume	1.5	1.5	1.5
max DT neutron yield	3.7×10^{15}	1.3×10^{16}	1.8×10^{16}
max fluence (n/cm^2)	2.9×10^{15}	1.0×10^{16}	3.6×10^{14}

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NIF Neutron Sources: Reference Table

topic	reference
NIF facility	B M Van Wonterghem et al 2016 Fusion Sci. Technol. 69 452-469
NIF optics loop	K R Manes et al 2016 Fusion Sci. Technol. 69 146-249
NIF laser performance optimization module (optics use calculation)	M Shaw and R House, *Proc SPIE, High Power Lasers for Fusion Research III*; 93450E (2015)
NIF debris and shrapnel	N D Masters et al 2016 J. Phys.: Conf. Ser. 717 012108
NIF diagnostic instrument manipulators	R Plummer 2013 Proc. SPIE 8850 885005
NIF neutron spectra (DT)	B Appelbe and J Chittenden, High Energy Density Physics 11 (2014) 30-35
NIF neutron spectra (DT downscatter)	D C Wilson et al 2002 Nucl. Instrum. Meth. A 488 400–409
NIF neutron spectra (TT)	D T Sayre et al 2013 Phys. Rev. Lett. 111 052501
NIF neutron spectra (DD)	H Brysk 1973 Plasma Phys. 15 611
polar direct drive	N S Krasheninnikova, S M Finnegan, and M J Schmitt, Phys. Plasmas 19, 012702 (2012)
polar direct drive	R S Craxton et al., Physics of Plasmas 22, 110501 (2015)
Indirect drive Symcaps (experiment)	G A Kyrala et al., Physics of Plasmas **18**, 056307 (2011)
Indirect drive Symcaps (simulation)	S V Weber *et al.*, Physics of Plasmas **21**, 112706 (2014)
indirect drive layered sources	N B Meezan et al 2017 Plasma Phys. Control. Fusion 59 014021
indirect drive layered sources, HDC	S Le Pape et al “Energy gain from an imploding shell at the National Ignition Facility,” submitted to Physical Review Letters
indirect drive target engineering	A V Hamza et al. 2016 Fusion Sci. Technol. 69 395-406
indirect drive target engineering	T Parham et al 2016 Fusion Sci. Technol. 69 407-419
indirect drive exploding pushers	S Le Pape et al. Phys. Rev. Lett. 112 225002 (2014)
IDEPs for nuclear forensics	D A Shaughnessy et al 2016 J. Phys.: Conf. Ser. 717 012080
NIF solid debris collection capability	D A Shaughnessy et al 2012 Rev. Sci. Instrum. 83 10D917
enhanced NIF solid debris collection capability	C Waltz et al 2017 Proc. SPIE 10390 103900H
NIF HEU fission yield measurements	N Gharibyan et al. 2015 J. Radioanal. Nucl. Chem. 303 1335
NIF passive neutron experiments	C B Yeamans and N Gharibyan 2016 Rev. Sci. Instrum. 87 11D702
gas cell capability at NIF	A Ratkiewicz et al 2016 Rev. Sci. Instrum. 87 11D825
neutron effects measurements at NIF	W J Martin et al 2017 Journal of Radiation Effects, Research and Engineering 35
neutron effects measurements at NIF	W J Martin, submitted to Journal of Radiation Effects, Research and Engineering

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