Nuclear Physics at the National Ignition Facility

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Current status of demonstrated NIF capabilities

- Brief review of implosion diagnostic capabilities.
  - Necessary for experimental design and analysis.
- Selective summary of the stagnation conditions achieved to date.
  - NIC (“low foot”) implosions
  - Symcap “buried CD layer” implosions
    - Recent development of Xe-doped capsules as a prototype in Symcaps.
  - Recent “high foot”, higher yield implosions.
- HYDRA radiation-hydrodynamic modeling capabilities with Monte Carlo transport.
  - Necessary for experimental design and analysis.
- Alternate ablator choices (HDC, Be), shell configurations (double shells, high-Z shells) or drives (direct drive, indirect drive exploding pushers) require further platform development and will not be discussed.

Motivation

NIF nuclear physics experiments will feature integrated physical effects thus will require integrated diagnostic capabilities and analysis.

Examine possible near-term nuclear physics based NIF experiments using low-cost platforms with demonstrated performance.

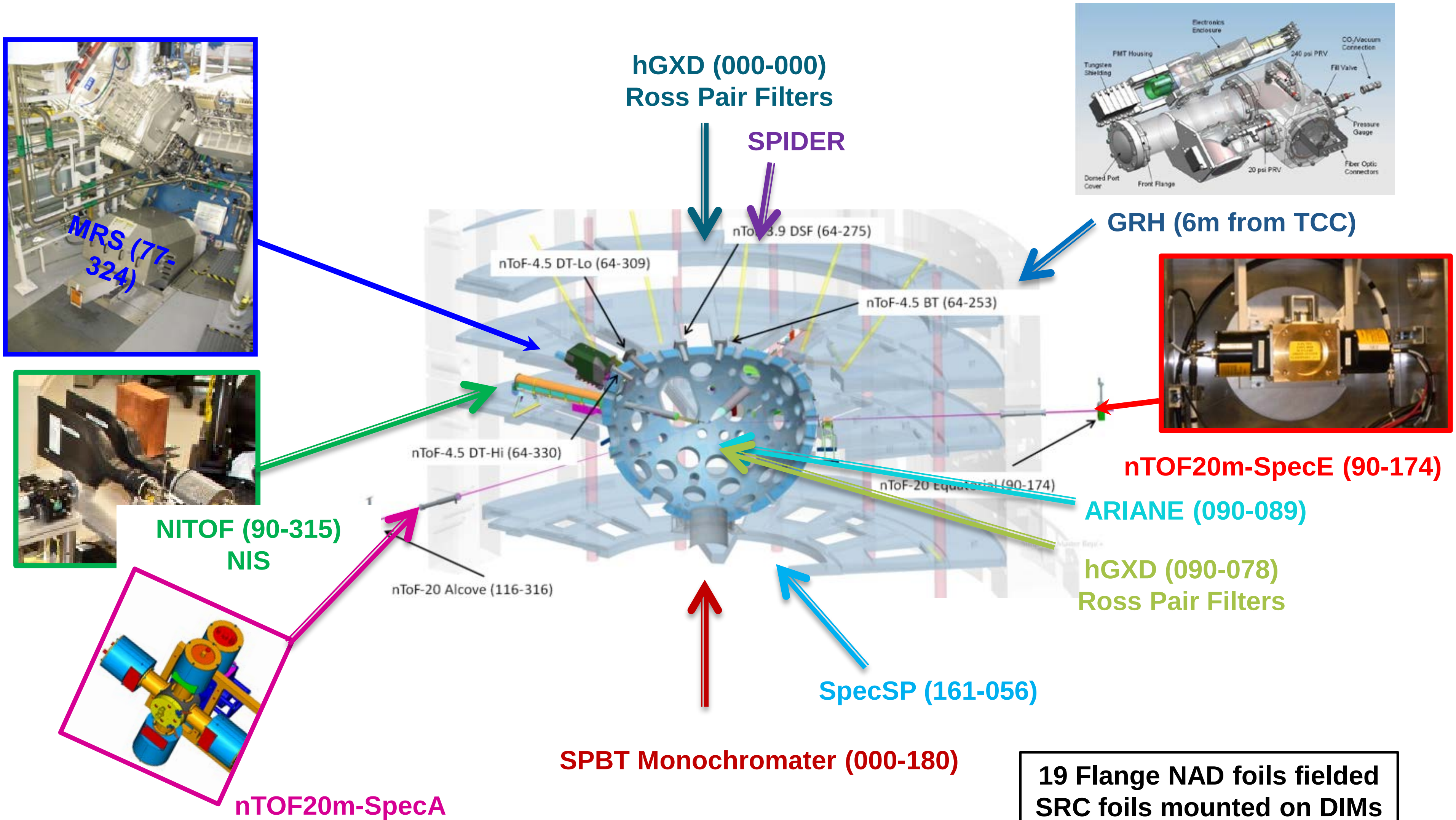
- **Dopant implantation in a capsule**
  - **Low adiabat ("low foot") NIC have high fuel areal density but are more sensitive to dopants (~10^{14} dopant atoms at fuel interface).**
    - **Significant yield and stagnation conditions variability.**
  - **Symmetry Capsules (SymCaps) have lower convergence ratio, low fuel areal density but much less restrictive dopant limits (~ 10^{16} atoms).**
    - **Small experimental variability in stagnation conditions.**
  - **High adiabat compression ("high foot") provides moderate compression and fuel areal density.**
    - **Small experimental variability in stagnation conditions.**

Motivation (continued)

Examine possible near-term nuclear physics based NIF experiments using low-cost platforms with demonstrated performance.

- **Activation at the hohlraum wall or at greater distances.**
  - **In principle, greatly reduces fielding and development effort.**
  - **Balance lower neutron flux with larger material mass.**
  - **Solid Radchem Diagnostic (SRC) is currently a NIF diagnostic complementary to ^{12}C-γ GRH detection (CH ρr).**
  - **Multiple material foil capability demonstrated (TOAD).**
  - **Thulium (n,3n) and rising edge nTOF signals for "RIF" (Reactions In Flight) or tertiary neutron spectrum for stopping power model tests (Coulomb logarithm).**

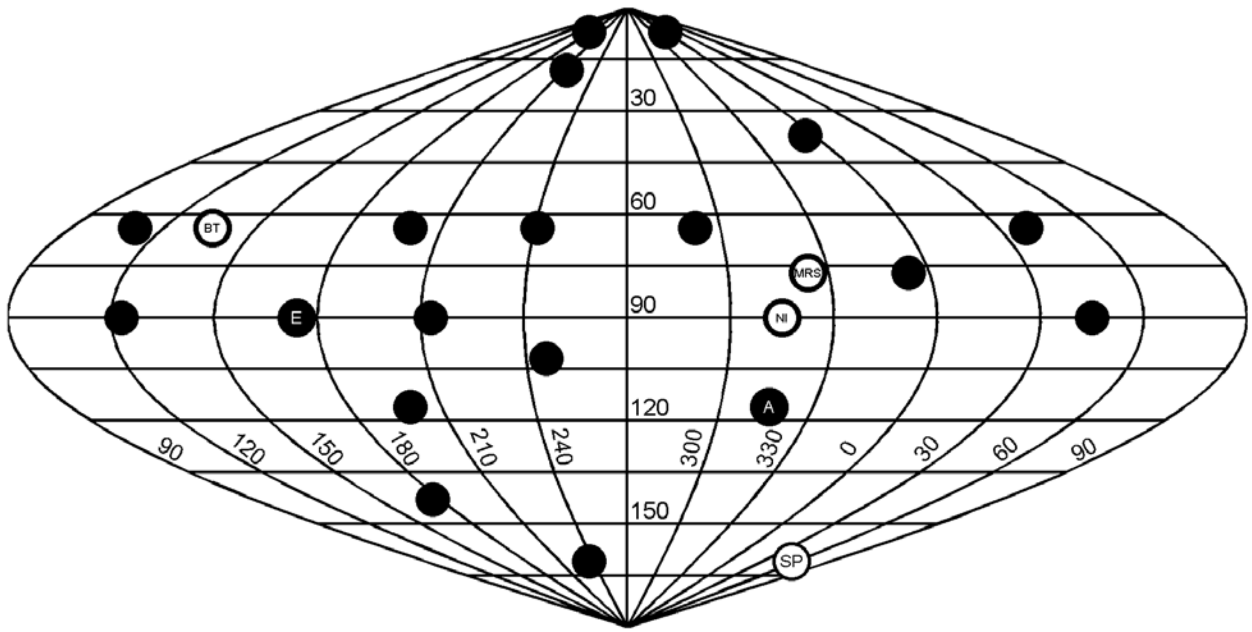
The line-of-sight information provided by the x-ray and nuclear diagnostics are correlated to determine implosion performance and conditions.



19 Flange NAD foils fielded
SRC foils mounted on DIMs

Flange-NAD Diagnostic (Charles Yeamans)

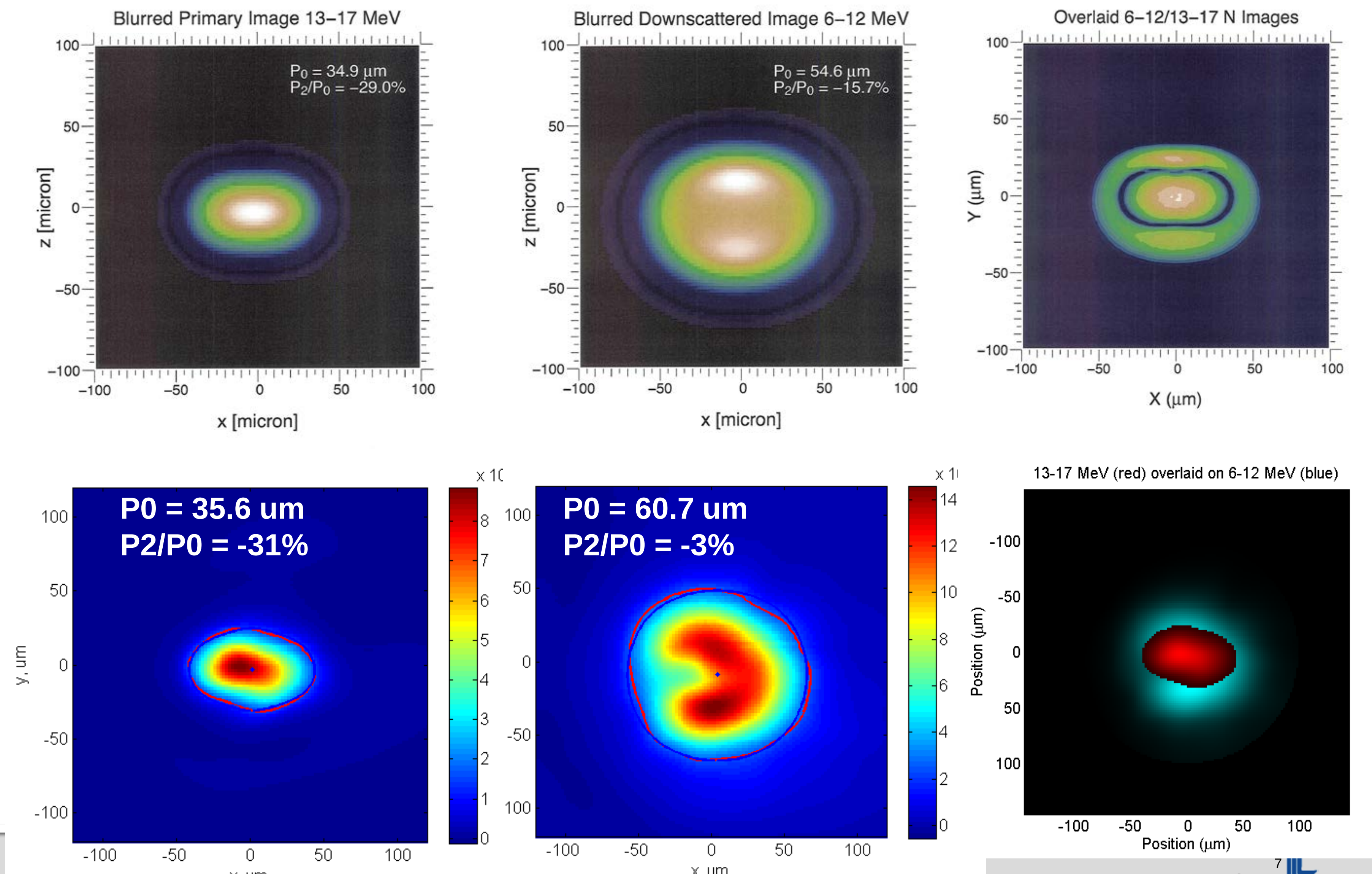
current coverage



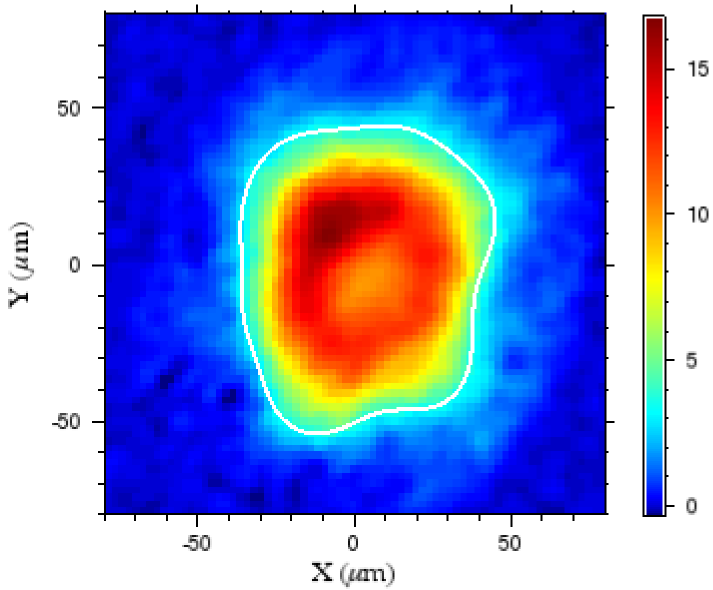
● Flange-NAD
○ other neutron diagnostics

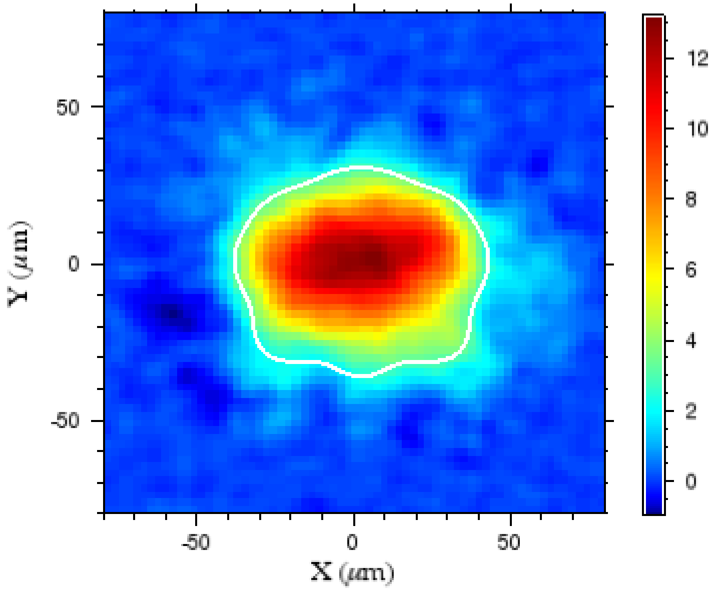
Neutron time-of-flight detectors are located at 090-176 (SpecE), 116-316 (SpecA), and 161-056 (SpecSP); the MRS detector location is 077-324.

N130927 (high foot) neutron images



N130927 time-integrated x-ray images





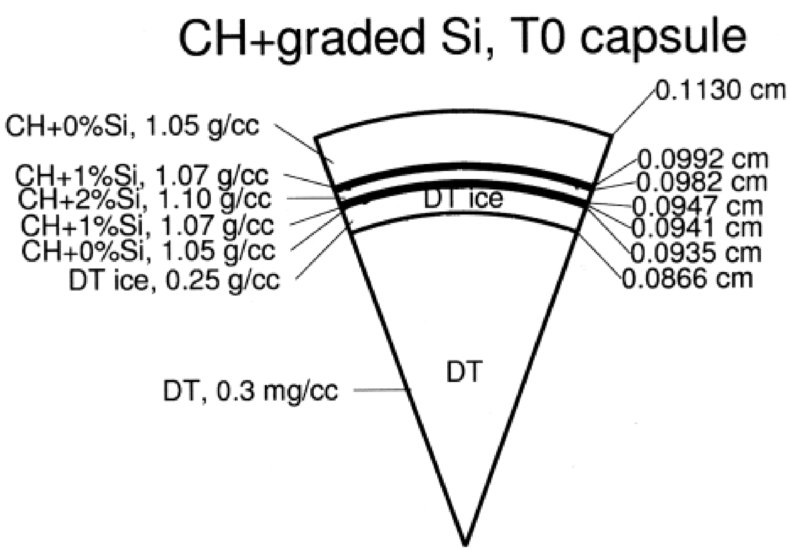
Polar View (000-000)

Equatorial View (090-078)

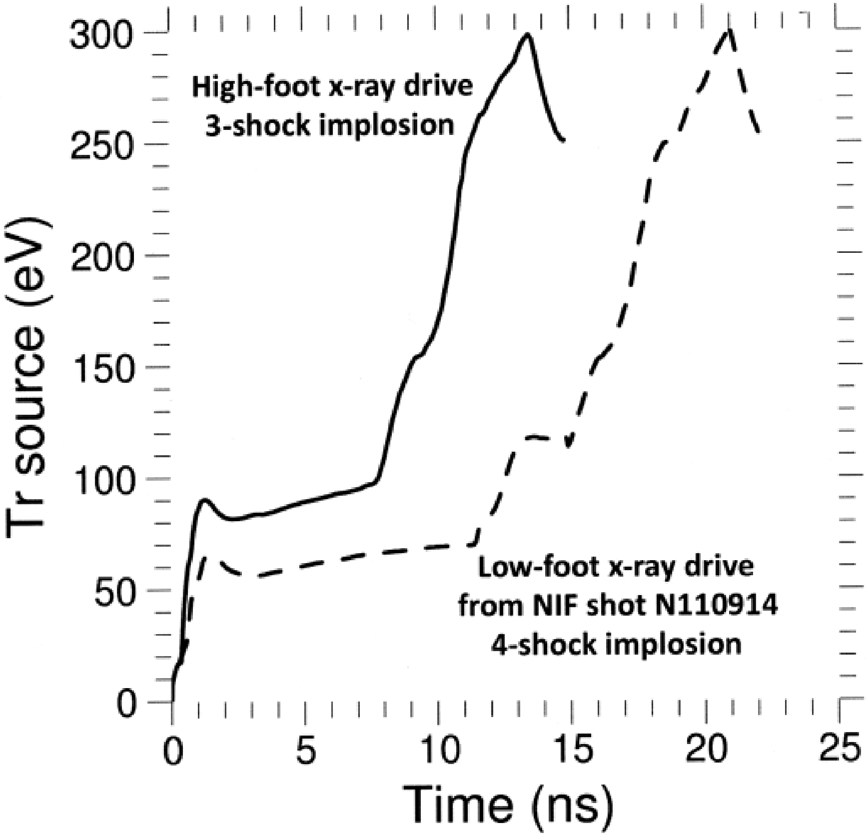
Ross Pair filter subtraction: 11 – 20 keV

Comparison of low and high foot laser drives.

Use the NIC capsule.

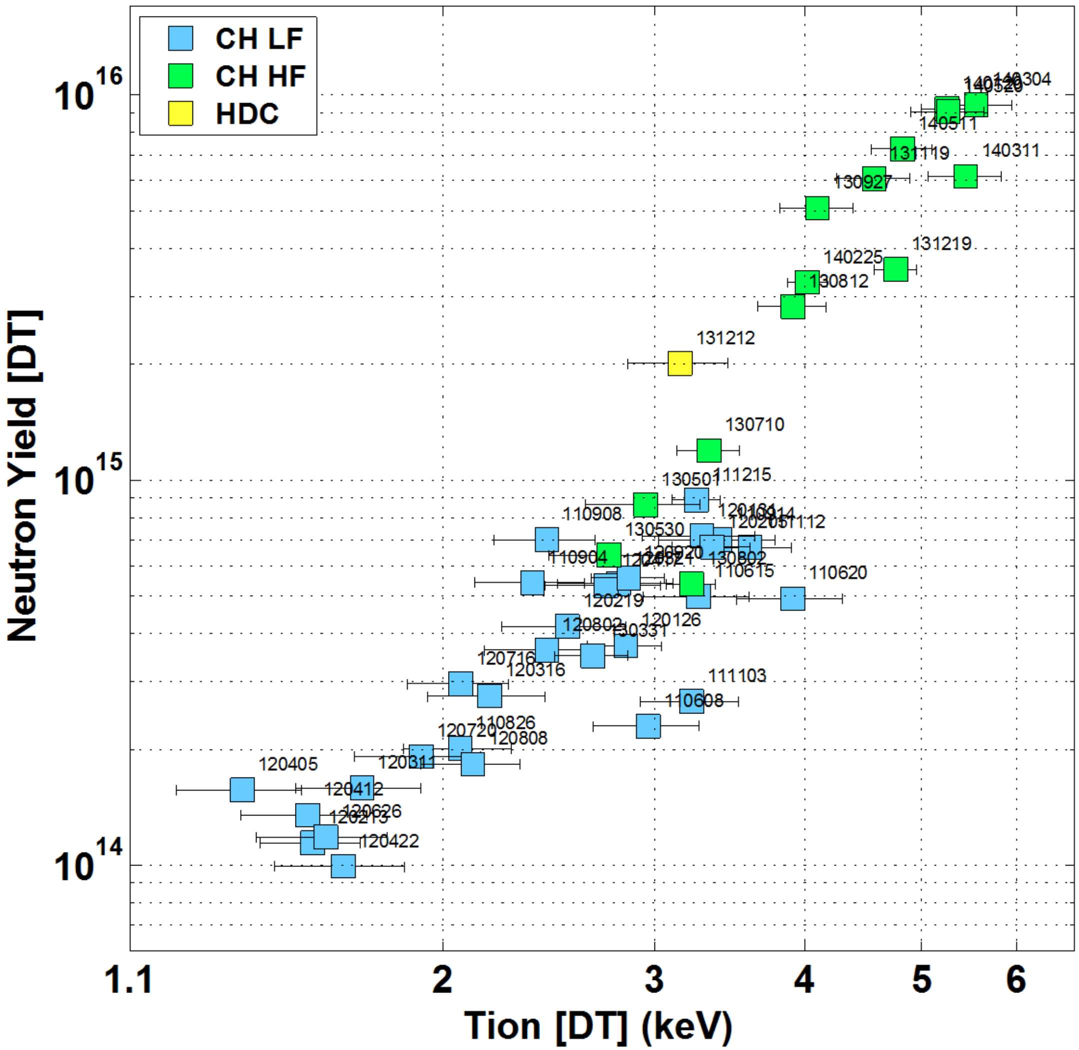


Introduce a larger first pulse and compress the overall drive.



Figures from T. Dittrich *et al.* Phys. Rev. Lett. 112,055002(2014).

Summary of neutron yields from DT-cryogenic implosions versus measured ion temperature.



The high foot laser drive sacrifices compressibility for yield compared to the low foot laser drive.

This drive produces consistently smaller fuel densities but higher ion temperatures.

Plot courtesy of Pravesh Patel

Stagnation properties of buried CD layer Symcap implosions were well-described by simulation.

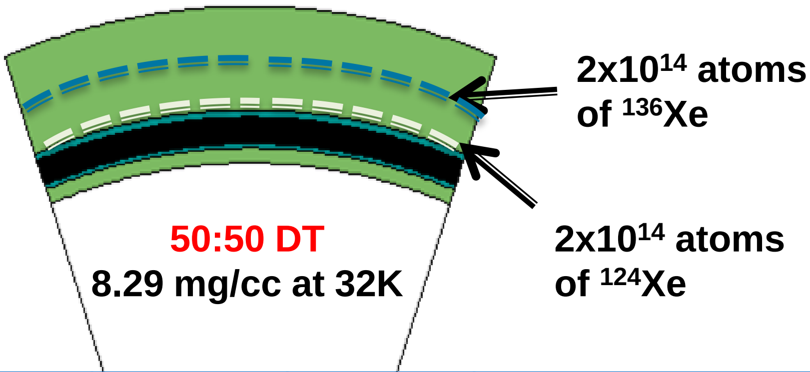
	N120923	N120923 sim	N130503	N130503 sim	N130505	N130505 sim	N130507	N130507 sim
Y_n	6.7e14	7.16e14	5.1e14	5.48e14	8.0e14	1.01e15	7.3e14	1.17e15
DT T_i (keV)	3.3	3.23	4.62	4.83	2.72	2.92	2.81	2.94
DD Y_n	7.53e12	8.14e12	1.54e12	1.84e12	3e12	4.05e12	2.82e12	4.28e12
DD T_i (keV)	3.12	3.05	4.19	4.34	2.45	2.73	2.36	2.76
DT ρr (mg/cm^2)		75.7		13.2		87.5		98.2
C ρr (mg/cm^2)		485		28.5		460		495

Reasonable agreement between experiment and HYDRA. (simulations courtesy of S. Weber).

Near-term applications will focus on a doped Symcap platform.

- Xe-doped SymCap experiments ready to be fielded in FY14/FY15.
  - Buried CD layer SymCap campaign displays < 20% variability and reasonable agreement with HYDRA simulations.
    - Use this well-understood platform for the first radiochemical activation experiments.
  - Two regions of a CH/Si SymCap have been doped with ^{136}Xe (outer region) and ^{124}Xe (inner region) by GA and S. Kucheyev (LLNL).
  - In-line radiochemical simulations in HYDRA predict a small ratio of the (n,2n) activation products ^{135}Xe/^{123}Xe due to ablative stabilization.
    - First experimental test of this prediction.
    - Demonstration of RAGS capability with neutral atom AMS detection.

Activated xenon production will be tested as an ablator stability diagnostic (D. Casey).



Layer	Thick (μm)	Cumul. thick (μm)	r_{layer} (μm)	dopant
1 (in)	20±2	20	20	0% Si
2	6±2	26	6	Si 1±0.2 at. %
3	35±2	45	19	Si 2±0.2 at. %
		45	implant	Xe124 $2x10^{14}$ atoms
		61	16	Si 2±0.2 at. %
4	10±2	71	10	Si 1±0.2 at. %
5 (out)	139.8	134	63	
		134	implant	Xe136 $2x10^{14}$ atoms
		211	77	0% Si

- The goals of this diagnostic technique are to measure:
  - Differential ablator penetration into the fuel
  - Location of the ablator region that penetrates into the fuel

- Use 1.3 MJ, 360TW laser energy
- Expected $Y_n \sim 7x10^{14}$ neutrons for a Symcap shot (e.g. N130507)
- Measure isotope products from the interactions of:

$$^{124}Xe + n \rightarrow {}^{123}Xe + 2n$$
$$^{136}Xe + n \rightarrow {}^{135}Xe + 2n$$

- At this low dopant level, there is no issue with implosion performance
  - Should not affect the diag signature
  - Non-perturbative
  - No seeding RT on its own

Higher neutron yield with larger DT fuel areal density provides a wider neutron spectral range.

- **High foot laser drive with a conventional CH ablator capsule represents an improvement upon the performance of the Symcap platform.**
  - **Stable, repeatable platform with ~5 x 10^{15} neutrons in 150 ps.**
  - **Higher doping levels possible (?).**
  - **Dopant loading during fabrication must be demonstrated.**
- **High energy neutron spectrum (> 14 MeV)**
  - **Reaction-In-Flight (RIF) neutrons populate this energy range.**
  - **Stopping power experiments require larger neutron yields to reduce experimental uncertainties.**
- **Thermalization neutron spectrum (< 1 MeV)**
  - **Larger DT areal densities required to produce sufficient low-energy signal.**
  - **SRC diagnostic probes this energy range and provides late-time ablator areal density and remaining shell temperature dependence.**
  - **Low Energy Neutron Spectrometer (LENS) would be very desirable.**

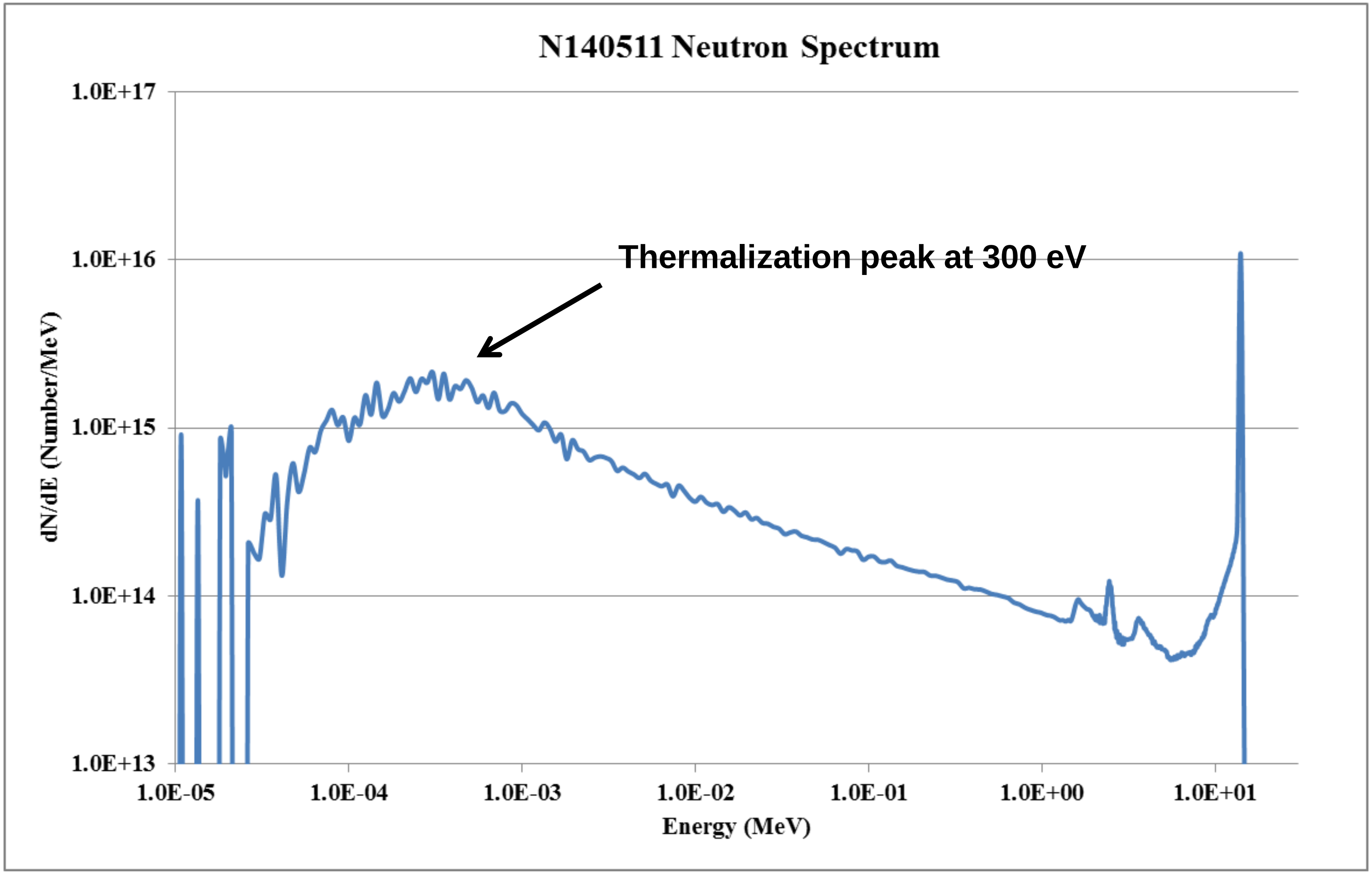
Stagnation properties of selected high foot implosions.

- All four shots were roughly similar for the burn-averaged quantities.

	N130927 (exp)	N130927 (fit)	N131119 (exp)	N131119 (fit)	N131219 (exp)	N131219 (fit)	N140304 (exp)	N140304 (fit)
ρr (g/cm²)	0.720	0.700	0.760	0.680	0.800	0.780	0.760	0.780
Y (total)*	5.10e15	5.10e15	6.31e15	6.13e15	3.57e15	3.53e15	9.43e15	9.54e15
T_{ntof} (keV)	4.60	4.68	5.00	5.02	5.10	5.09	6.35	6.21
T_{bw} (keV)		4.80		5.13		5.32		6.48
t_{burn} (ps)	187/161	160	152/156	155	148/135	140	168/128	160
ρ_{bn} (g/cm³)		38		30		32		26
P (Gb)		132		112		115		116

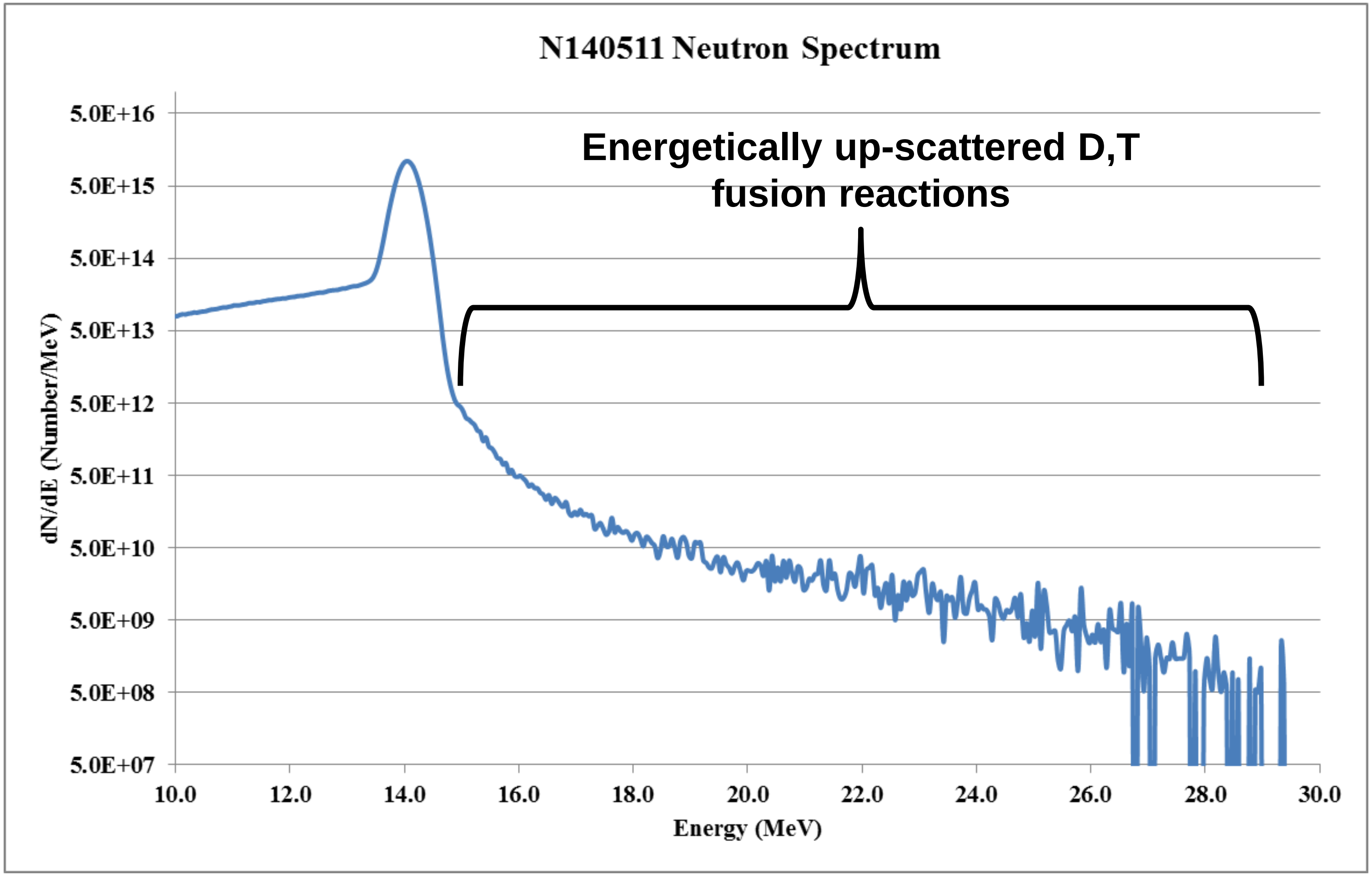
*Y(total) = Y(13-15)*exp(4.0*DSR)

N140511 (high foot) low energy neutron spectrum



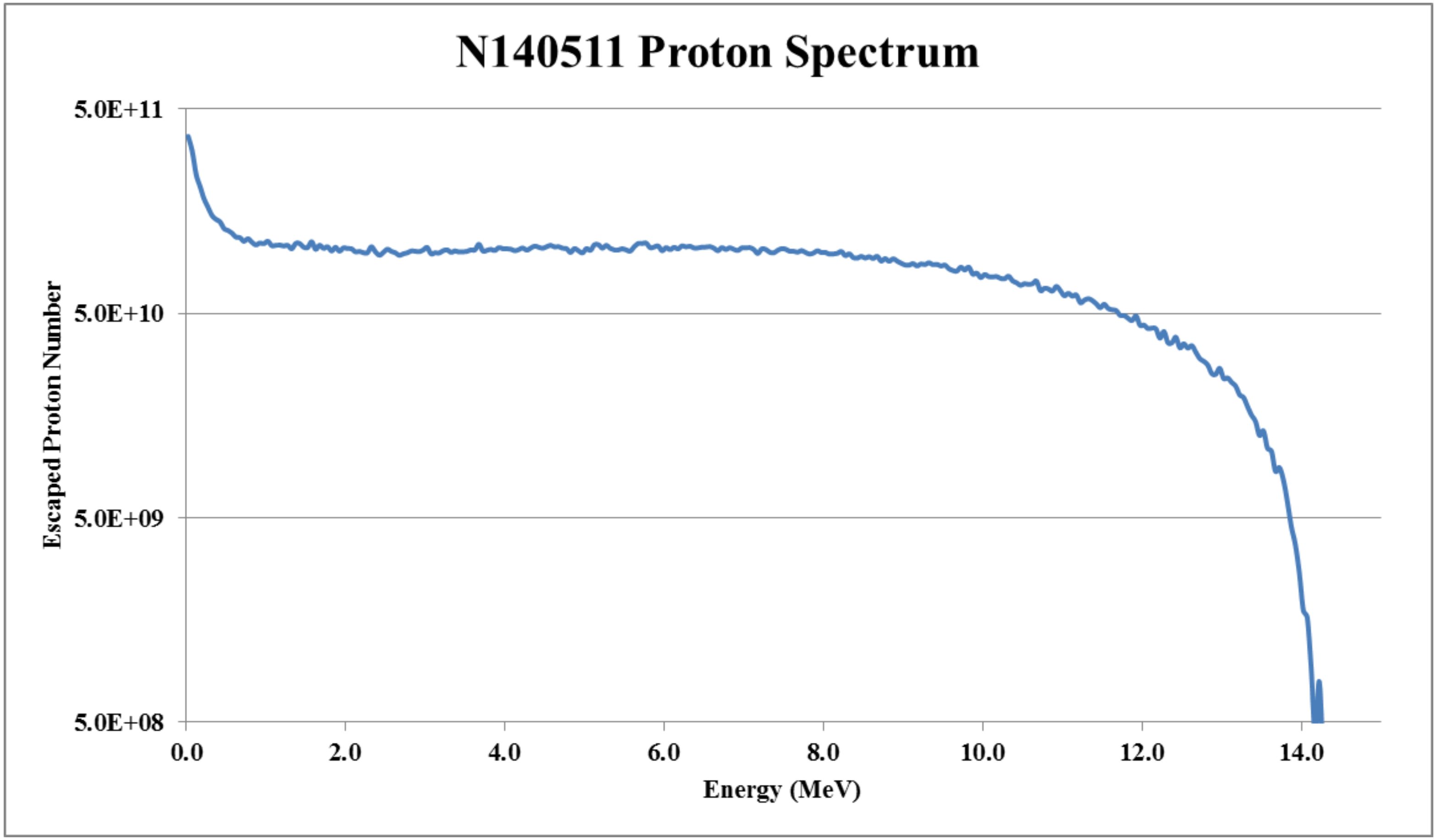
Total yield = 7.4 x 10^{15}

N140511 (high foot) high energy neutron spectrum



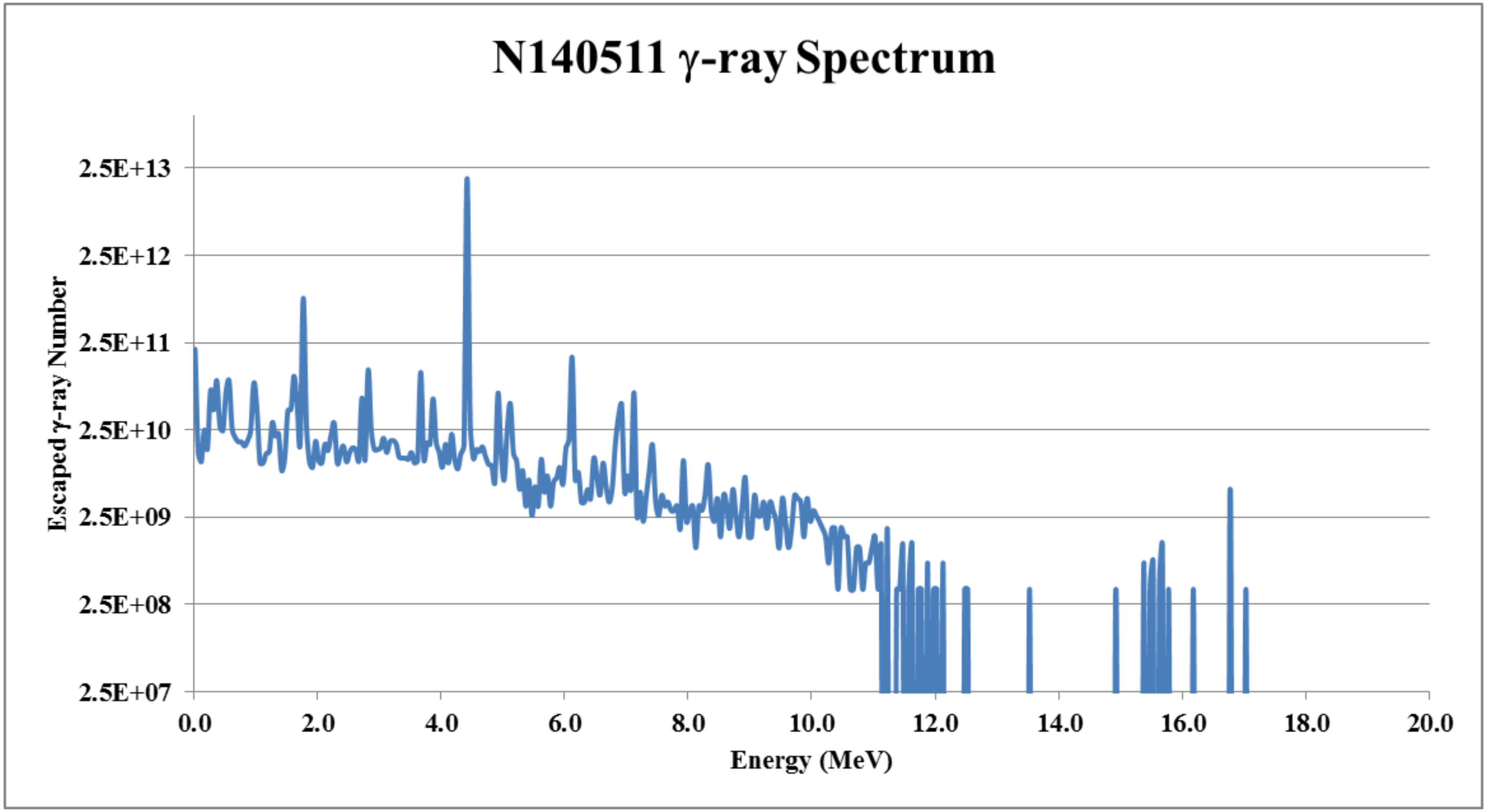
Total yield = 7.4 x 10^{15}

N140511 (high foot) escaped protons from n-p scattering in the remaining CH ablator.



Total yield = 2.5 x 10^{13}

N140511 (high foot) γ-ray spectrum dominated by $^{12}C(n,n'\ \gamma)$ scattering.



Total ^{12}C-γ yield = 2.0 x 10^{13}

HYDRA (very briefly)

- The primary implosion experiment simulation tool used for NIF experimental design and analysis.
    - ALE (Adaptive Lagrange-Euler)
    - Finite element based (quadrilateral in 2D or hexahedral elements in 3D)
    - Massively parallel
    - PYTHON user scripts may be readily linked.
- Physics capabilities are extensive.
    - Consistent numerical treatment of the hydrodynamic equations, diffusive radiation transport, and diffusive electron conduction.
    - Substantial flexibility exists for different EOS and conductivity model choices.
    - Implicit Monte Carlo photon transport.
    - Particle Monte Carlo neutron, charged particle, and gamma-ray generation and transport.
    - In-line or post-processing radiochemistry available (KUDU).
- A static three-dimensional model exists that correlates implosion diagnostics and quantifies the stagnation properties.

Noteworthy nuclear physics-based capabilities at the NIF not discussed.

- **Proton Time-of-Flight (pTOF)**
  - Fielded and analyzed by Hans Rinderknecht/MIT.
  - Shock flash bang time in D/^{3}He gas fills.
- **Wedge Range Filters (WRF)**
  - Fielded and analyzed by Alex Zylstra/MIT
  - Capsule areal density at shock flash bang time in D/^{3}He gas fills.
- **Both techniques probe charged particle stopping power.**
  - Both are limited to low areal densities currently.

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Nuclear Physics

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HYDRA

M. Marinak, M. Patel, S. Sepke

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BACKUP

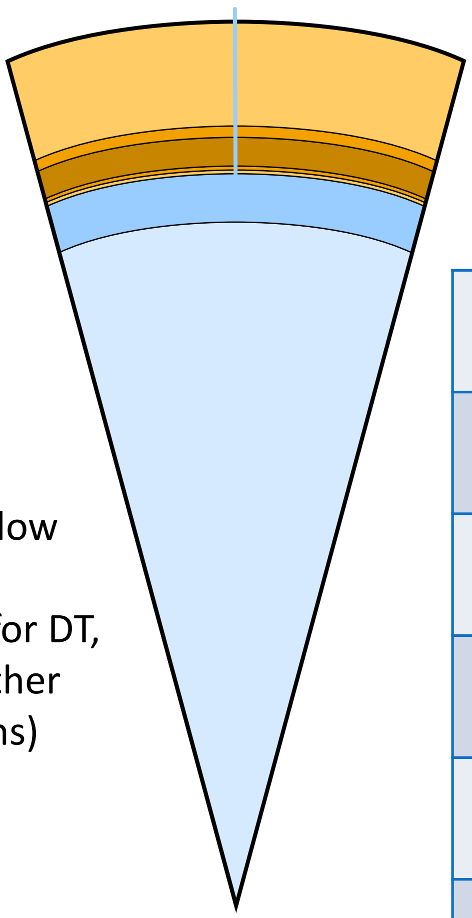
Qualitative description of an implosion experiment

- Indirect drive assumed throughout this discussion.
- Temporally and spatially shaped laser deposition onto hohlraum wall produces temporally and spatially varying x-ray drive.
- Ablator mass is ejected; shocks form and propagate; isentropic condition at peak implosion velocity on a low adiabat.
- Transfer of incoming shell kinetic energy to PdV work on the capsule interior which leads to temperatures sufficiently large to initiate fusion reactions.
- Temperature rise also leads to pronounced increase in energy losses due to Bremsstrahlung and electron conduction.
- Balance between energy production (fusion reactions) and loss mechanisms characterizes the implosion performance.

CH(Si) THD Design v3.3 (from Haan 8/15/11, updated 9/28/11, densities updated 9/13/11)

(all dimensions and densities at cryogenic temp)

Inner CH radius = 935 (± n/a) um
Outer radius = 1130 ± 5 um
Wall 195 ± 3 um
CH density(cryo) = 1.034 +0.025*Si% +0.029*Ox%
Densities below assume 0.5 at% oxygen
Thermal contraction taken to be 1/1.0127

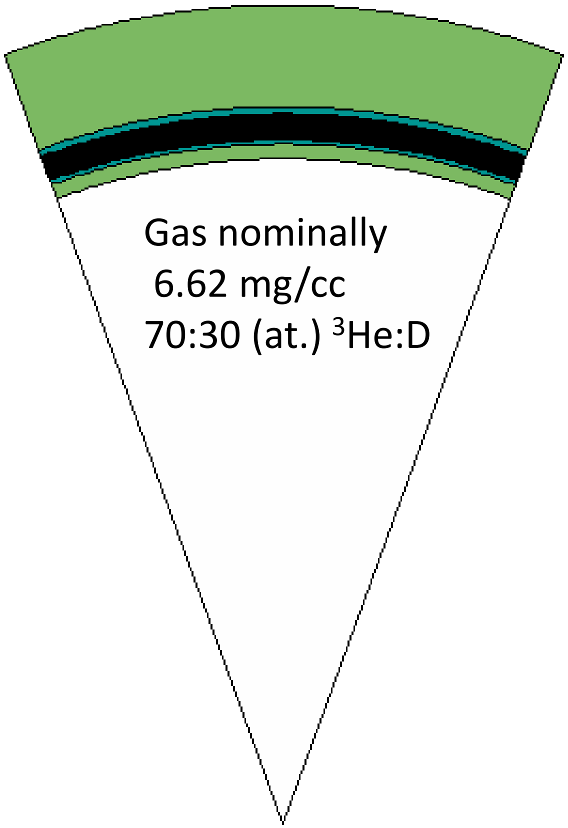


Fuel layer
69 microns

Gas density
set 1.5 K below
triple point
(0.3 mg/cc for DT,
varies for other
compositions)

Layer	Thickness (um)	Si dopant (at%)	Cryo density (g/cc)
1 (inside)	6±2	Nominally 0, req't <0.1	1.049
2	6±2	1±0.2	1.074
3	35±2	2±0.2	1.099
4	10±2	1±0.2	1.074
5 (outside)	(balance)	Nominally 0, req't <0.05	1.049

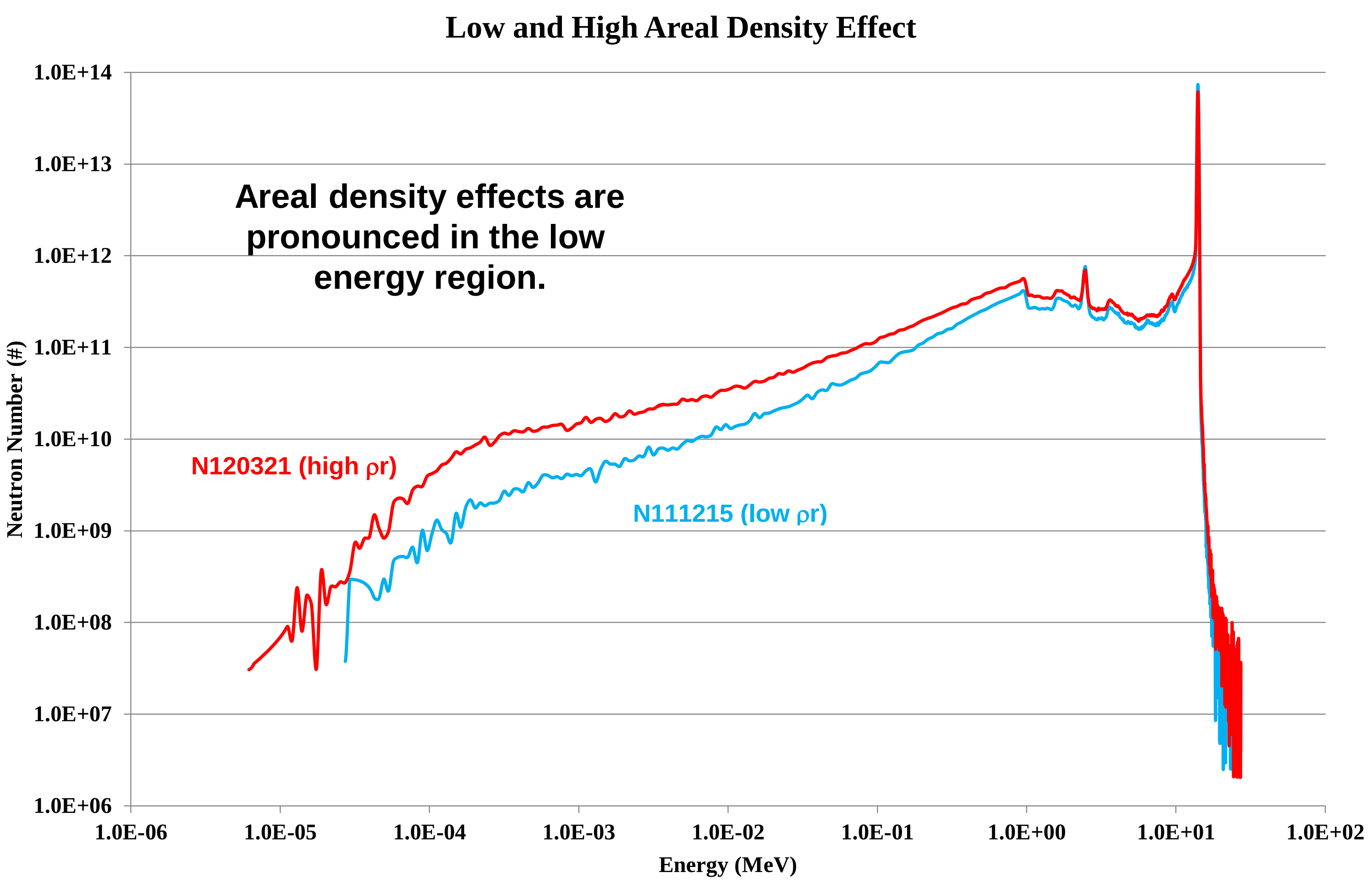
CH(Si) Symcap Design v3.2 (from Haan 7/1/11, densities updated 9/13/11)
(all dimensions and densities at cryogenic temp)



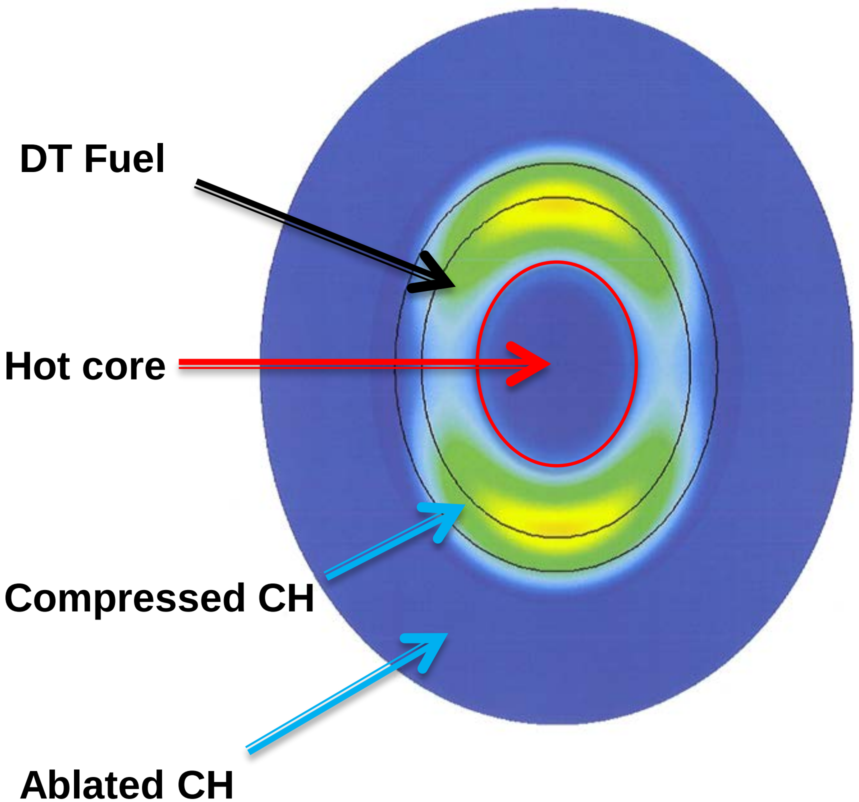
Inner radius = 928 (± n/a) um
Outer radius = 1137 ± 5 um
Wall 209 ± 3 um
CH density(cryo) = 1.034 +0.025*Si% +0.029*Ox%
Densities below assume 0.5 at% oxygen
Thermal contraction assumed to be 1/1.0127

Layer	Thickness (um)	Si dopant (at%)	Estimated density (g/cc)
1 (inside)	20±2	Nom. 0, req't <0.1	1.049
2	6±2	1±0.2	1.074
3	35±2	2±0.2	1.099
4	10±2	1±0.2	1.074
5 (outside)	(balance)	Nom. 0, req't <0.05	1.049

Highly resolved energy bins and sufficient time to approach neutron thermalization is required.



Static Isobaric Model Overview



Density distribution

The pressure, density and temperature are deduced from an isobaric model fit to the x-ray and nuclear data.

Input from experiment

- **X-ray Images: equator and pole**
- **Burn history: x-ray or GRH**
- **Neutron time of Flight (NTOF) trace**
- **Yield (13-15 MeV)**
- **DSR**

χ^2 fit

P_{hs}, $\rho(r,\theta,\varphi)$, $T(r,\theta,\varphi)$

Output

Derived parameters

- **Volume**
- **Hot core Energy (PV)**
- **Hot core density**
- **Neutron images**
- **Directional neutron spectra**

Generalized Lawson's Criterion

- Hot core pressure (not experimentally accessible) is a useful measure of implosion performance.
- PdV work on the DT gas and fuel matches alpha-particle energy deposition.

$$Q \approx \frac{Y_n}{\frac{3}{2}PV} \approx 1$$

$$P(Gb) = 2 \times 10^{-19} \boxed{\sqrt{\frac{Y_n T^2}{V\tau_n \langle \sigma v(T) \rangle}}}.$$

Experimental or known quantities

Lawrence Livermore National Laboratory