Nuclear Science in High Energy Density Plasmas

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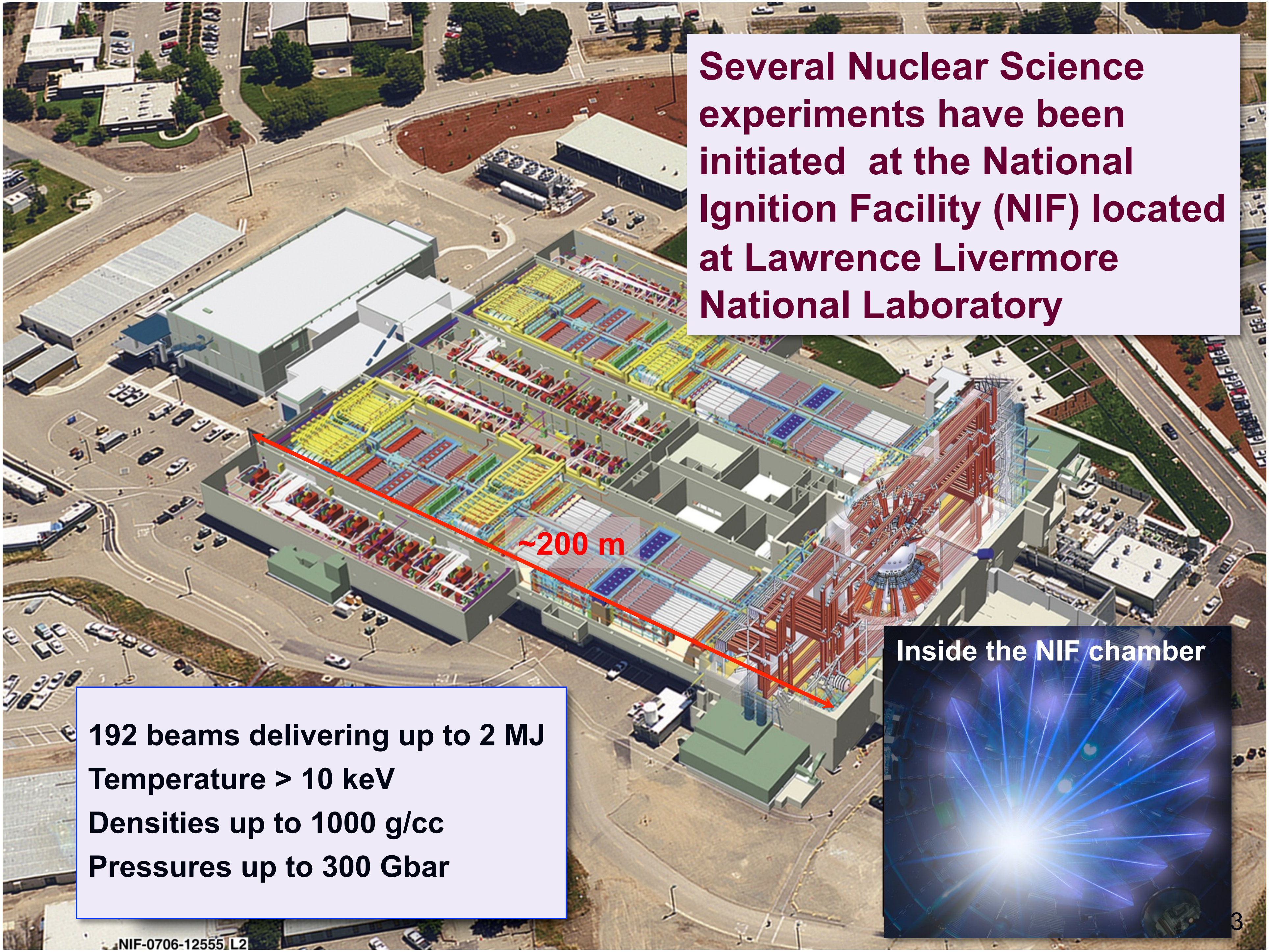
Outline

- Background and History
- National Ignition Facility
- Nuclear Diagnostics
  - Neutron detection
  - Prompt Gamma-ray studies
  - Radiochemistry (gas and solid collection)
- Nuclear Science in HED Plasmas:
  - Hydrogen and Helium Isotope Reactions
  - Neutron-Induced Reactions (e.g., capture)
  - Reactions on Excited States

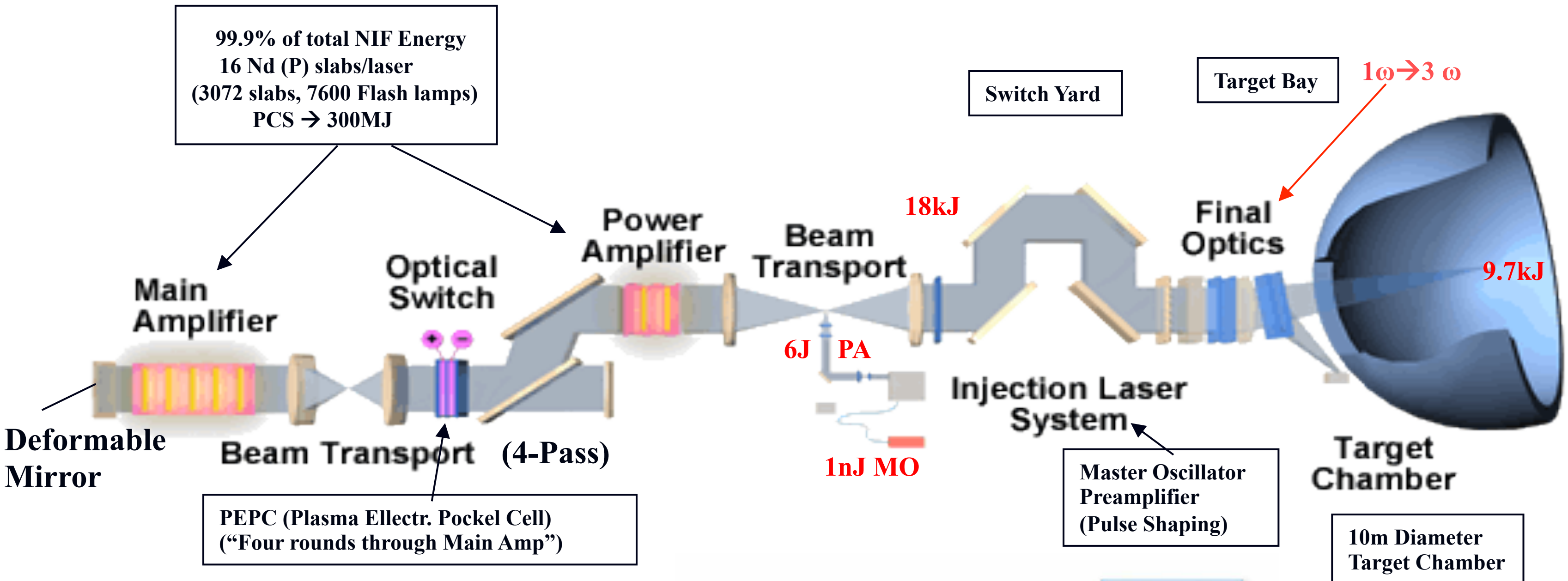
Several Nuclear Science experiments have been initiated at the National Ignition Facility (NIF) located at Lawrence Livermore National Laboratory

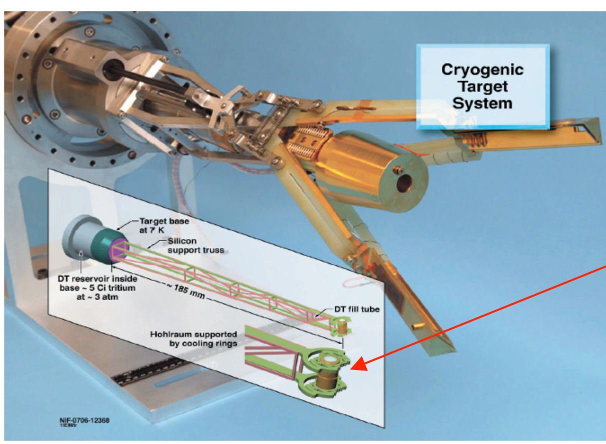


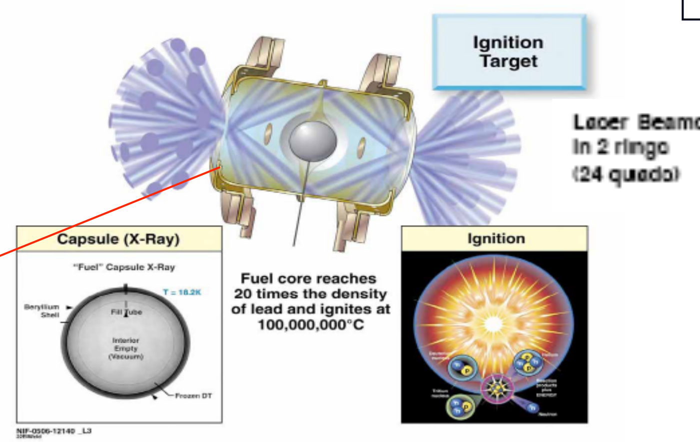
192 beams delivering up to 2 MJ
Temperature > 10 keV
Densities up to 1000 g/cc
Pressures up to 300 Gbar

National Ignition Facility – 2MJ laser-

(One NIF Laser (9.7kJ) and Target Set-Up (1 Shot every 8h))

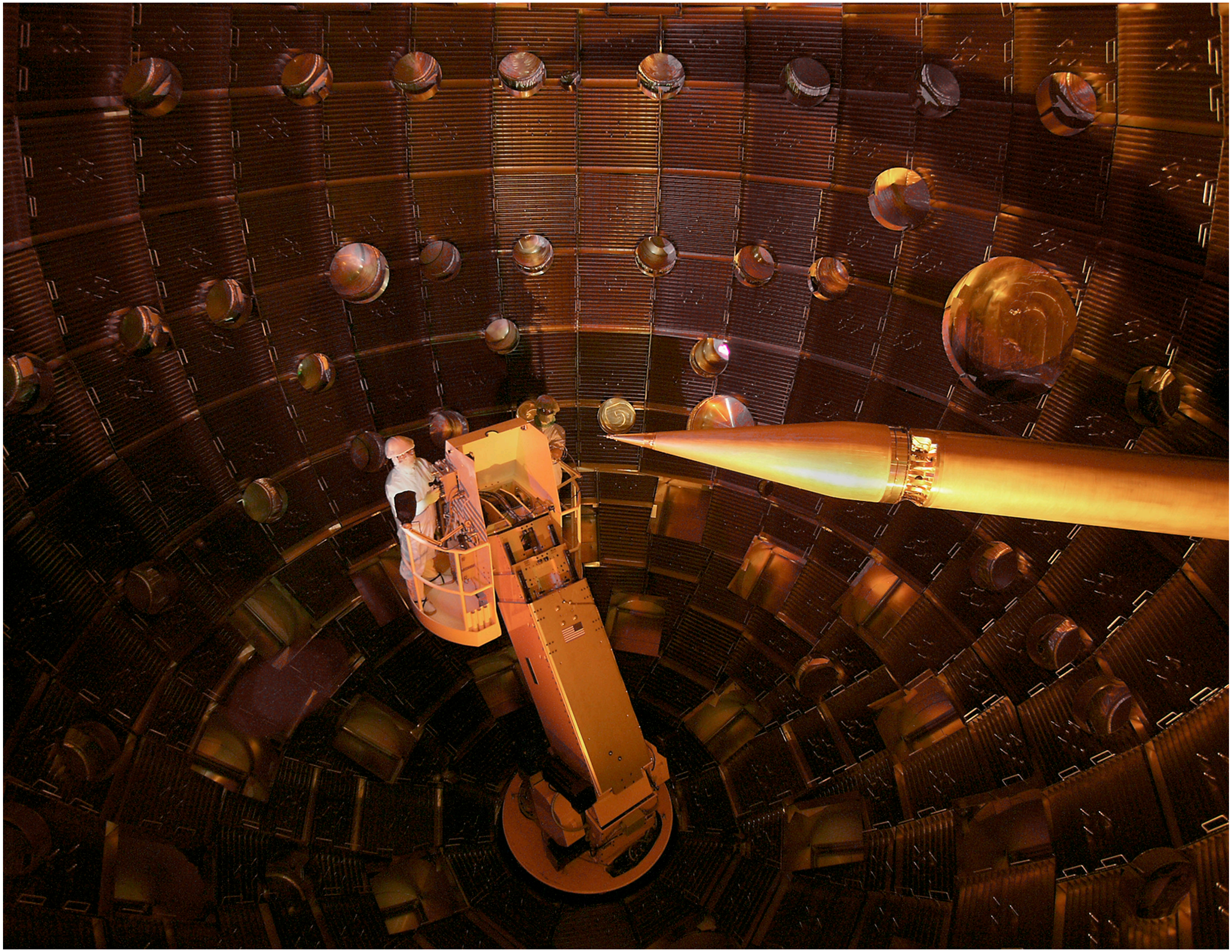






NIF – Laser Bay 2

NIF – Chamber

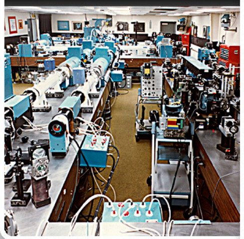


NIF Background

- Groundbreaking for construction in 1997
- Cost: ~$4B
- Dedication May 2009
- NIF can deliver 1.8 MJ of laser power to the target
  - OMEGA (LLE, Rochester NY), the previous record, can supply 40 kJ
- NIF may have the opportunity to achieve "IGNITION"
  - Releasing ~20 MJ of fusion energy (= ~5-kg TNT explosion)
- France: Laser Megajoule under construction
- Technology and Science:
  - Ignition
  - Intertial Fusion Energy
  - National Security
  - Basic Science (laser, plasma, nuclear, materials,…)

NIF is the culmination of a long line of glass laser systems developed at LLNL

Janus, 1973

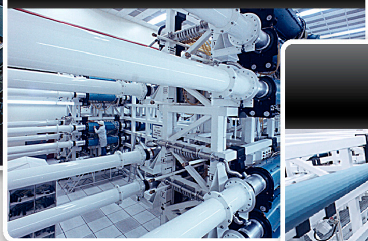


100J IR

Argus, 1976

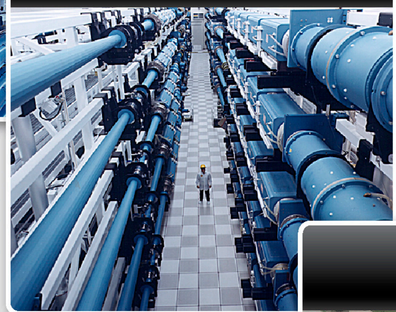
1kJ IR

Shiva, 1977



10kJ IR

Nova, 1984



30kJ UV

NIF, 2009

1.8MJ UV

Main Focus to date is on *Ignition*

Thermonuclear energy created faster than it is lost

Nuclear Diagnostics

- An important application of nuclear physics
- Nuclear methods are critical for understanding what happens
- All reactions occur within ~100 ps
- Challenging electromagnetic environment
- New detection techniques must be used

NIF now has > 40 diagnostics (>12 nuclear)
≈40 nuclear scientists involved

LLNL
- NToF
- FABS,NBI
- Dante I & II
- VISAR
- *GRH*
- RAGS
- hGXI
- ARIANE
- DIXI
- NAD
- *Solid Radchem*

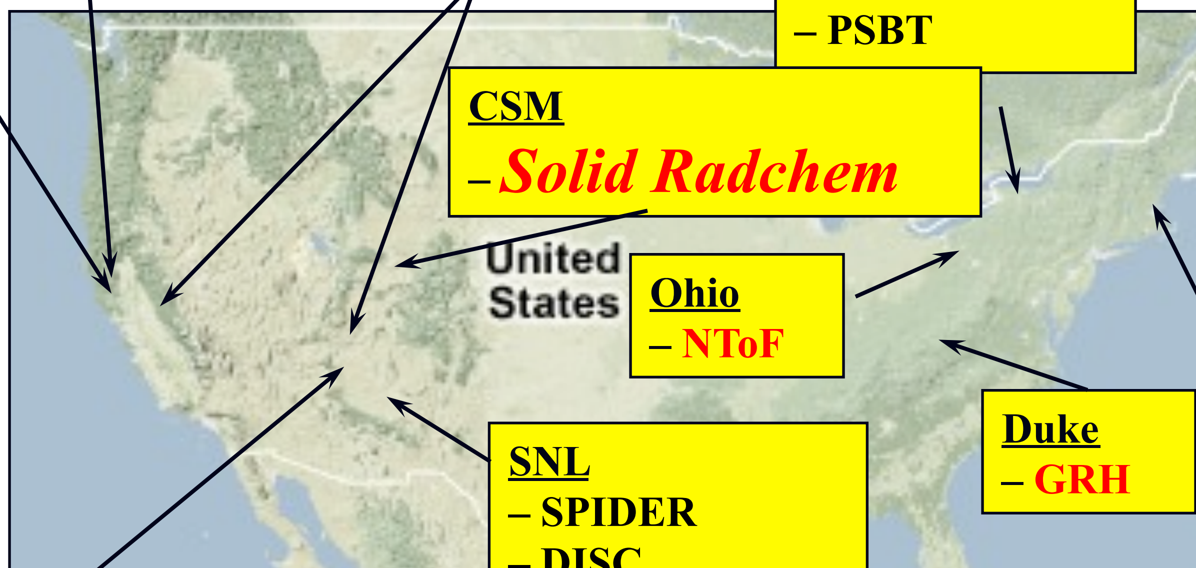
LBNL
- Calibration
- Rad. Chem.

NSTec
- Calibration
- NToF

LLE
- NToF
- 4ω fidu system
- MRS, NADS
- SPBT
- HEXRS
- PSBT

AWE
- FFLEX
- Dante
- *GRH*

CSM
- *Solid Radchem*



Ohio
- NToF

Duke
- GRH

LANL
- *GRH*
- GXD
- Rad. Chem. II
- n imaging

SNL
- SPIDER
- DISC
- NAD (Cu)
- NToF
- RAGS

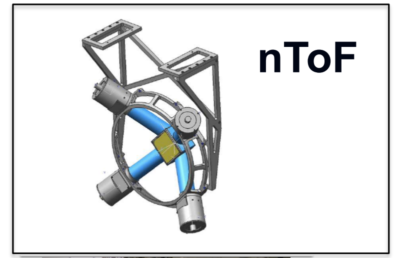
MIT
- MRS
- WRF
- *PTOF*

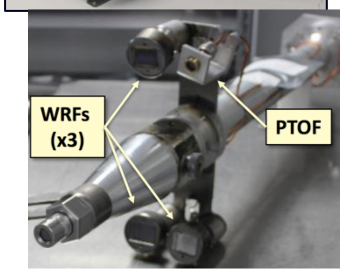
Nuclear Diagnostics in red

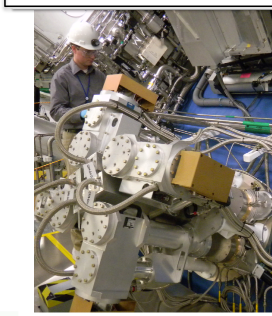
Improvements made to the nuclear diagnostic suite facilitate new measurement capability have yielded unprecedented diagnosis of implosions

Diagnostic	Improvement	New capability
NToF	Low n scattering Faster scintillator Faster recording	Drift velocity of burning plasma Carbon scattering edges n-T and n-D scattering edges
GRH γ reaction history	Absolute calibration of 4.4 MeV line of C	Carbon ρr total birth yield
NADS Flange NADS NAS	19 detectors Multi-foil spec.	Calibration using 2 shock system With NToF for v_{drift}, ρr anisotropy Finer neutron spectral measr.
MRS	Smaller more uniform Foils sputtered on High z backing	Improved resolution and High yield (>1E16) capability
RadChem Solid (SRC) Gas (RAGS)	SRC collection Gaseous collection implemented	Ability to catch fission fragments Both gaseous and solid
PTOF	CVD diamond close to TCC	Shock and compression nuclear bang times
WRF	More locations	Shock rhoR asymmetry
N Imaging	More sophisticated algorithms	Better images

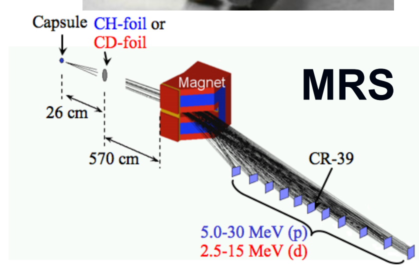
RAGS

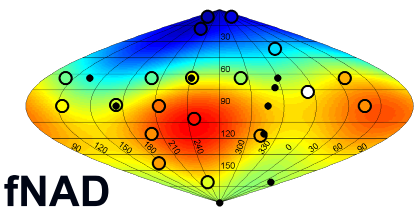






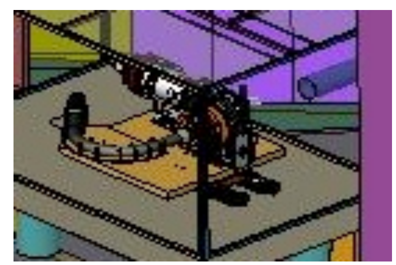
GRH



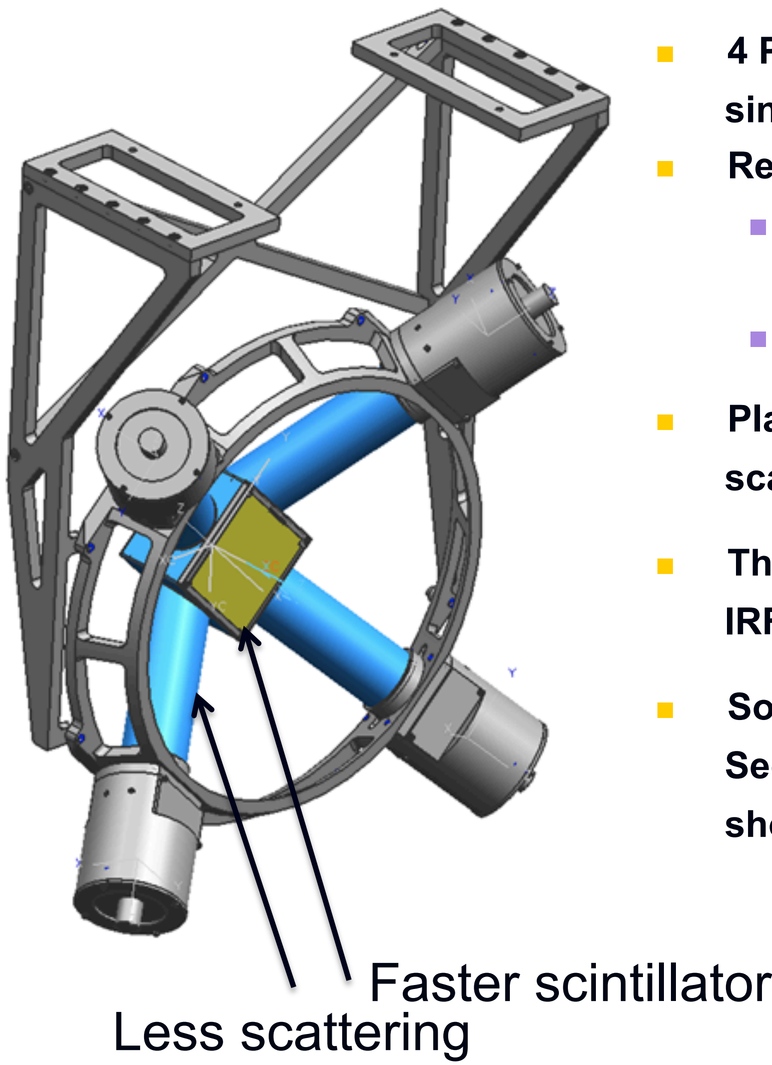


fNAD

N imaging

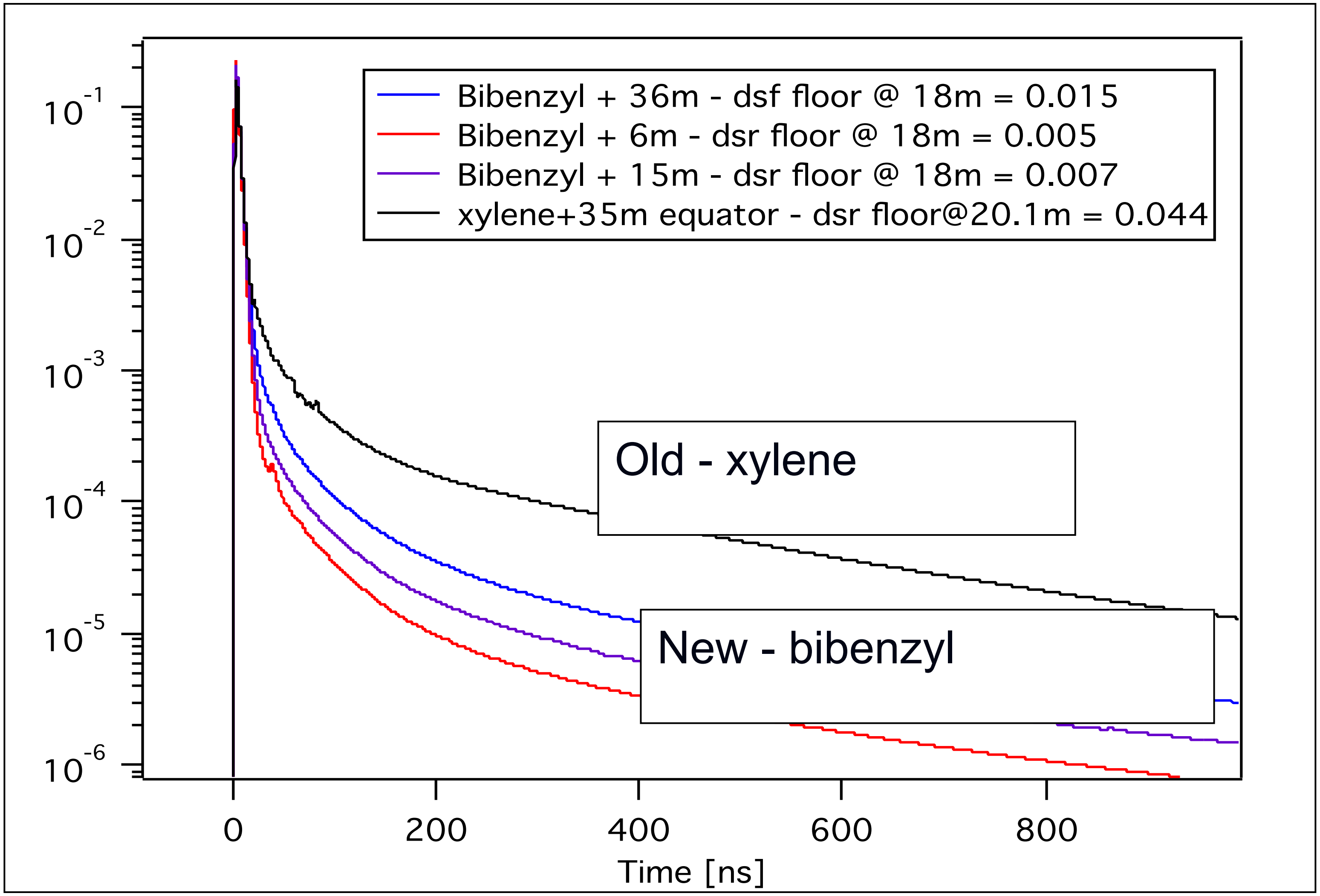


New NTOF detector design has replaced all 20 meter neutron spectroscopic detectors



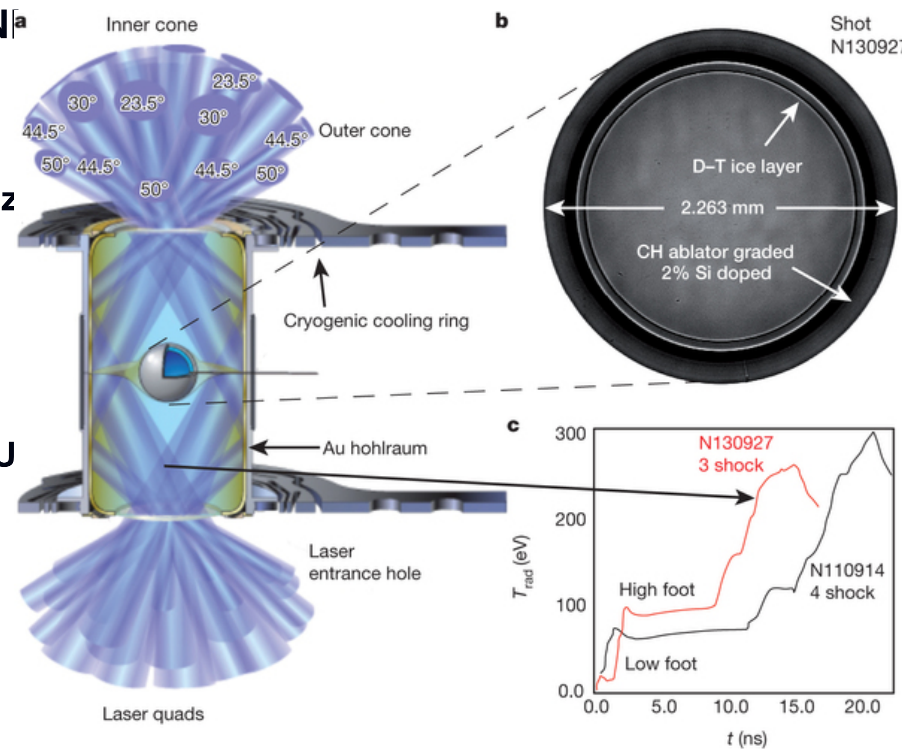
- 4 PMT system covers wide dynamic range ($\approx 10^6$) on a single shot
- Reduced mass near the scintillator
  - minimize re-scatter signal in the scintillator and PMTs
  - Minimize (n,γ) signal generation
- Placement of PMTs takes advantage of forward scattering bias
- Thinner scintillator reduces transit time contribution to IRF
- Solid bibenzyl scintillator (developed with Global Security) has superior late-time decay properties and should be more stable over time

New Bibenzel Scintillator is Much Faster



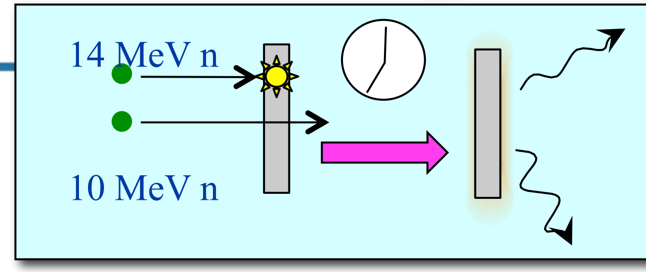
Nuclear observable highlights from the HiFoot campaign

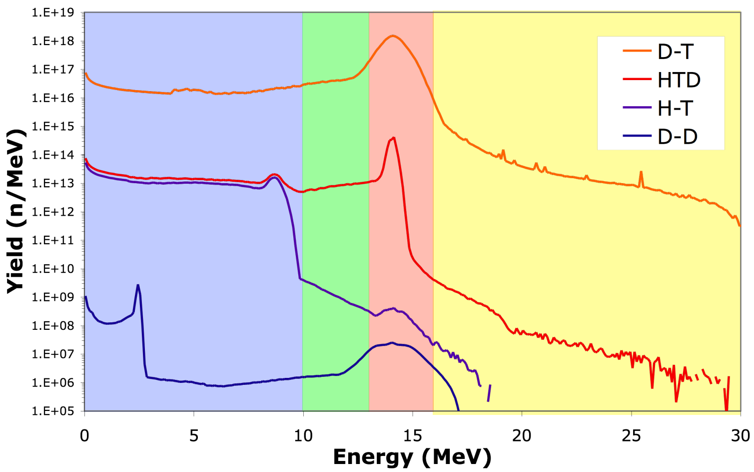
- HiFoot campaign* – layered DT shots with Au or DU hohlraum:
  - Higher adiabat implosions with “high foot” on the laser pulse
  - Reduced compression but much improved stability
  - Yields 10^{15}-10^{16} (current record is 9.6×10^{15} total DT birth yield)
- From the newly fielded NTOFs, MRS, and N
  - Tion asymmetry
  - DSR asymmetry
  - Hot spot mean burn-weighted velocities not z
- From the expanded Flange NAD
  - Better fuel anisotropy maps
- From the newly fielded RAGS
  - Overwhelming fission fragment data from DU hohlraum
- From the GRH
  - Carbon rho.R measurements
  - Total yield

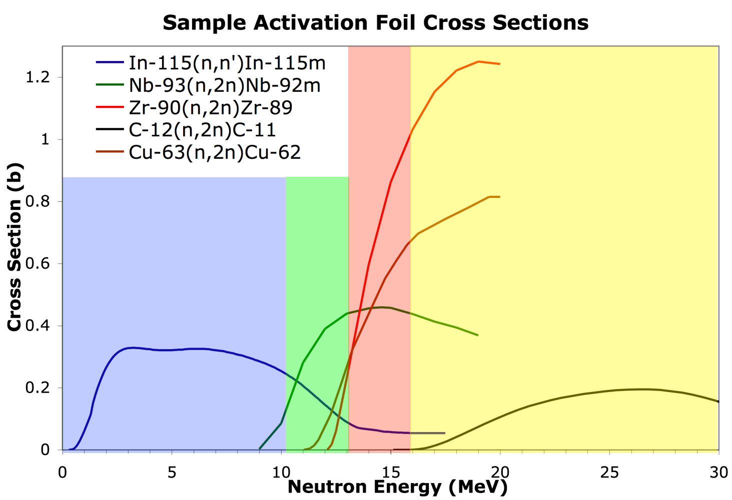


* See O. Hurricane *et al.*, Nature 506, p343-348, 20-Feb-2014

NAD Physics Basis
Activation Concept





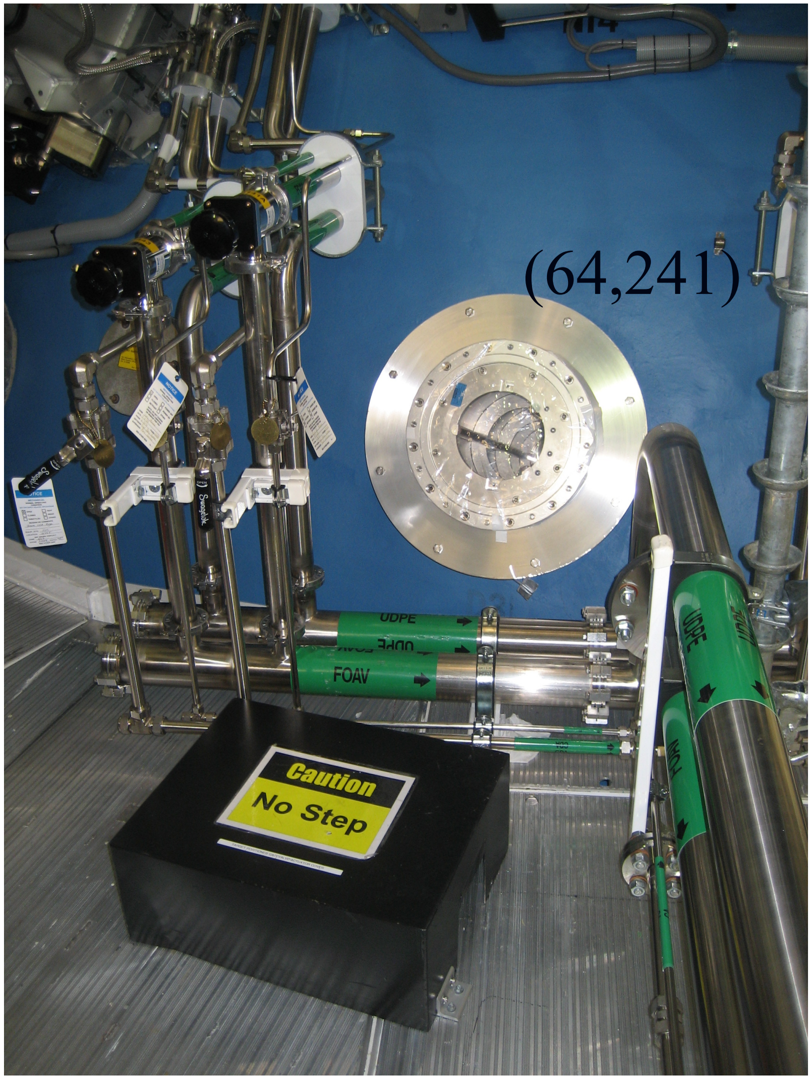


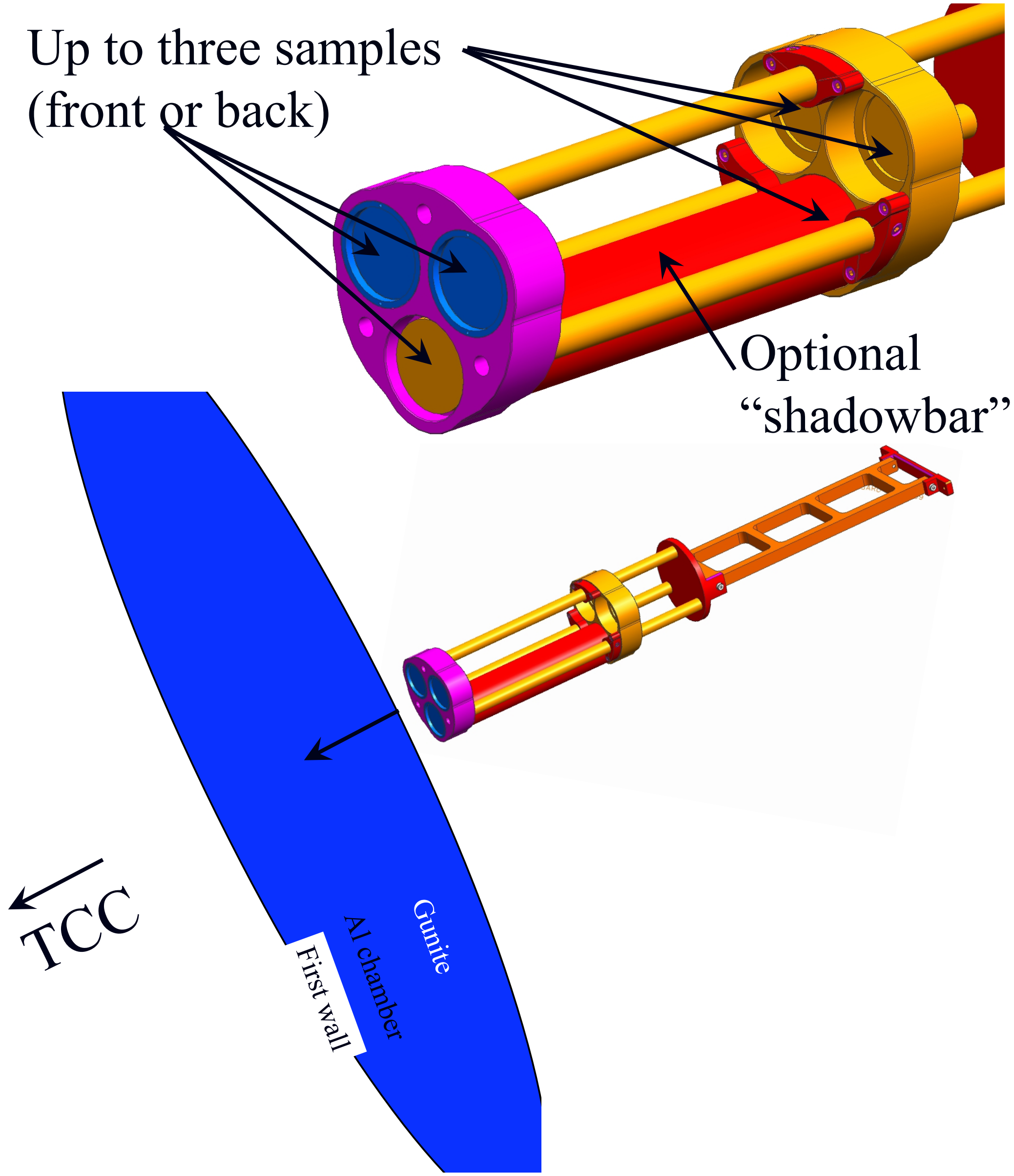
Four energy regions of interest:

1-10 MeV	(T-T / D-D spectrum)
10-13 MeV	(Downscattered)
13-15 MeV	(Primaries)
15-30 MeV	(Tertiaries)

$^{115}In(n,n') \Rightarrow {}^{115m}In$	($t_{1/2}$=4.5 h)
$^{93}Nb(n,2n) \Rightarrow {}^{92m}Nb$	($t_{1/2}$=10 d)
$^{90}Zr(n,2n) \Rightarrow {}^{89}Zr$	($t_{1/2}$=3.3 d)
$^{63}Cu(n,2n) \Rightarrow {}^{62}Cu$	($t_{1/2}$=9.74 m)
$^{12}C(n,2n) \Rightarrow {}^{11}C$	($t_{1/2}$=20 m)

$^{90}Zr(n,2n)^{89}Zr$ Activation for 14 MeV D-T Yield "Well-NAD" Implementation





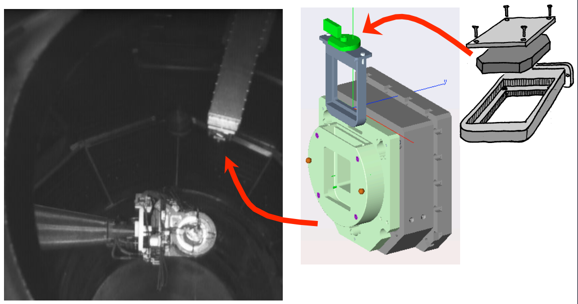
The five "flavors" of Neutron Activation

Access times are for yield <10^{16}

DIM-NAD (DD)

In

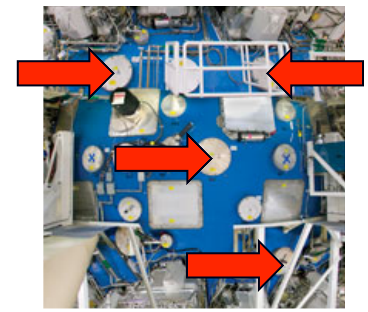
$t_{1/2}$=4.5h



Flange-NAD (DT)

Zr

$t_{1/2}$=3.3d

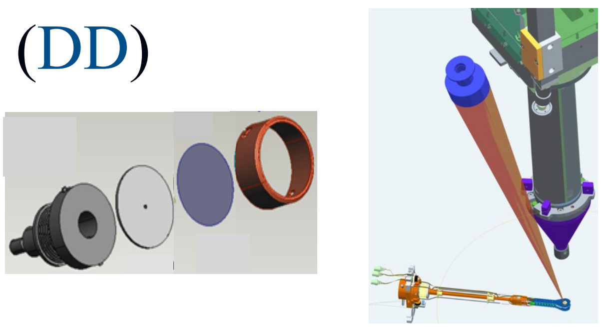


(not actual locations)

PPD-NAD (DD)

In

$t_{1/2}$=4.5h

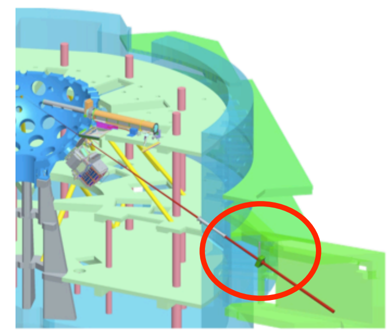


NAD20 (DT)

Cu Zr

$t_{1/2}$=9.7m

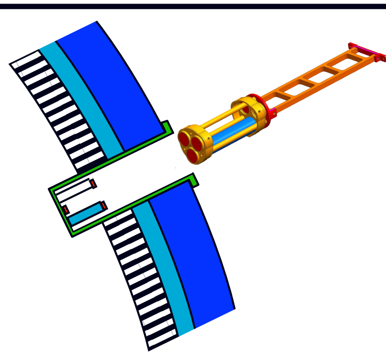
$t_{1/2}$=3.3d



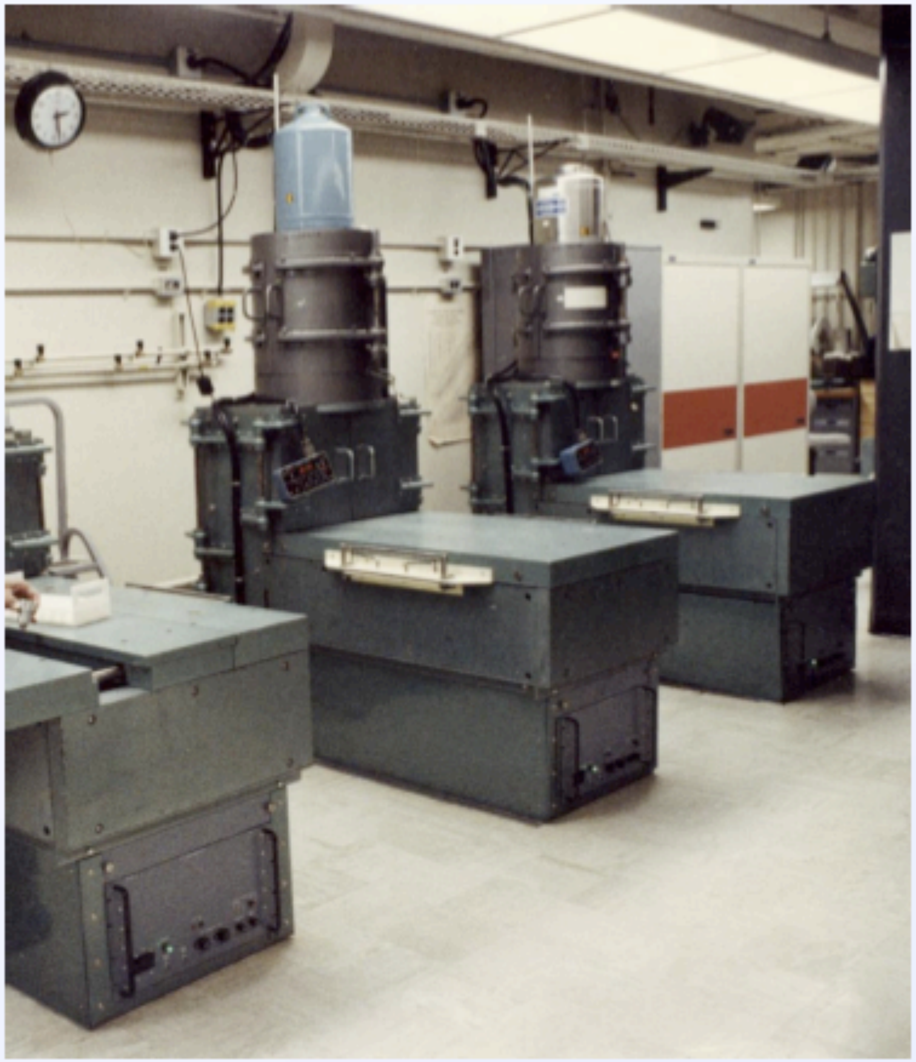
Well-NAD (DT)

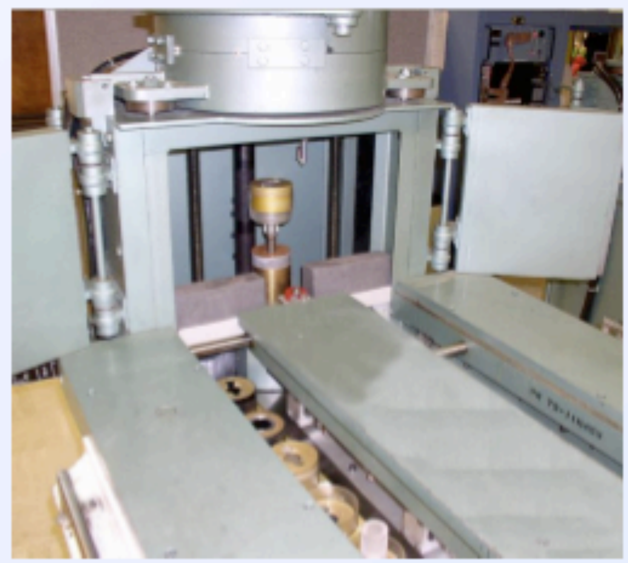
Zr

$t_{1/2}$=3.3d

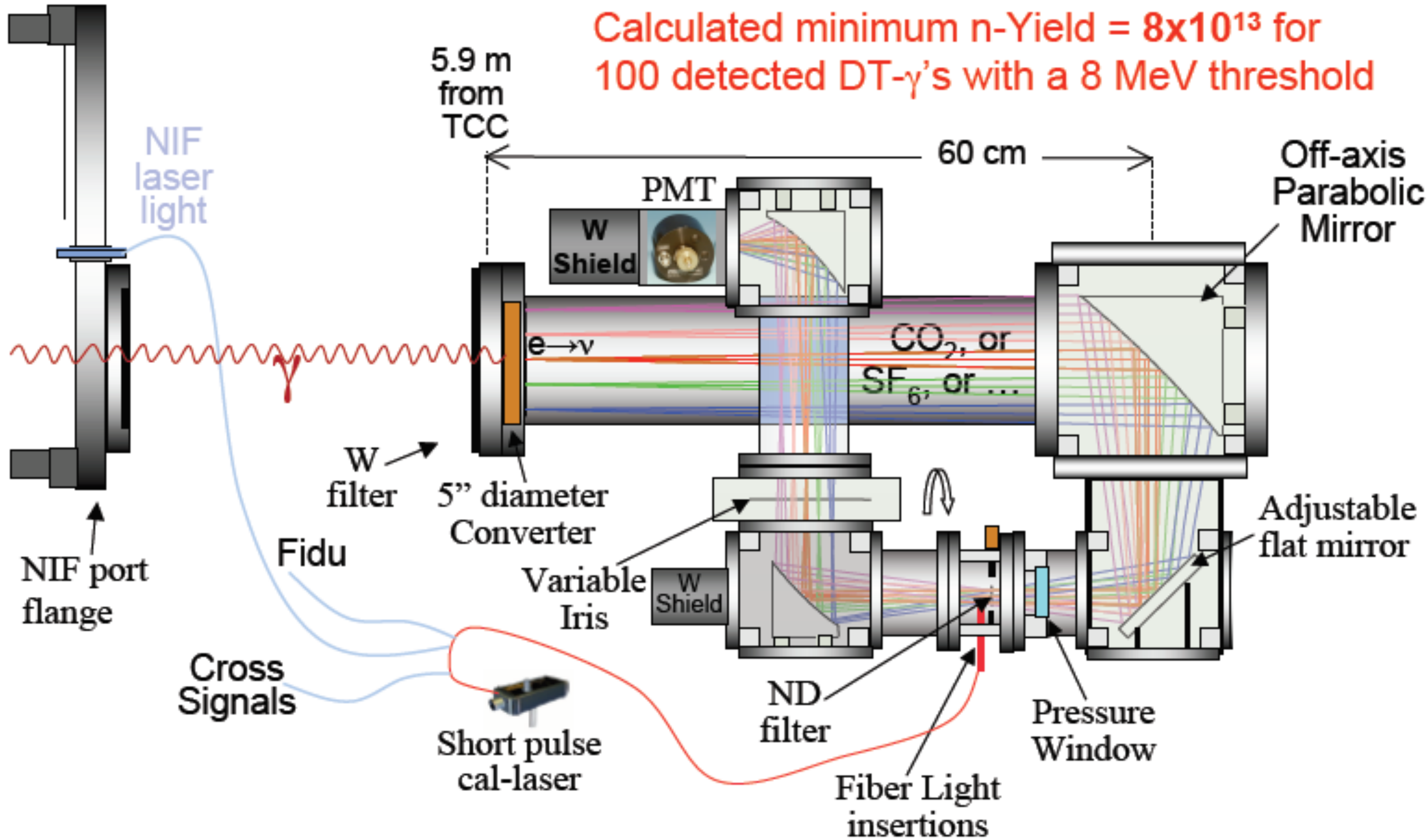


Detector calibration
B151 NCF has >40 years experience





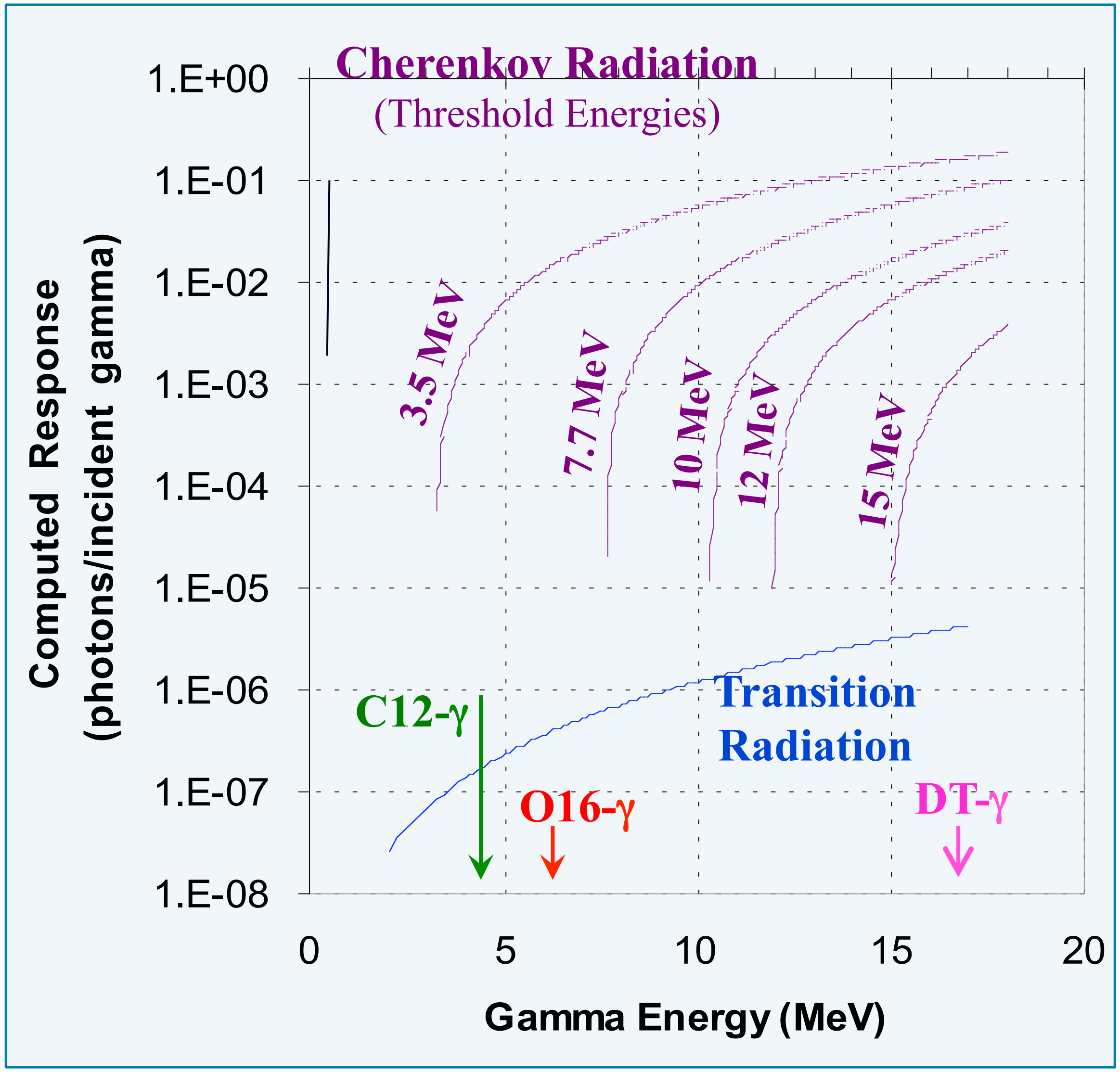
Gas Cerenkov Detectors are used to see high energy gammas (4.4 MeV, 17.6 MeV…)



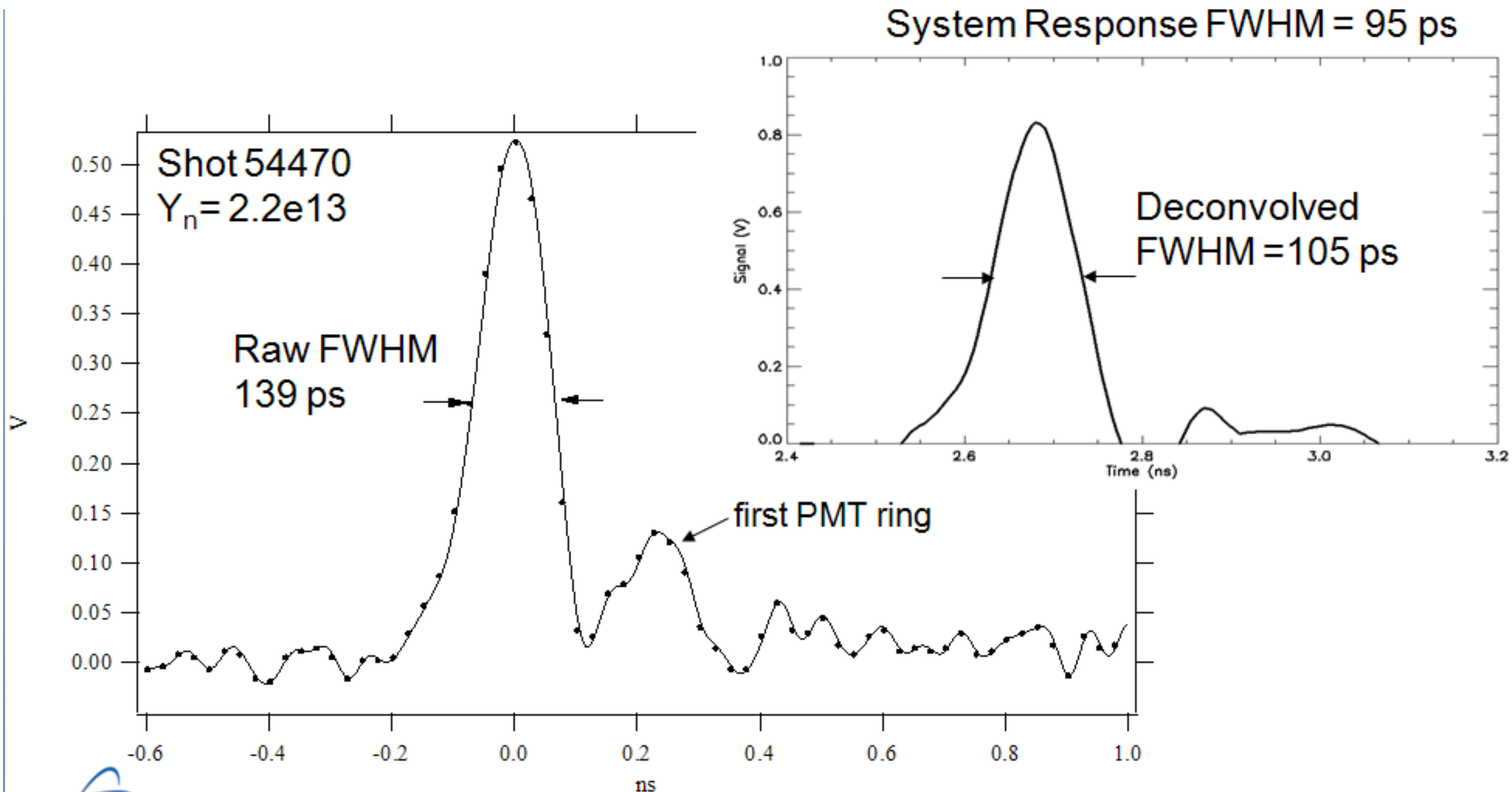
GCD Response to Various Gamma Ray Energies

Mack J.M. et al., Rad Phys Chem, 75 (2006) 551, Fig 5

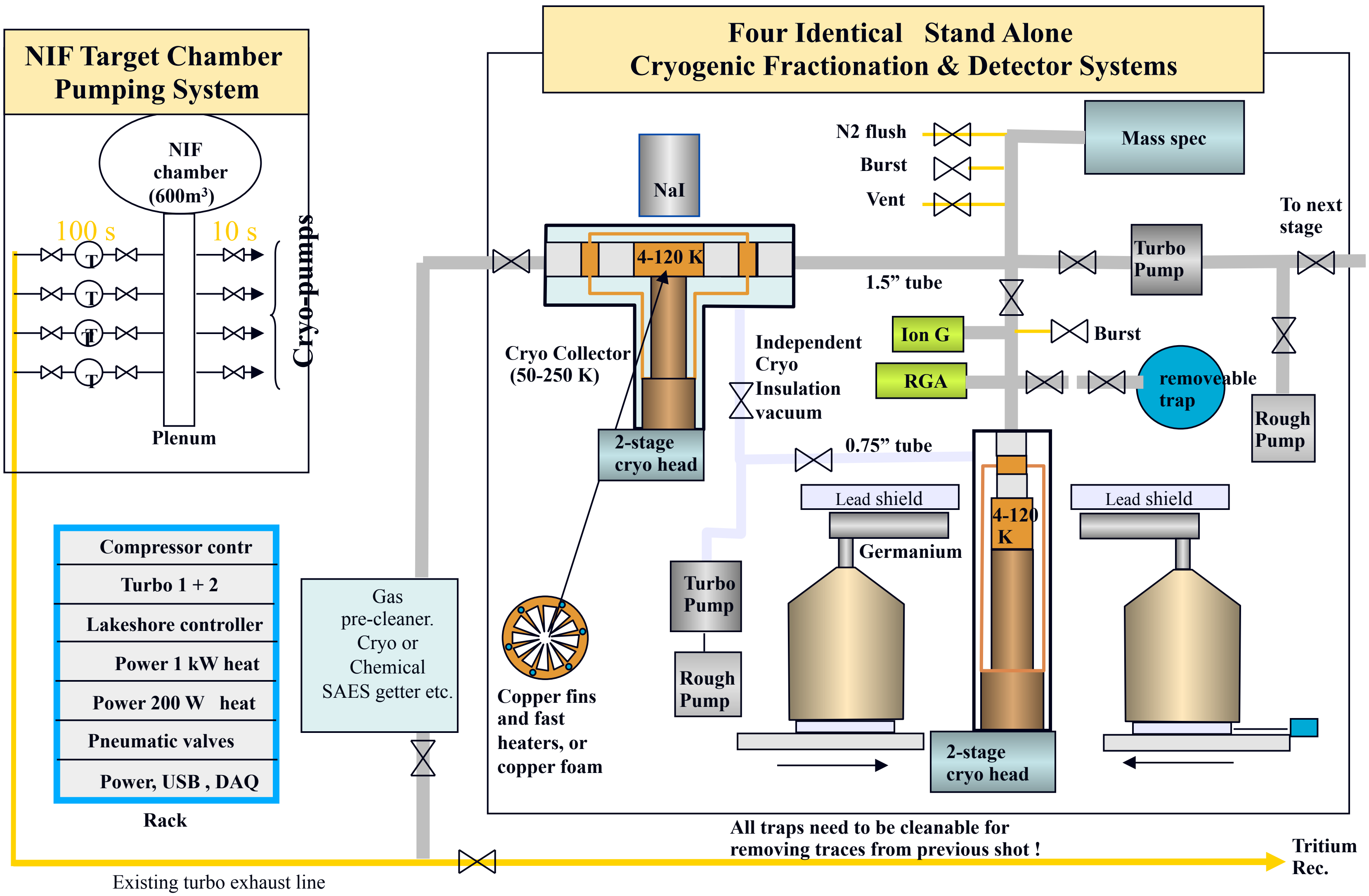
- GCD Sensitivity determined by:
  - γ energy and;
  - Cherenkov Threshold Energy (determined by gas index of refraction)
- For γ energy below threshold, no Cherenkov, but there is still:
  - Transition Radiation (shown)
  - possibly fluoresence (not shown)
- Using detectors with different thresholds allows for γ-ray spectroscopy
- Scattering off othese these states could be measured radiochemically too



Recent measurements with a GCD show excellent timing (compliments of W. Stoeffl)



Collecting Noble-gas products from a NIF Capsule



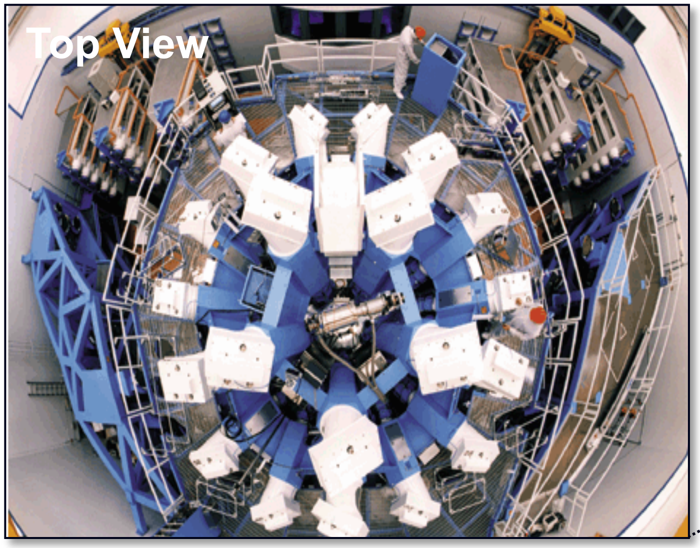
W. Stoeffl

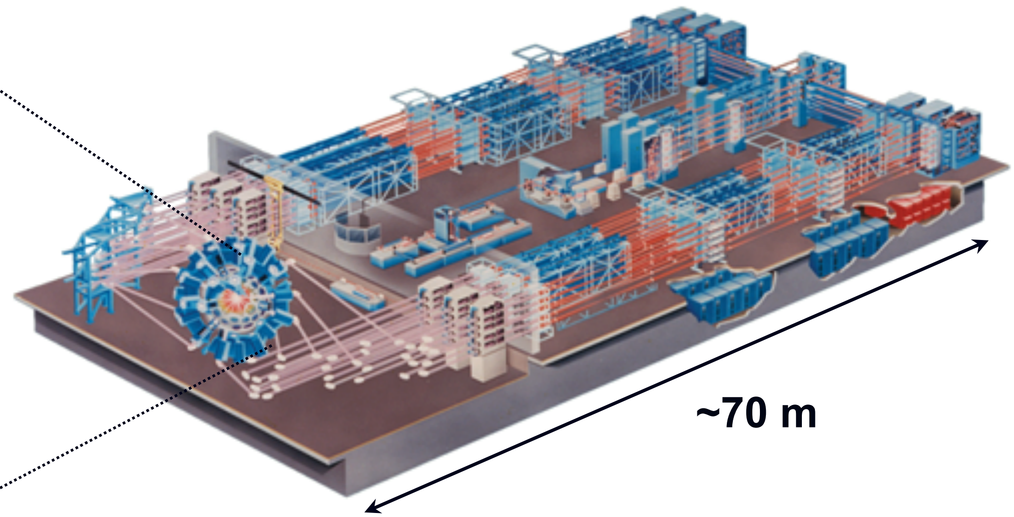
Unique Features of ICF Environment for Nuclear Physics

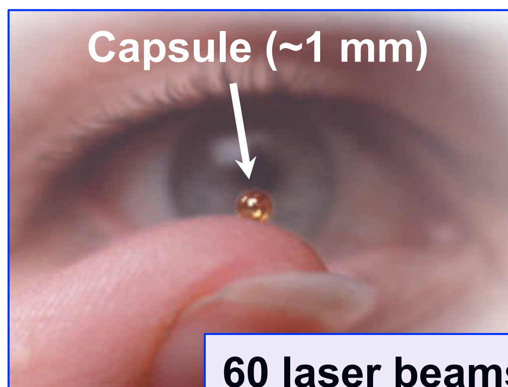
as compared to accelerator-based approaches

- Low mass near target
- Sharp time structure
- Possibility of high neutron fluxes
- Willingness to work with tritium
- Largely limited to low-Z nuclei and nuetron-induced reactions, due to the Coulomb barrier

The first Nuclear Science experiment using HED plasmas was conducted at the OMEGA laser at University of Rochester

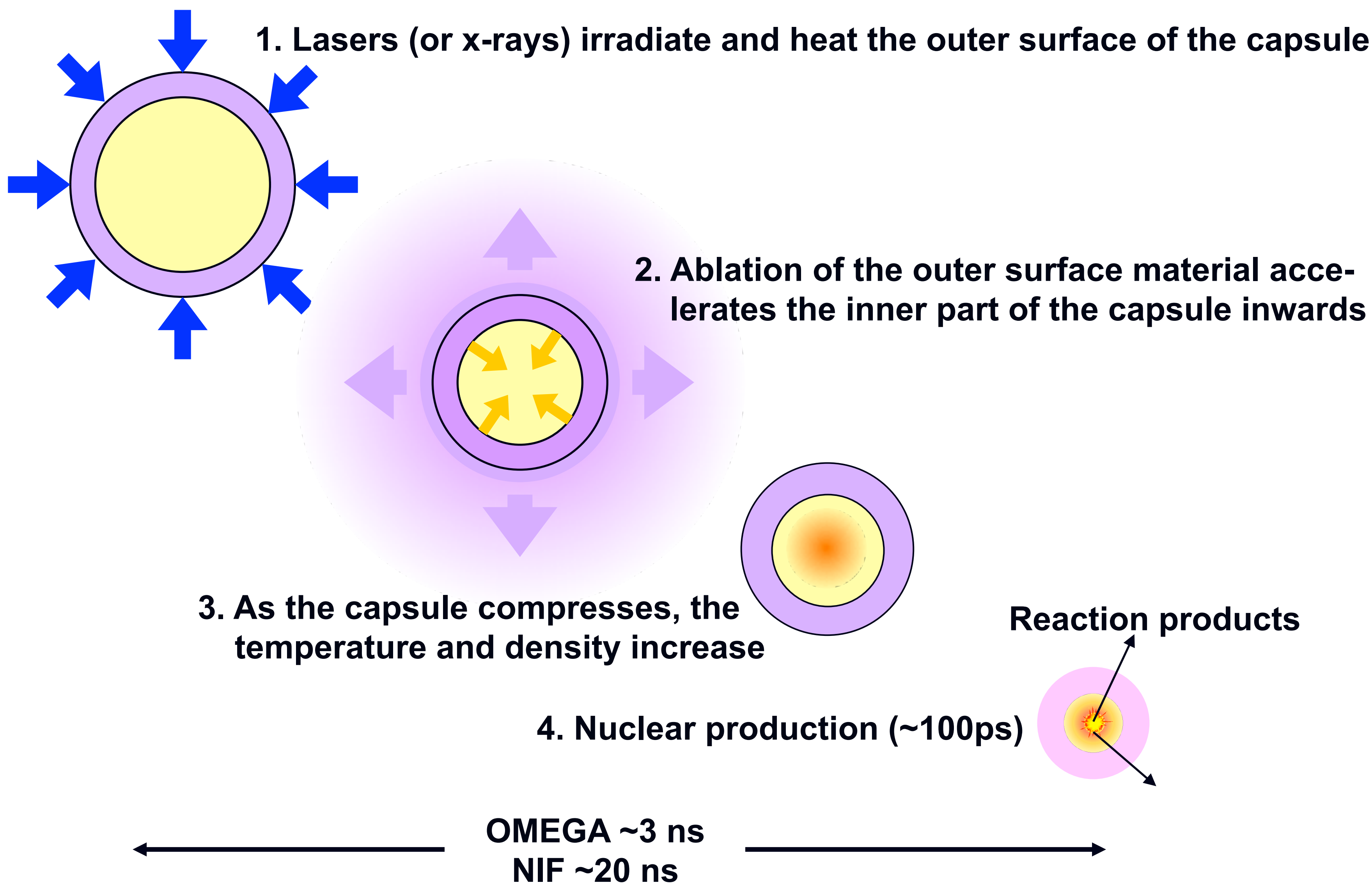




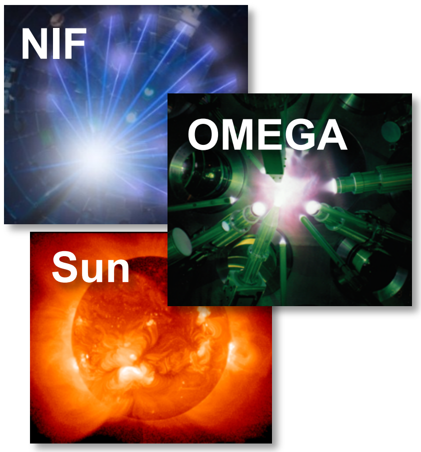


60 laser beams delivering up to 30 kJ
Temperatures > 10 keV
Densities up to 100 g/cc
Pressures up to 50 Gbar

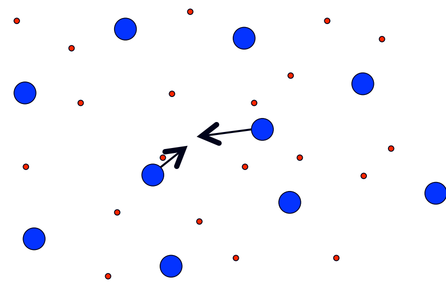
At OMEGA and the NIF, HED plasmas are created by spherically compressing a capsule



The conditions in HED plasmas (and in stars) are quite different from those created by accelerators

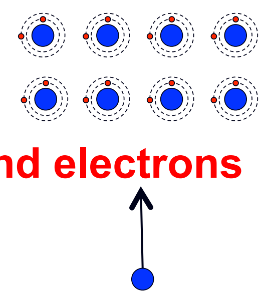


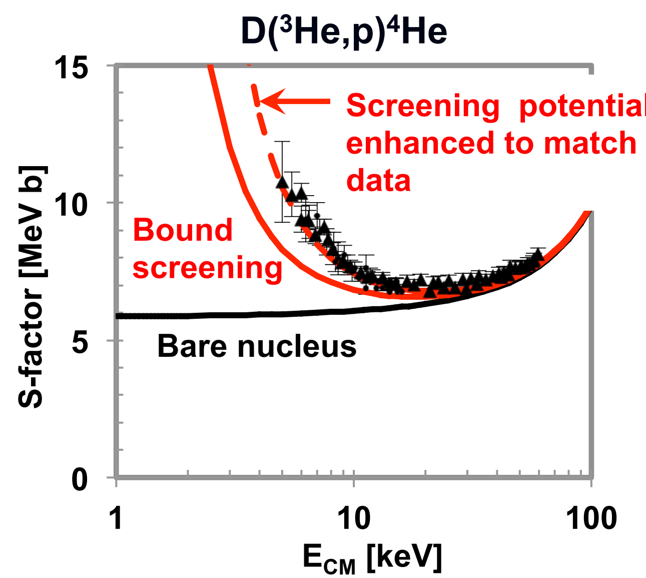
Dense and hot plasma



Accelerator experiments

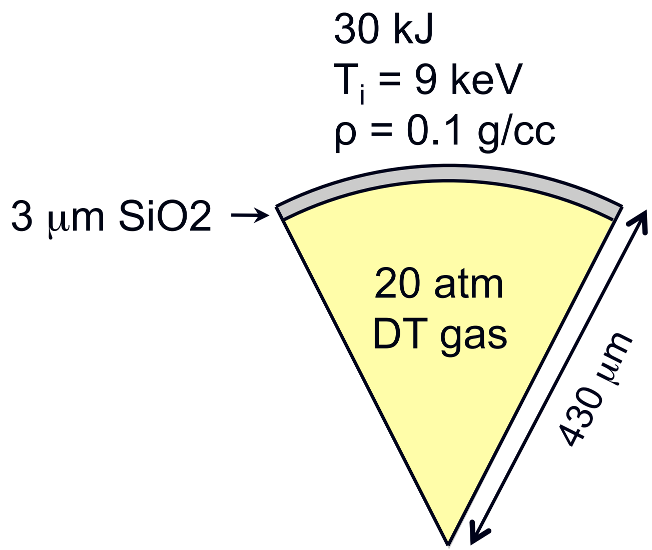
Cold Target

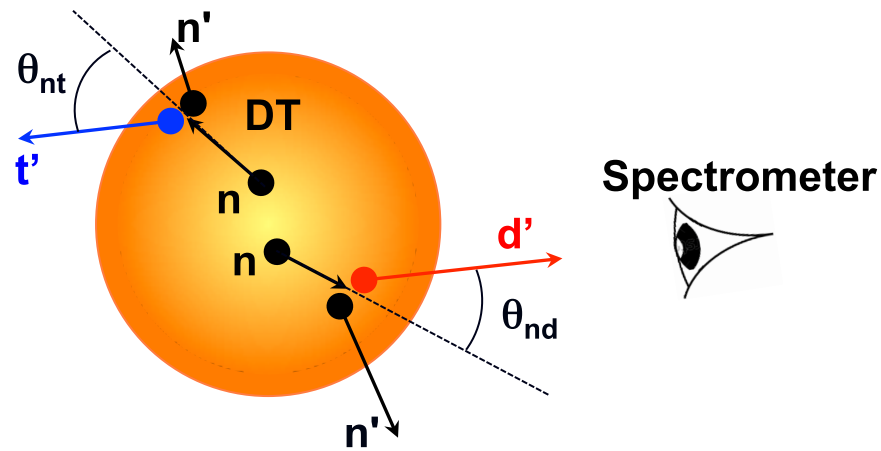




M. Aliotta *et al*, NP A (2001).
U. Schröder *et al*, NIM B (1989).
H. J. Assenbaum *et al*, ZP (1987).

The first nuclear physics experiment involving HED plasmas looked at the dσ/dΩ for the n+d/n+t elastic scattering at 14 MeV





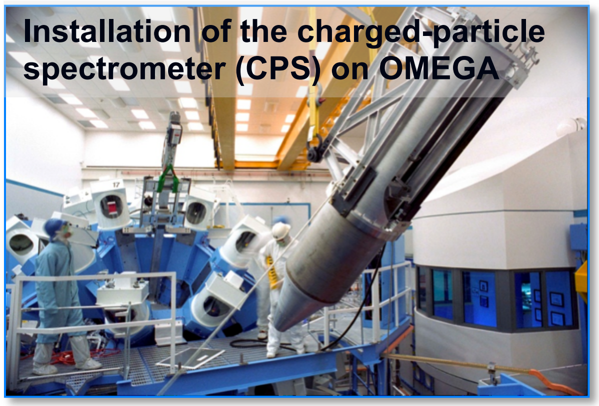
D + T → n(14 MeV) + ^{4}He

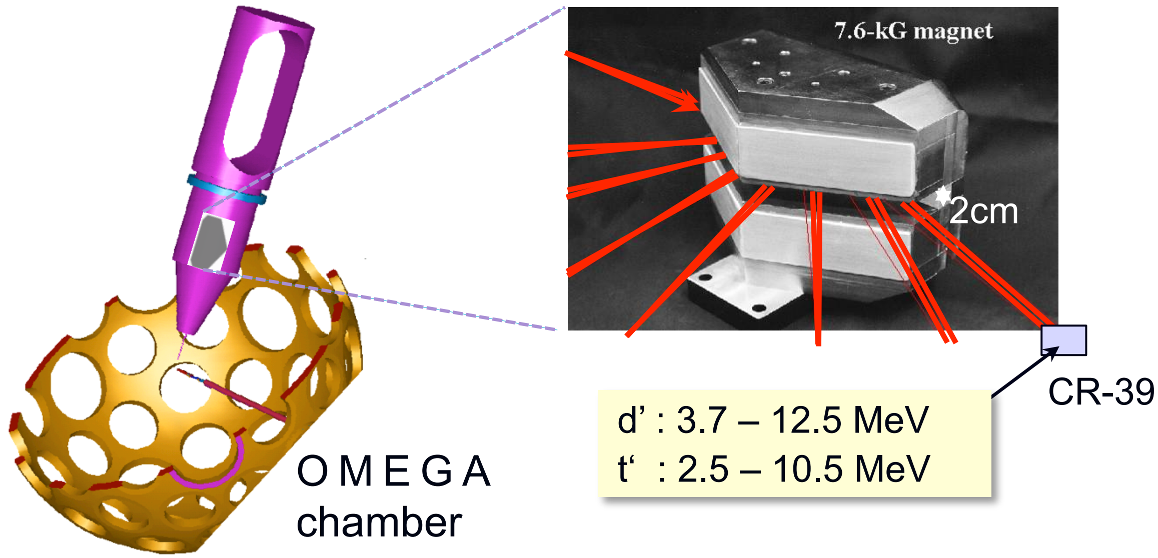
n(14MeV) + D → n' + d' (<12.5 MeV)
n(14MeV) + T → n' + t' (<10.5 MeV)

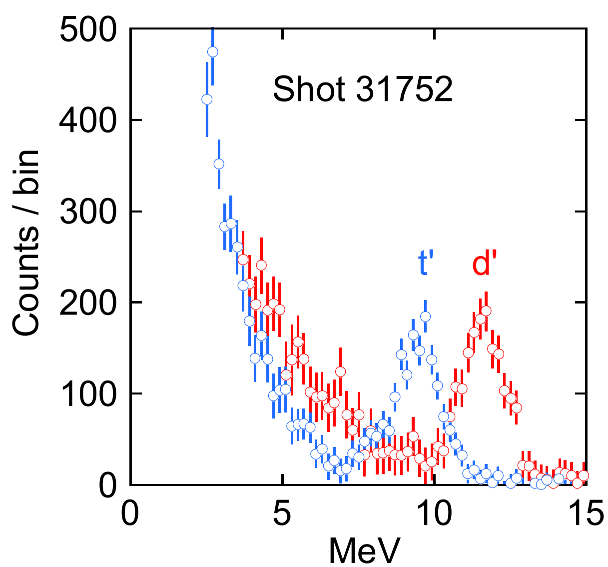
$E_{d'} = (8/9) \times E_n \times \cos^2\theta_{nd}$
$E_{t'} = (3/4) \times E_n \times \cos^2\theta_{nt}$

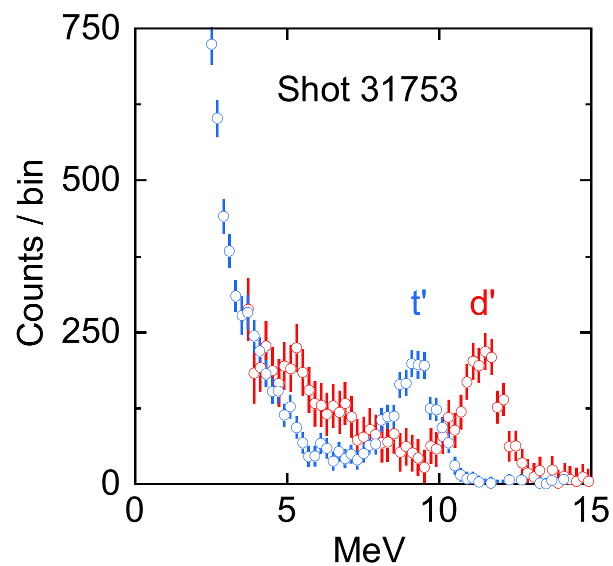
Plasma serves as a neutron source and target

Spectra of the d' and t' were measured simultaneously with a simple charged-particle spectrometer (CPS)

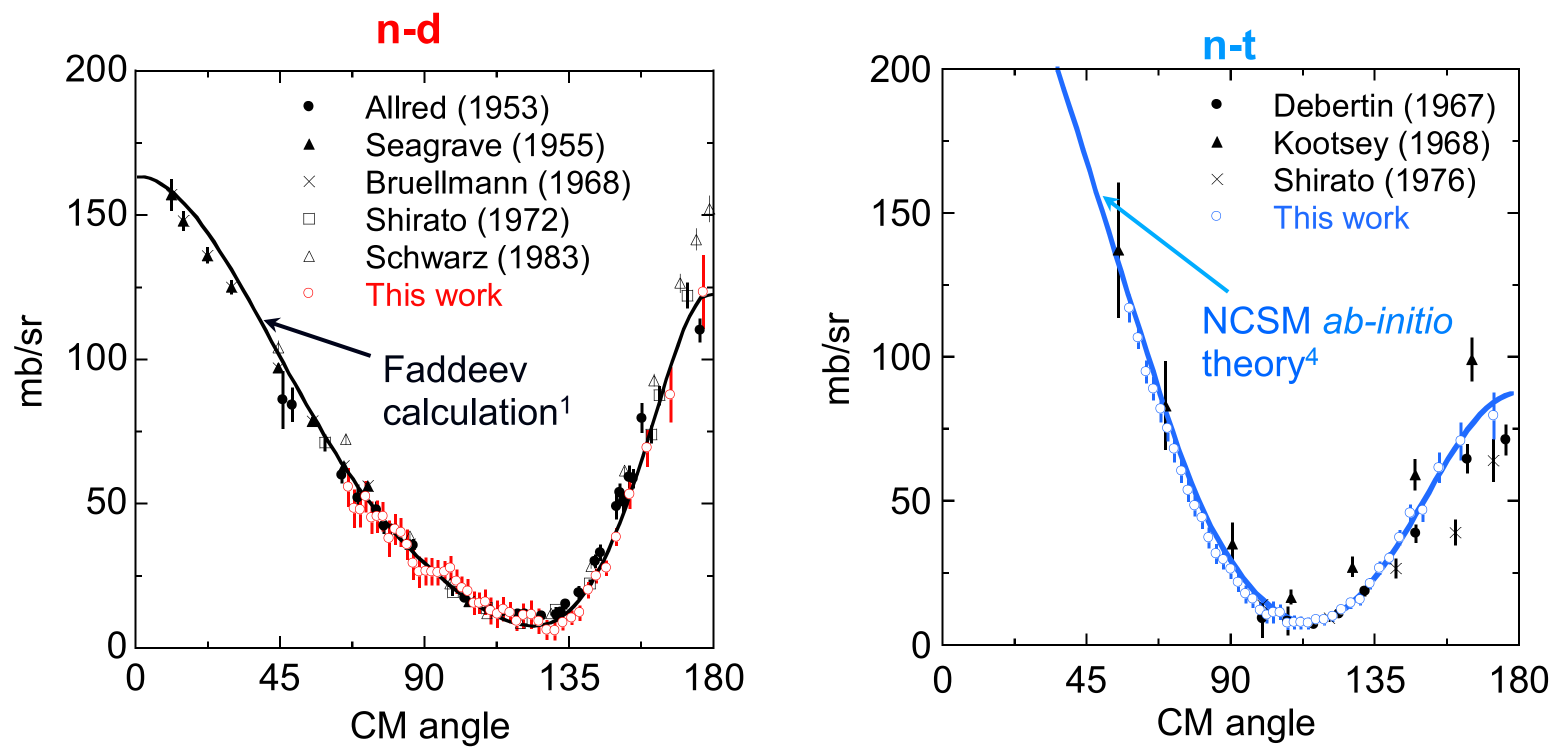








dσ/dΩ for the n+t elastic scattering determined in this experiment[3] is of much higher quality than data obtained in accelerator expts



These results indicate that recent advances in *ab-initio* theory[2),4)] can provide an accurate description of light-ion reactions

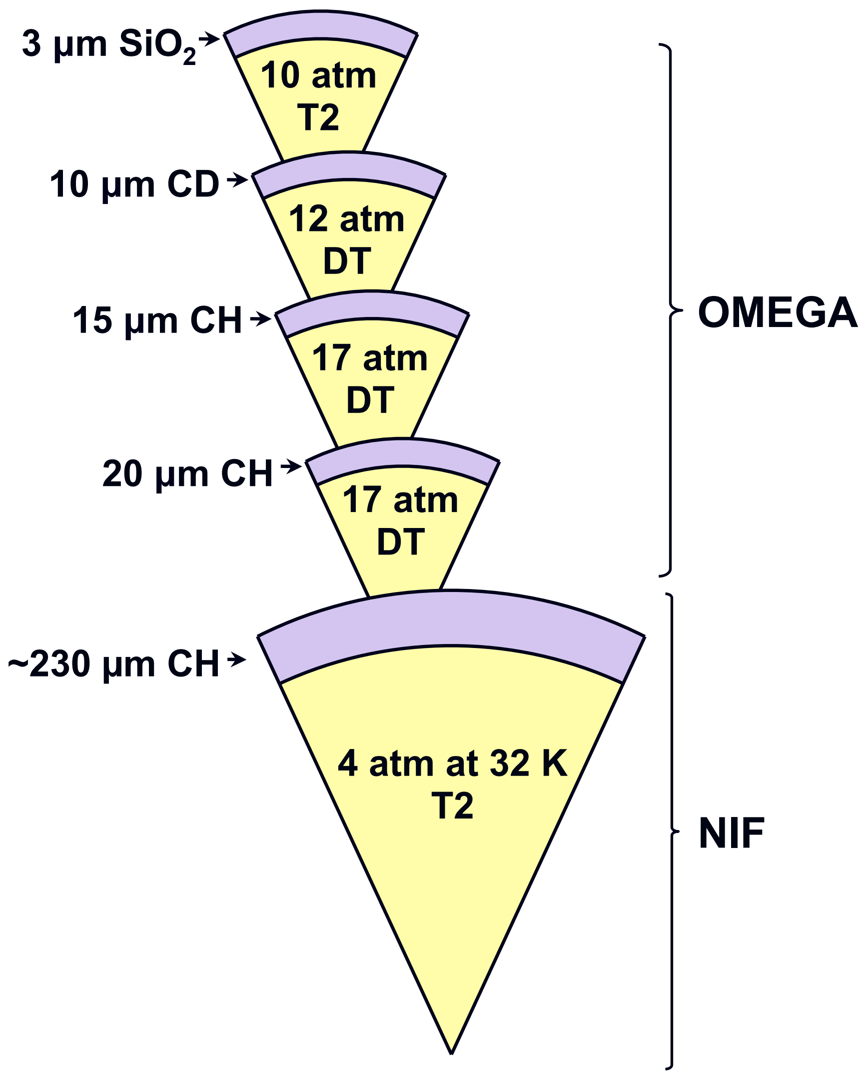
[1] Epelbaum et al., PRC (2002).
[2] Deltuva et al., PRC (2012).

[3] Frenje et al., PRL (2011).
[4] Navrátil et al., LLNL-internal report (2010).

T(T,2n)α Motivation

- Study reaction mechanism: ^{5}He and di-neutron correlations
- R-Matrix description of 3-particle final states
- Study mirror symmetry
- Demonstrate measurement of charged-particle reaction rate in plasma
- The cross section and neutron spectrum are important for inertial confinement fusion

The T+T reaction has been studied extensively at OMEGA and the NIF

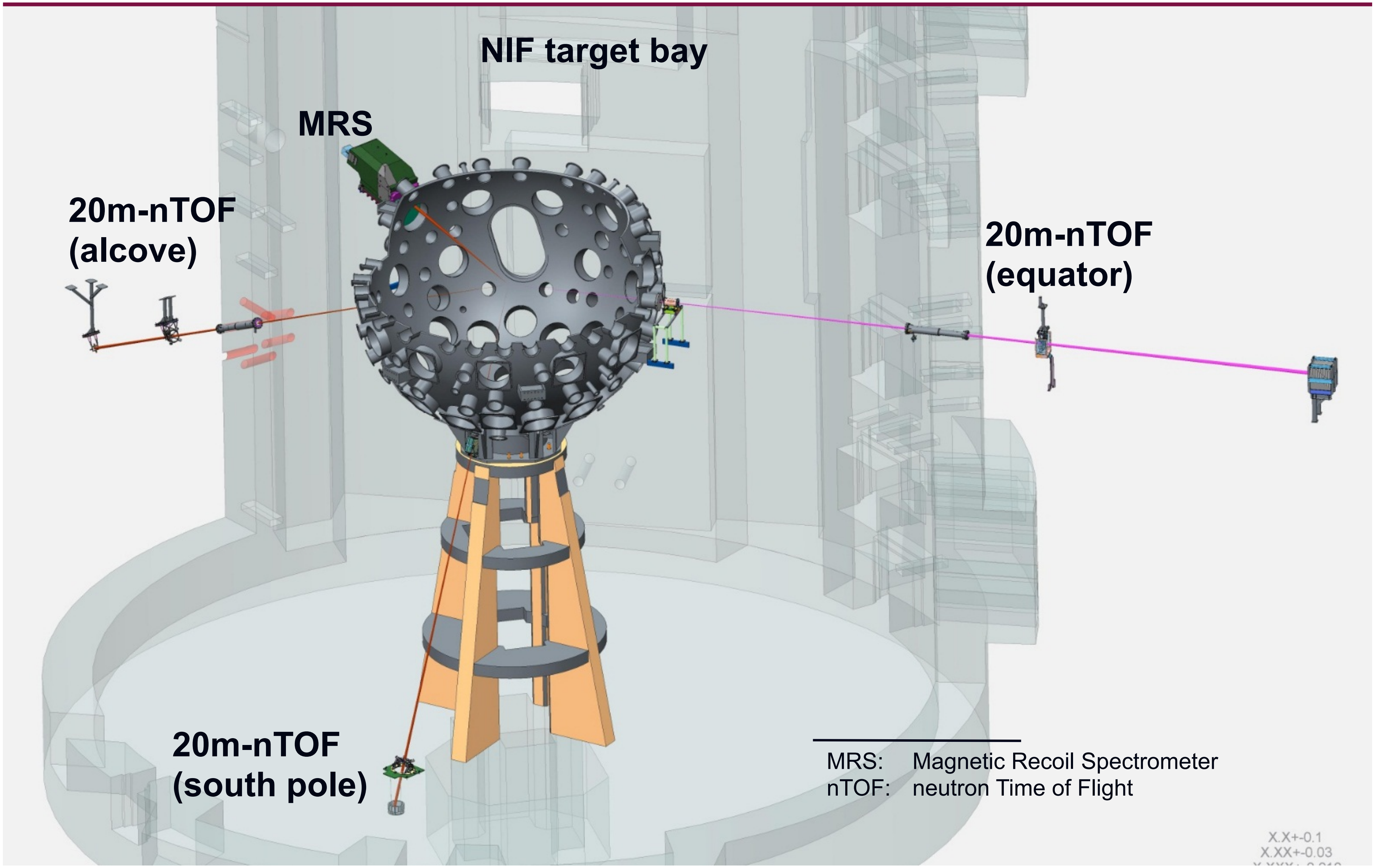


T + T	→	$^4He + 2n$ (< 9.5 MeV)
	→	$^5He + n$ (8.7 MeV)
	→	$^5He^* + n$
	→	$^4He + (nn)$

Understanding the T+T reaction has important implications for:

1. Basic nuclear physics
2. Stellar Nucleosynthesis
3. Inertial Confinement Fusion

On the NIF, neutron spectrometers, generally used to support the ICF program, were used to study the T+T reaction at low *ECM*

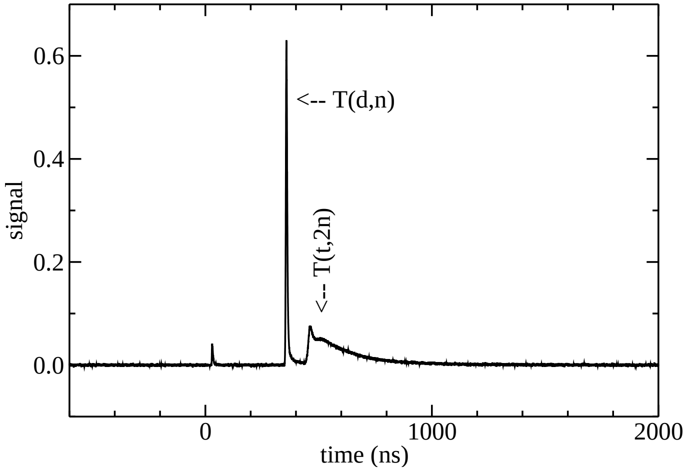


MRS: Magnetic Recoil Spectrometer
nTOF: neutron Time of Flight

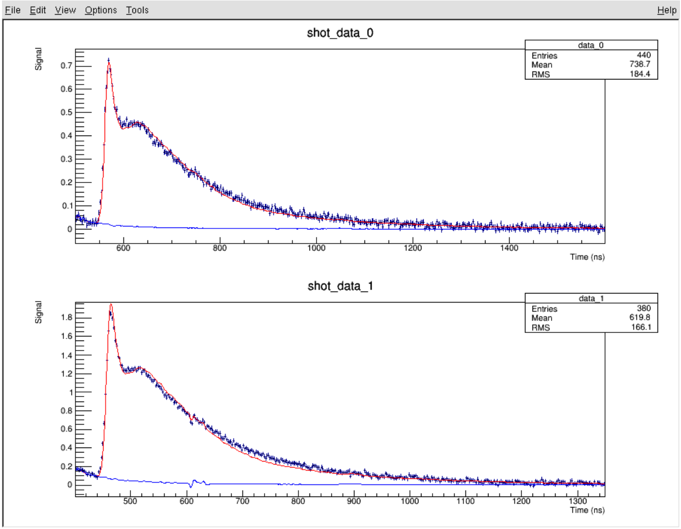
Measurement of the $T(t, 2n)\alpha$ at the National Ignition Facility

- Nearly pure tritium gas (0.1% D), low areal density "symcap" (gas-filled plastic capsule)
- ≈ 200 ps thermonuclear burn time
- $kT = 3.3(3)$ keV $\quad \rightarrow \quad E_{\text{Gamow}}(\text{T} + \text{T}) = 16$ keV
- 2 organic liquid scintillators (xylene) @ 20 and 22 meters, respectively
- Modeling includes:
  - Instrument Response Function (time response)
  - Scintillator response (efficiency)
  - Attenuation and scattering
  - Thermal broadening
  - Background from $\text{T}(d, n)$ (small)

Raw Data from Equator Detector @ 20.1 m

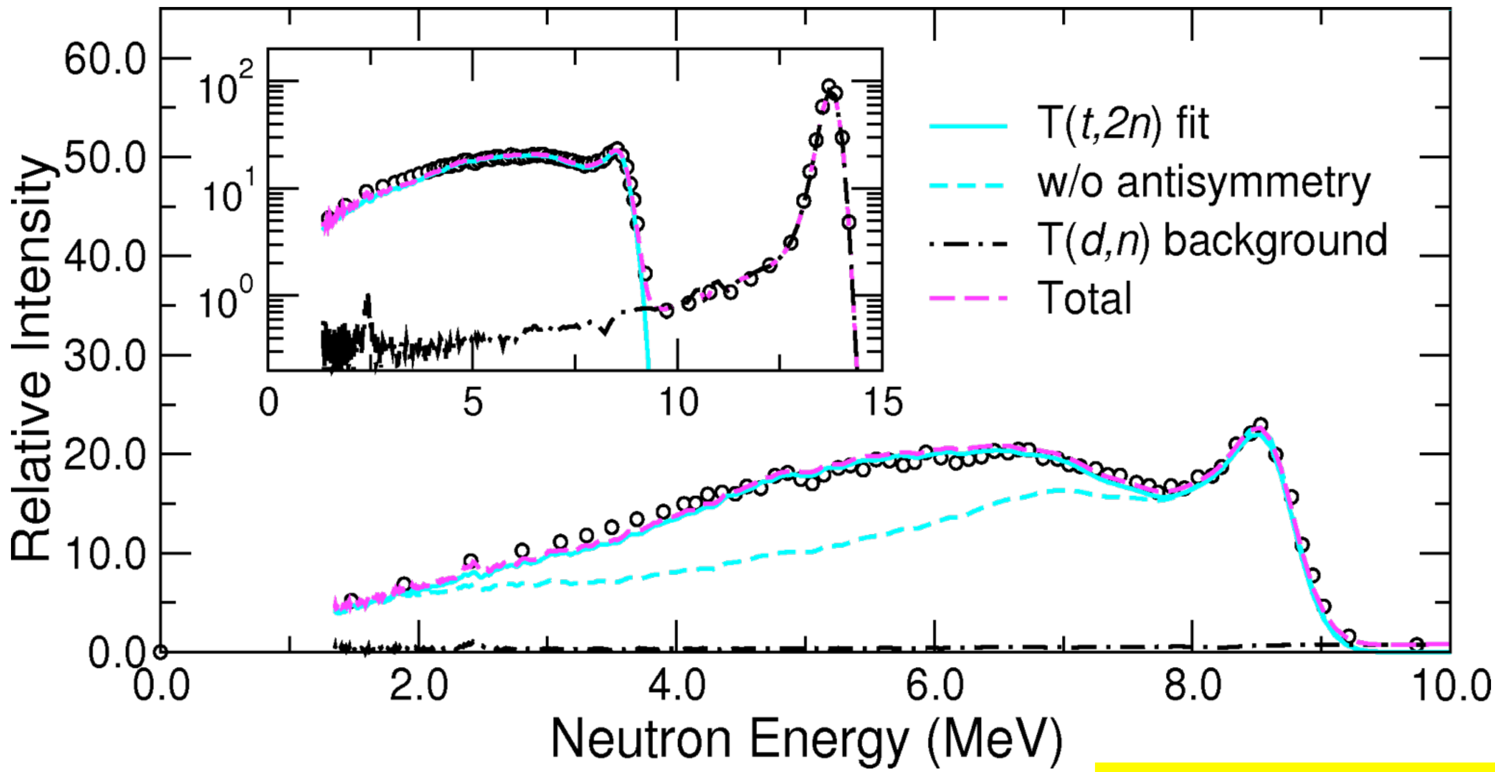


Fits to Time Spectra



TT neutron spectrum measured with unprecedented resolution and statistics -

D. Sayre, C. Brune, J. Caggiano *et al.*, Phys. Rev. Lett. 111, 052501 (2013)



Excellent statistics and energy resolution

- **10^{13} total neutrons produced over 200ps thermonuclear burn**
- **99.8% tritium target minimizes T(d,n) induced background**
- **Two 20-m nToFs measure spectrum with 280-keV resolution**
- **<σv> determination underway**

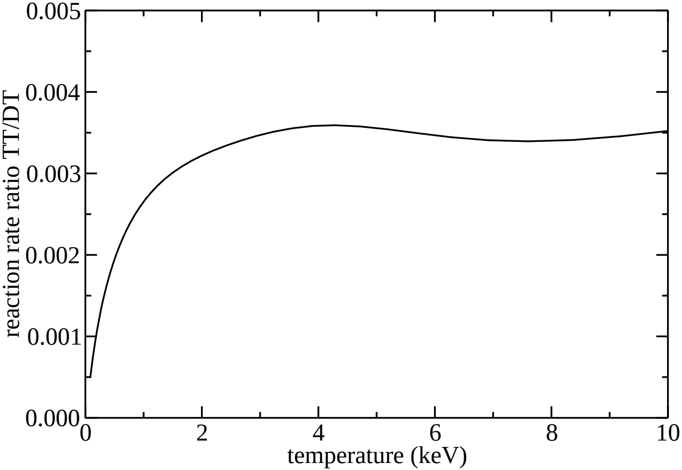
Key findings:

- **Presence of peak clearly established**
- **Antisymmetrization plays major role in spectrum shape**

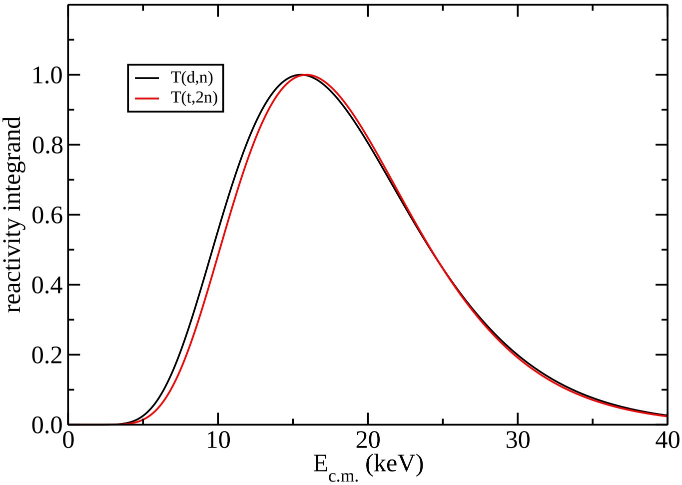
Determination of Thermonuclear Reaction Rate

- Definition:
  $$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu (kT)^3}} \int_0^\infty E\sigma(E) \exp[-E/(kT)] \, dE$$
- Principle of measurement:
  - Measure ratio to $\mathrm{T}(d,n)$ reaction rate (known to $\approx 1\%$)
  - H.-S. Bosch and G.M. Hale, Nucl. Fusion **32** 611 (1992)
  - Assume constant S factor for $\mathrm{T}(t,2n)\alpha$
- Mass spectrometry of capsule fill gas:
  - tritium: 99.598(4) %
  - deuterium: 0.082(1) %
  - remainder: protium and ^{3}He
- Yield-weighted ion temperature determination:
  - use width of "14 MeV" neutron peak from $\mathrm{T}(d,n)$
  - Brysk Formula: $\sigma[E_n] \approx \sqrt{\frac{2M_n \langle E_n \rangle}{M_\alpha + M_n}(kT)}$
  - H. Brysk, Plasma Physics **15**, 611 (1973)
  - Actual analysis uses a more sophisticated approach, including, e.g., relativistic kinematics

Reaction Rate Ratio is Insensitive to Temperature



T(d,n) and T(t,2n) Reactivity Integrands
for $kT = 3.3$ keV



Systematic Errors Considered:

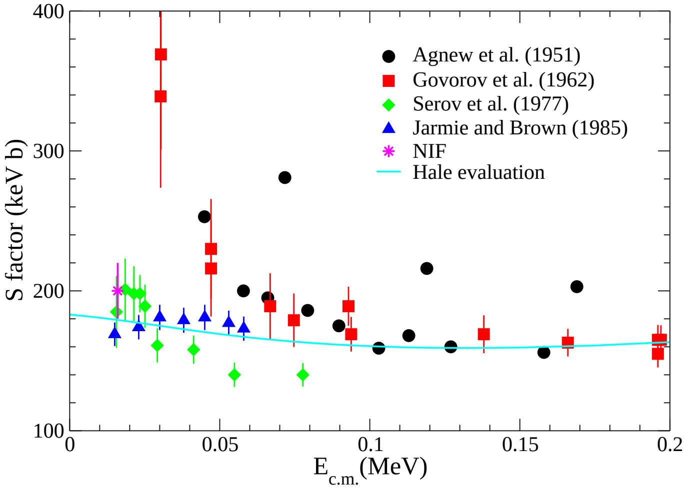
- Fuel mixture uncertainty
- Spectrum fitting
- Ion temperature determination (small)
- Total systematic error is estimated to be 10%

Analysis and Results

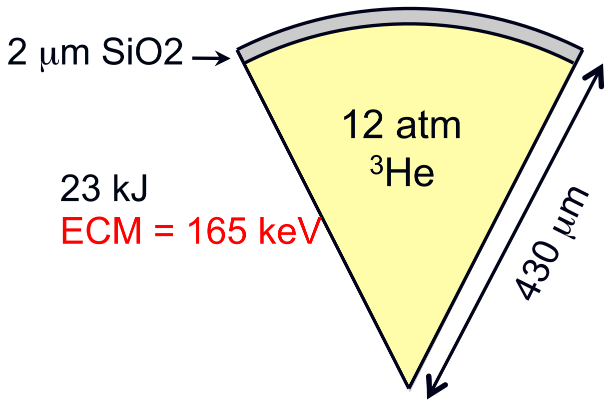
- Numbers of neutrons:
  - $N_{DT} \propto n_D n_T \langle \sigma v \rangle_{DT}$
  - $N_{TT} \propto \frac{n_T^2}{2} \langle \sigma v \rangle_{TT} \times 2$
  - $\frac{N_{TT}}{N_{DT}} = \frac{n_T}{n_D} \frac{\langle \sigma v \rangle_{TT}}{\langle \sigma v \rangle_{DT}}$
  - watch factors of two!
- Spectral fitting:
  - $N_{DT} = 3.9(3) \times 10^{12}$
  - $N_{TT}/N_{DT} = 4.5(4)$
  - $kT = 3.3(3)$ keV (burn-weighted)
- $S(16 \text{ keV}) = 200(20)$ keV-b

Comparison to other Data

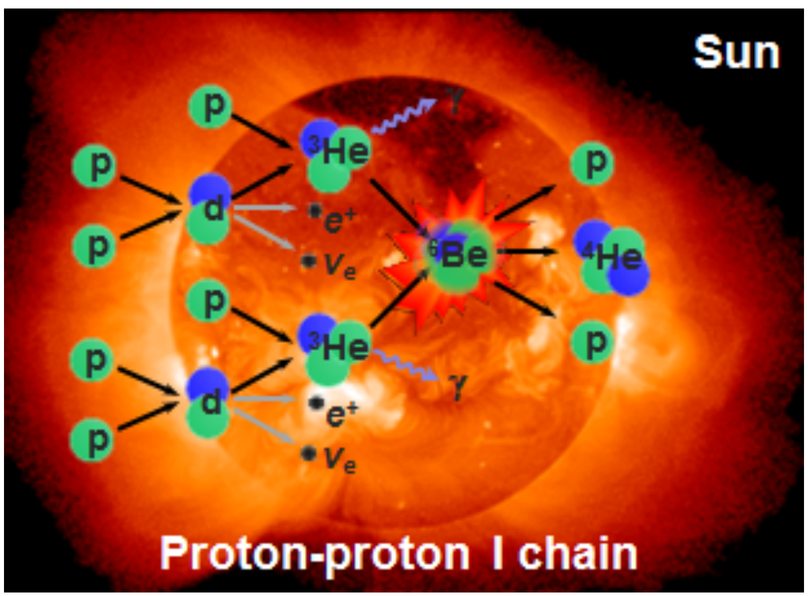
Note the energy averaging in the plasma is not that different than many of the accelerator measurements, e.g., if a “stopping” target is used.

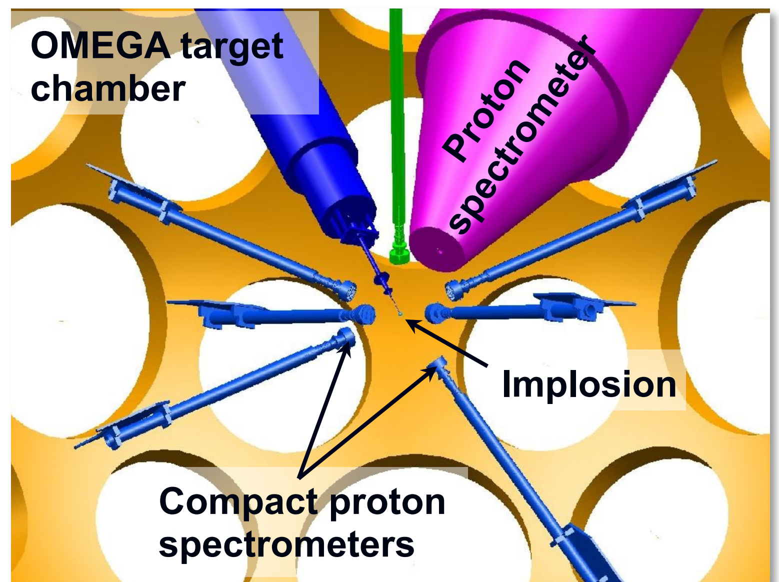


In a proof-of principle experiment, HED plasmas have been used to study the $^3He+^3He$ reaction



$^3He + ^3He$	$\rightarrow$	$^4He + 2p$ (0-10.8 MeV)
	$\rightarrow$	$^5Li + p$ (9.2 MeV)
	$\rightarrow$	$^5Li^* + p$
	$\rightarrow$	$^4He +$ (pp)

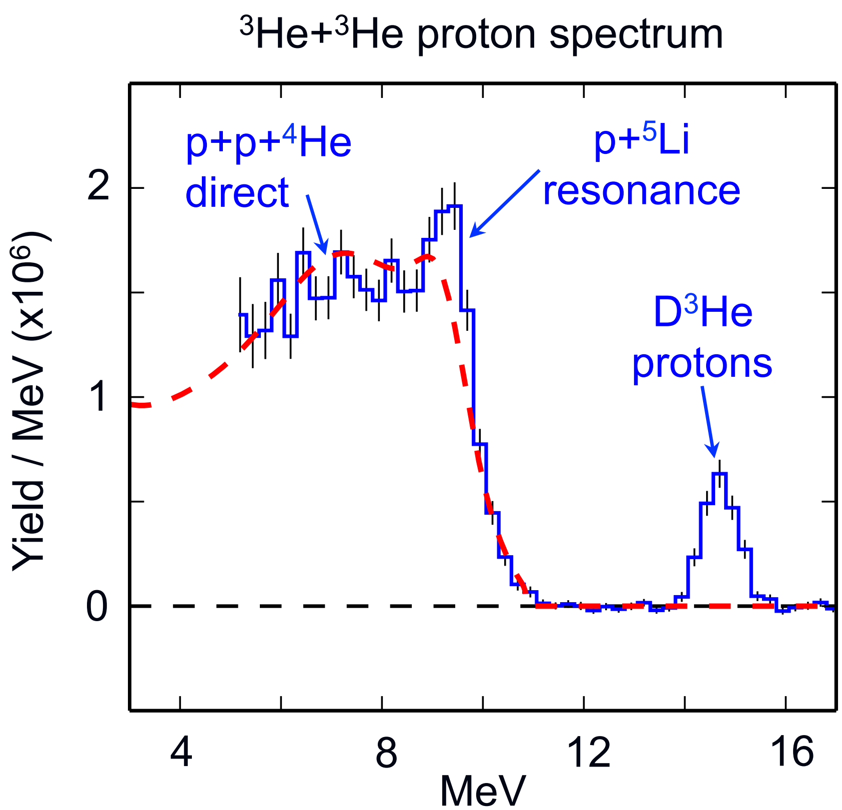


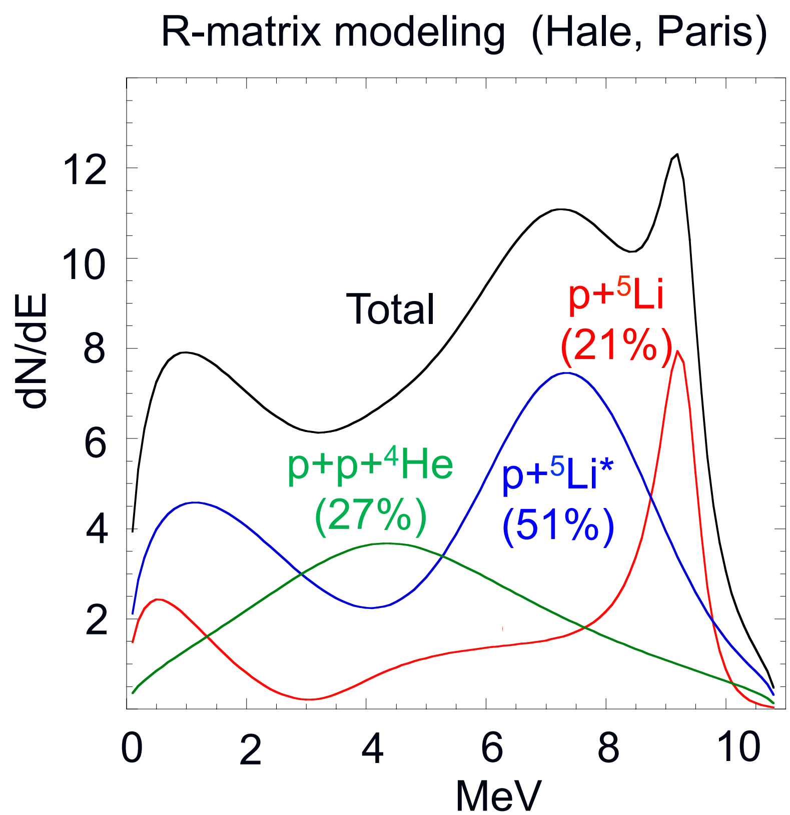


$$E_{CM} \propto T^{2/3}(Z_1Z_2)^{2/3}m^{1/3}{}_r$$

Zylstra et al, to be submitted to PRC (2015).

The measured $^3He+^3He$ proton spectrum indicates both a $p+^5Li$ and $p+p+^4He$ in final state at ECM=165 keV





R-matrix model is based on feeding ampl determined from the fit to the Wong TT-n spectrum.
Understanding spectral shape is important for determining cross-section from accelerator exps

** Mark Paris et al., private communication.
Zylstra et al., PRC to be submitted (2015).

Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a nascent field with much potential

- **To date HED plasmas have been used to probe:**
  - n+d / n+t elastic scattering[1)] (basic nuclear science)
  - D(n,2n) reaction (basic nuclear science)
  - T+T reaction[2),4),5)] (mirror reaction to ^{3}He+^{3}He reaction)
  - ^{3}He+^{3}He reaction[6)] (hydrogen-burning stars)
  - T+^{3}He reaction[6)] (basic nuclear science and BBN)
  - D(p,γ)^{3}He (protostars, brown dwarfs and BBN)
  - D(t,γ)^{5}He[3)] (basic nuclear science)
  - D(^{3}He,γ)^{5}Li (basic nuclear science)

Future efforts will involve studies of about a dozen reactions

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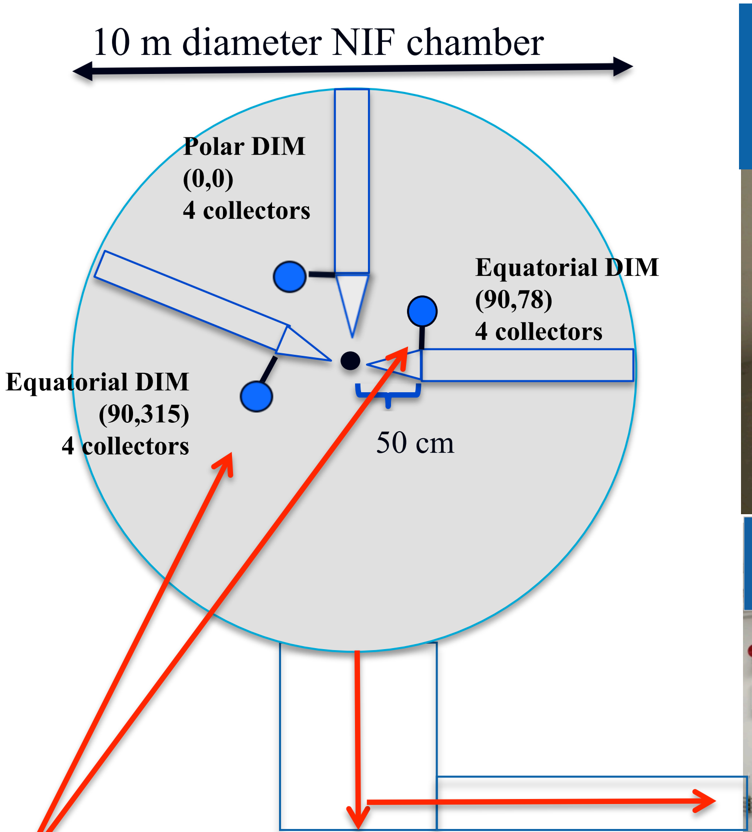
1) Frenje et al., PRL (2011).
2) Casey et al., PRL (2012).
3) Kim et al., PRC (2012).
4) Sayre et al., PRL (2013).
5) Brune et al., ArXiv (2015).
5) Zylstra et al., to be submitted (2015).

Collection of solid and gaseous debris has been implemented at NIF



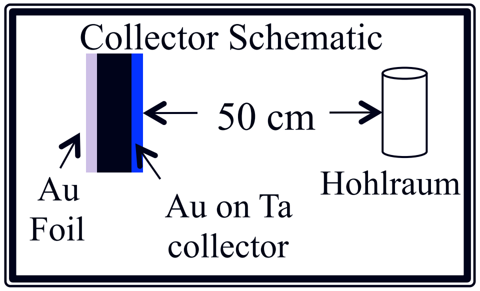
- Solid RadioChemistry (SRC) detectors (2”-diameter metal or graphite foil disks)
- Up to 4 can be fielded on 3 DIMs (total of 12 collectors)

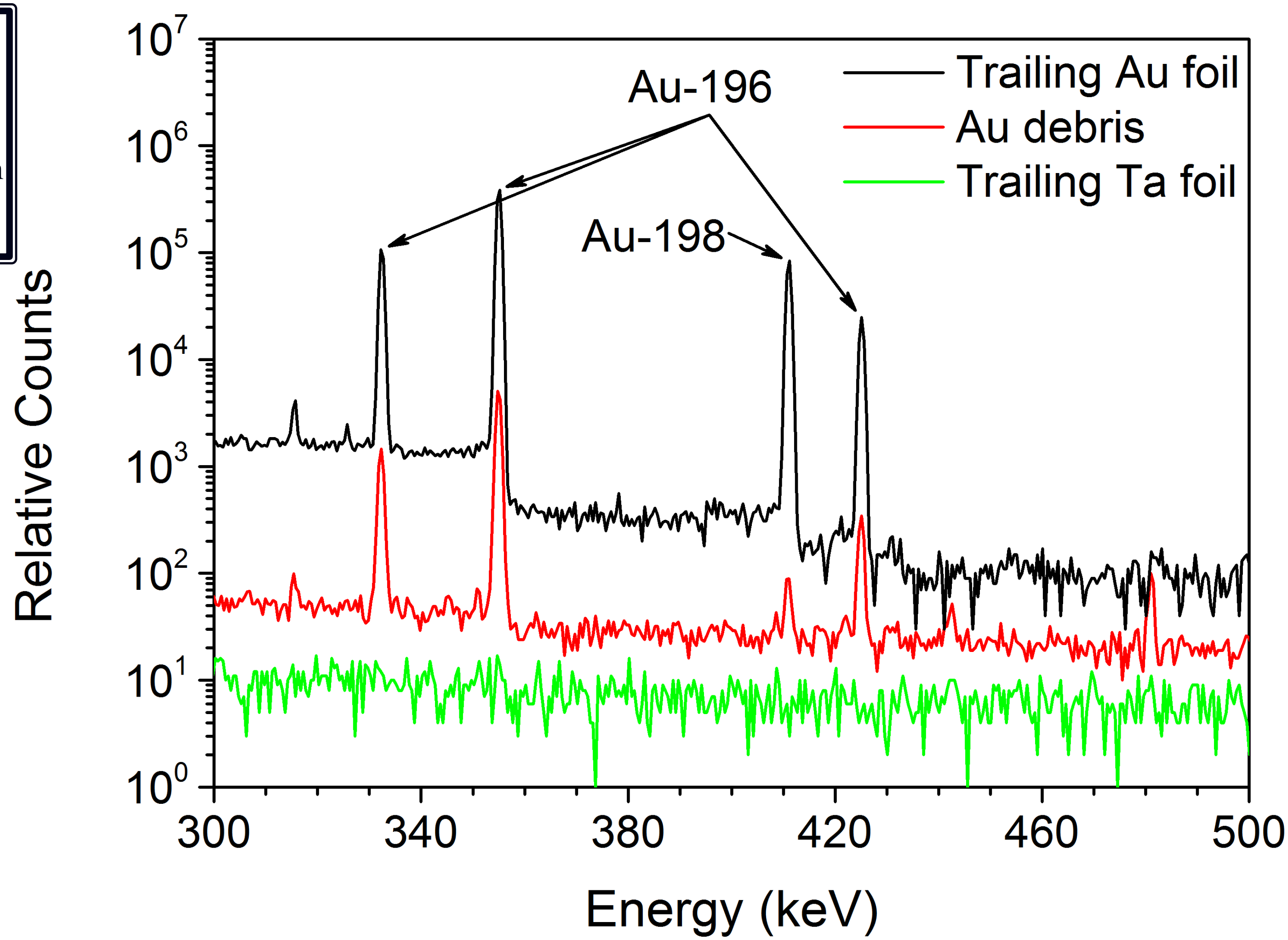
Diagnostic Insertion Manipulator (DIM) nose cone with Solid RadioChemistry (SRC) collectors

Radiochemical Analysis of Gaseous Samples (RAGS)

- Gas load from the chamber is collected with RAGS

The first neutron reactions observed with the SRC were (n,γ) and (n,2n) on ^{197}Au from the gold hohlraum

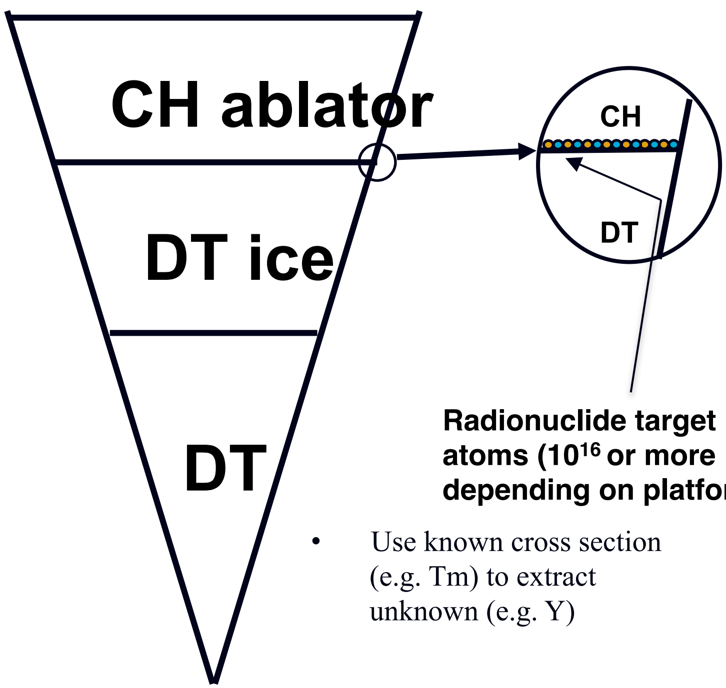




Gold in the debris and backing foil had different (n,γ) signals
The debris "sees" fewer low-energy scattered neutrons

Experimental Concept – We will add radioactive tracers to Symcap capsules to study production and cross sections of excited state and second-order capture species

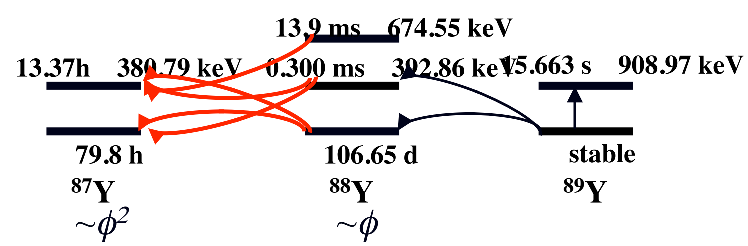
- **Goal: Measure capture and excited state cross sections relevant to WCI and GS programs**
- **Experiment: Add 10^16 atoms of radioactive tracers to DT Symcap**
- **Evaluate collection of capsule material and cross section determination**
- **Required diagnostics: SRC**



Radionuclide target atoms (10^{16} or more depending on platform)

- Use known cross section (e.g. Tm) to extract unknown (e.g. Y)

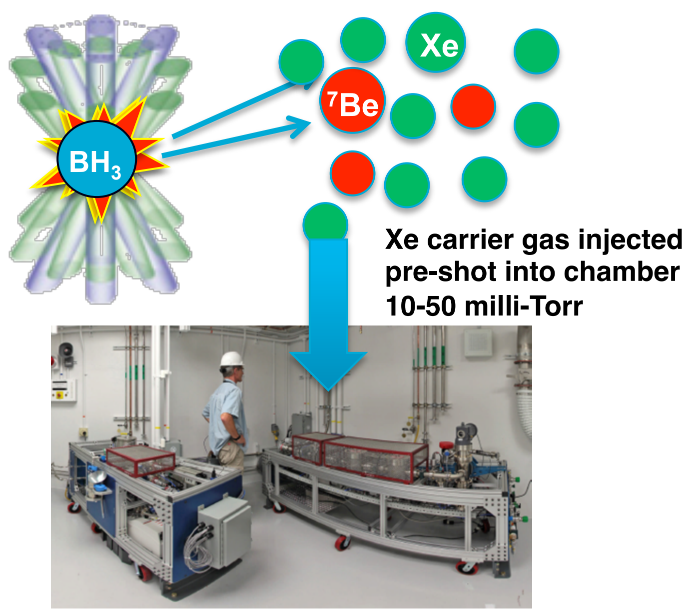
Measure cross sections (n,γ and n,2n) for radioactive species



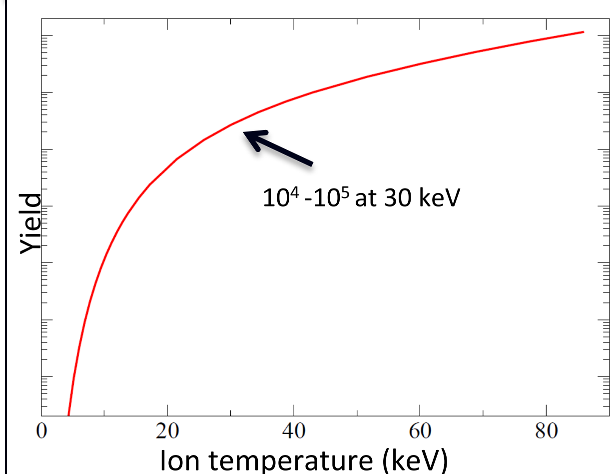
- Run two similar capsules, one loaded with ^{89}Y and the other with ^{88}Y (radioactive)
- Extract unknown cross sections from the difference

Experimental Concept – We will use BH3 filled targets to study the astrophysical $^{10}B(p,a)\ ^{7}Be$ reaction and explore physics of plasma screening. Paves the way for studying $^{3}He(^{4}He,\gamma)^{7}Be$.

- **Measure reactivity of 10B(p,a) in plasma**
- **Run 10B(p,a) reaction in plasma and**
- **collect radioactive debris with RAGS**
- **Novel collection concept needs tested**
- **Laser Energy range < 1 MJ**
- **Complementary experiment measures same reaction on B in/on the hohlraum (non-plasma)**



^{7}Be yield vs. ion temperature



Measured yield will be compared to accelerator measurements at University of Notre Dame to study plasma screen- ing effects in astrophysical reaction

Summary and Conclusions

- A nuclear science program is under development at NIF and OMEGA
- A large range of nuclear diagnostics are implemented at NIF, including:
  - Neutron Time-of-Flight/Activation/Imaging
  - Prompt Gamma-ray detection
- Much remains to be done
  - Low-energy neutron detection
  - Solid debris collection

Collaborators

special thanks to J. Frenje, D. Sayre, and J. Caggiano for supplying slides for this presentation

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The End

Thanks for your attention!