Gamma-Ray Spectroscopy
2011 OMEGA Laser Users' Group Workshop
APS Briefing
Nov 15, 2011

H.W. Herrmann

Los Alamos National Laboratory

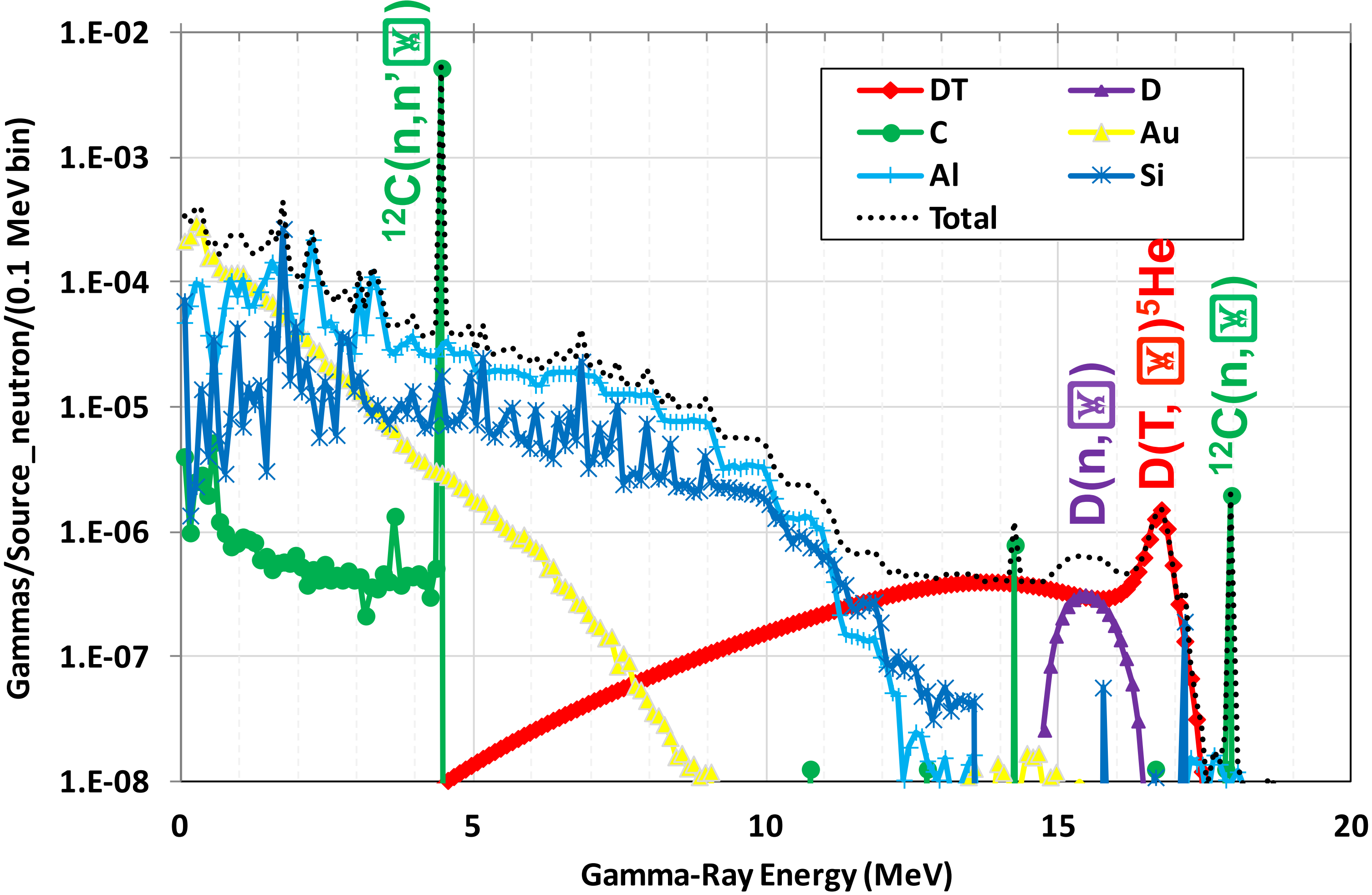
Los Alamos and Lawrence Livermore National Laboratories – National Ignition Campaign

LA-UR 10-07461

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

The γ-Ray Spectrum at NIF is complicated, but holds a wealth of information

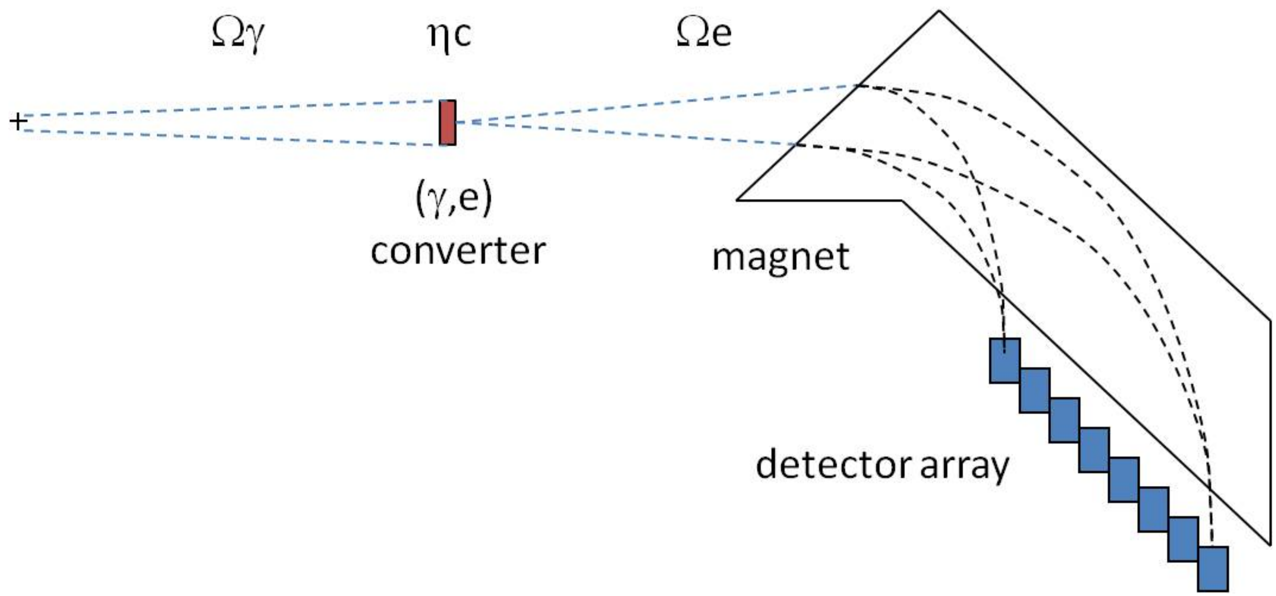
Simulated indirect-drive, prompt DT spectrum



Gamma-Ray Spectroscopy

- Gas Cherenkov Detectors are currently being used at OMEGA to perform energy-thresholded □-ray spectroscopy in the 3-20 MeV range
  - — DT Fusion □-ray spectrum has been mapped out (C. Horsfield NO6-10)
  - — DT Fusion □/n Branching Ratio has been determined in ICF conditions (~3e-5 □/n, Y. Kim NI3-6)
  - — ^{12}C(n,n' □) is being used to infer CH ablator □R (N. Hoffman CO8.10, H. Herrmann NO6.9)
- However, a true energy-resolving □-ray spectrometer could be used for much more to support NIC, such as:
  - — D(n, □) at 15.6 MeV □□ fuel □R diagnostic
  - — ^{12}C(n, □) at 17.9 MeV □□ CH ablator □R diagnostic
  - — HT fusion □-ray at 19.8 MeV □ Hot Spot H/D ratio in THD
- And for general Nuclear Plasma Science:
  - — Additional fusion reactions (e.g., T+T □^{6}He+ □(12MeV); p +D□^{3}He+ □(5.5MeV), A. Zylstra)
  - — Measure nuclear cross-sections on materials placed in extreme neutron flux (e.g,. pucks of known □R)
  - — Ablator dopants for S-process or possibly as mix indicators
    - – Stellar-like environment provides excited state nuclei

Gamma-Ray Compton Spectrometer



- Recommendations of the 2nd OLUG Meeting:
  - "The community felt that a new gamma-ray spectrometer needs to be designed, validated and commissioned for the facility. Users requested that the spectrometer have a spectral range up to 20 MeV."
- Design study underway in conjunction with LANL, LLNL, GA & NSTec

Backup Slides

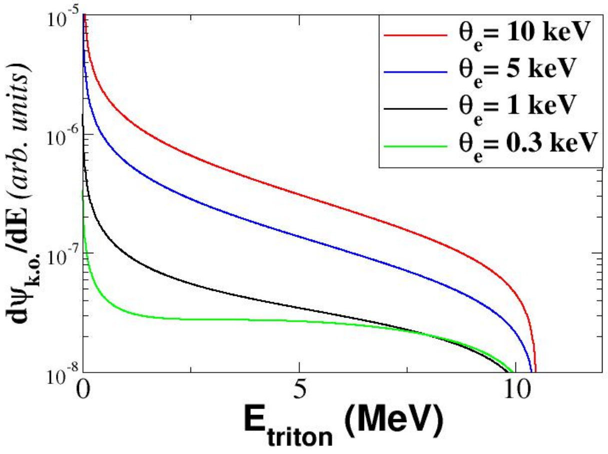
Reactions emitting gammas sensitive to stopping power with s_g>~10 mb/sr/gamma-ray

Energetic g-rays as Probes of Mixing and Stopping Powers at NIF (A. Hayes, LANL)

MeV alpha-particles born in the DT burn and MeV knockon deuterons and tritons interacting with ablator material (C or Be)

reaction	**Eg (MeV)**
$^{13}C(d,n)^{14}N^*$	3.94, 4.91, 5.1, 5.69, 7.0, 8.06
$^{9}Be(d,n)^{10}B^*$	2.8, 3.4 , 4.49, 6.03
$^{9}Be(a,n)^{12}C^*$	4.4

$$\frac{d\psi_{k.o.}}{dE}(E_f) = \frac{Q_0}{\left|dE/dx(E_f)\right|}\int_{E_f}^{E_{0\max}} dE_0\, q(E_0)$$

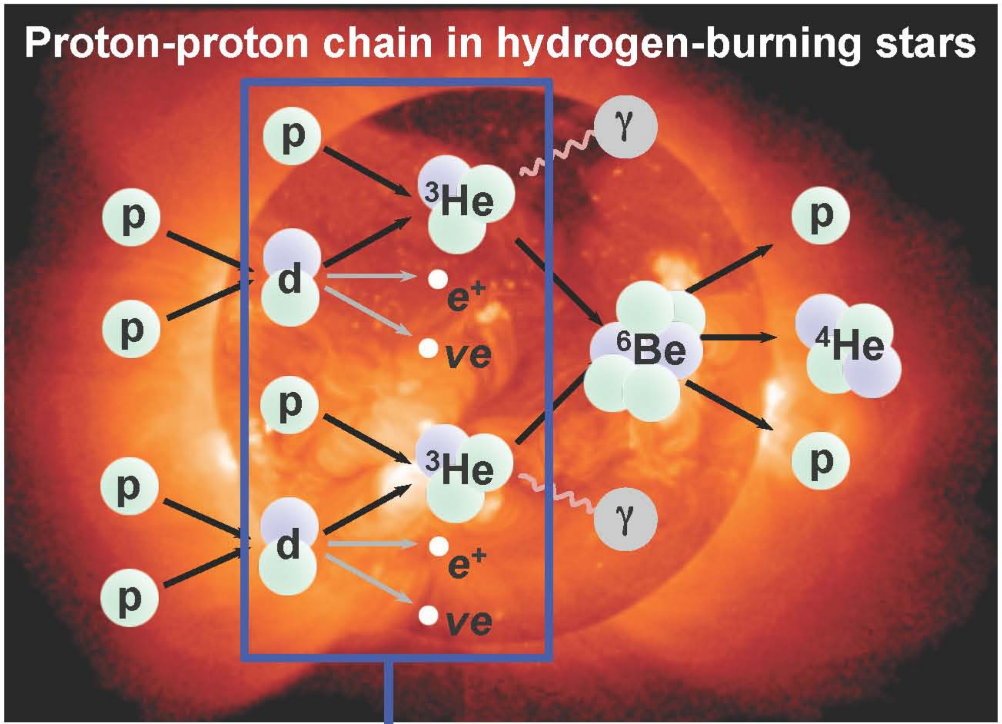


Shape of K.O. fluence determined by stopping
=> g-ray yields can determine form of stopping

Studies of the HD reaction: Next step in HEDP laboratory nuclear astrophysics

Alex Zylstra

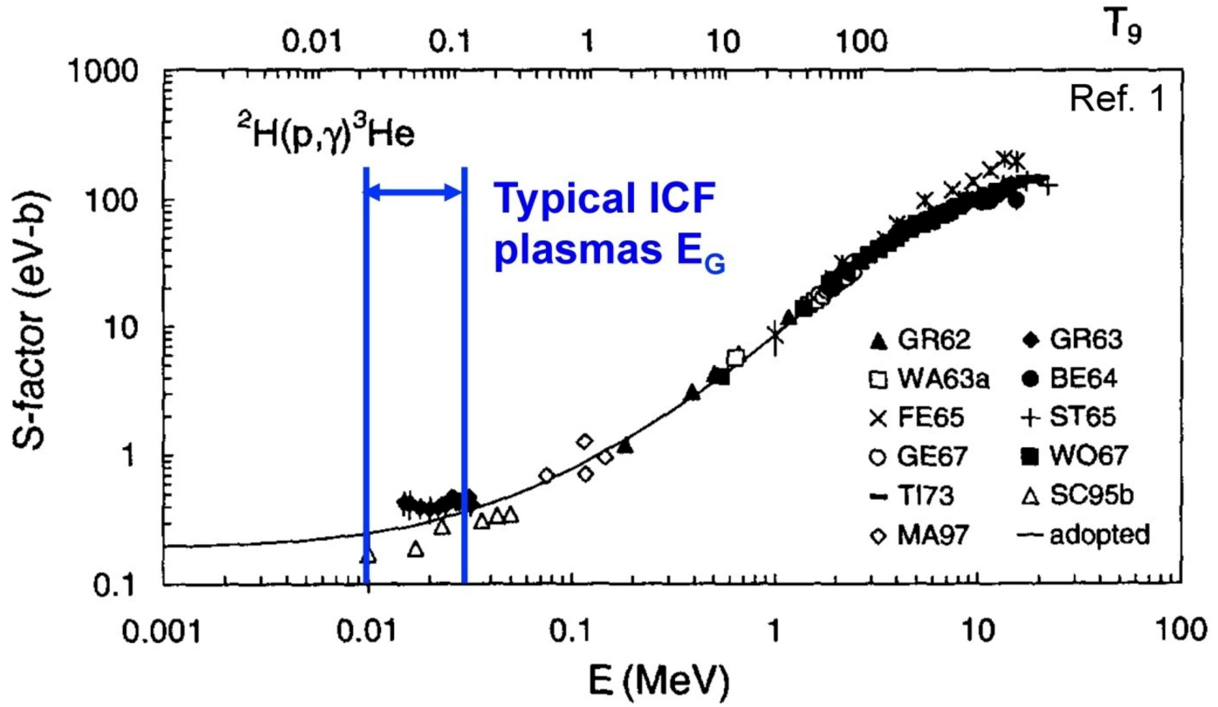
3rd OMEGA Laser User's Group Workshop
Rochester, NY, April 27-29 2011



Proton-proton chain in hydrogen-burning stars

Second step of stellar pp chain

The astrophysical S-factor for the HD reaction is poorly know at low energies



Data obtained in accelerator experiments differ by a factor of ~3 at energies relevant to ICF; accelerator data must also be corrected for electron screening effects using unreliable nuclear models.

1: C. Angulo et al., Nucl. Phys. A, 656 (1999).

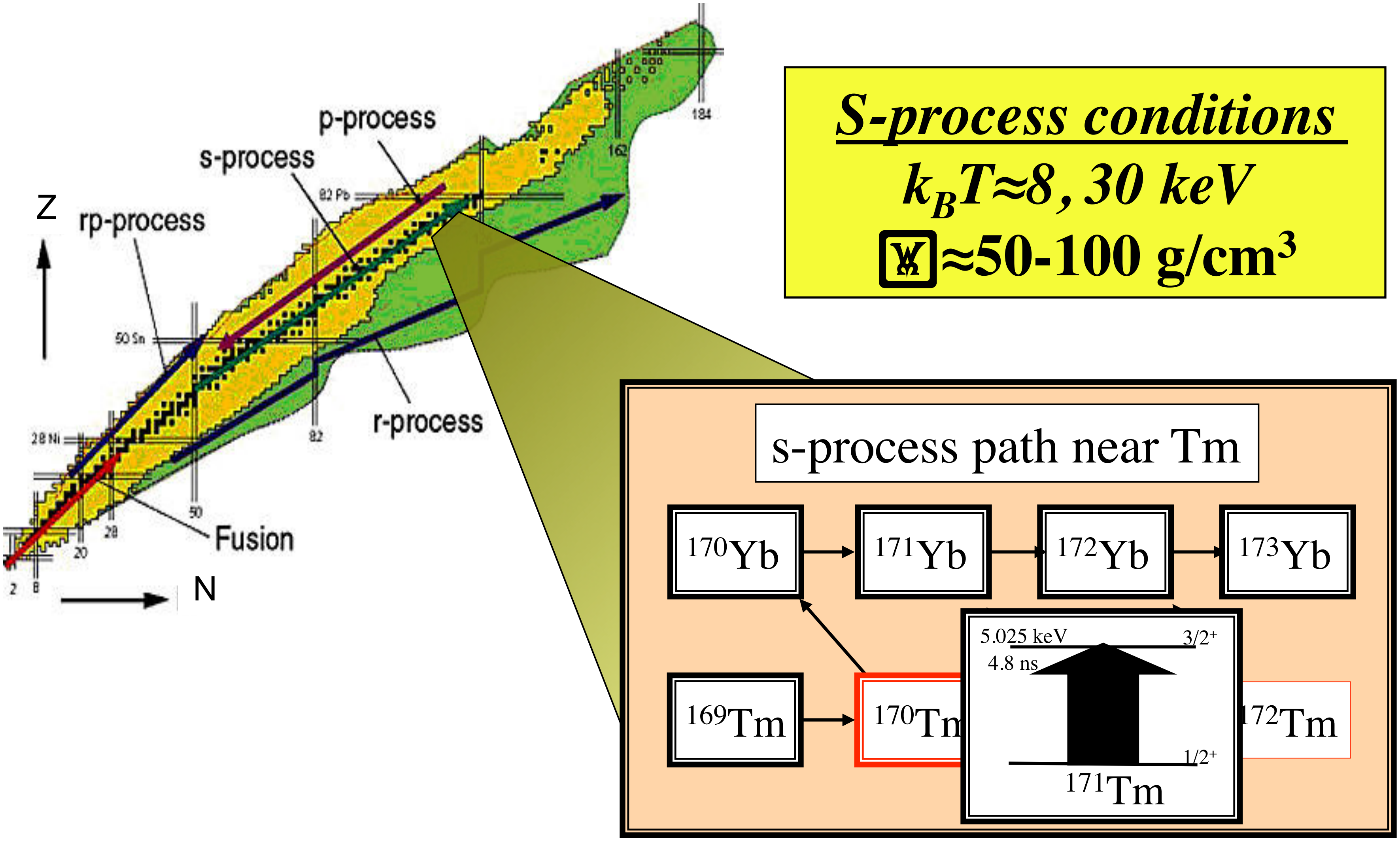
A. Zylstra, MIT

Most of the heaviest elements (A>56) are made via “slow” neutron capture (s-process) in the cores of massive stars

S-process conditions

$k_BT\approx 8, 30$ keV

$\rho\approx$50-100 g/cm^3



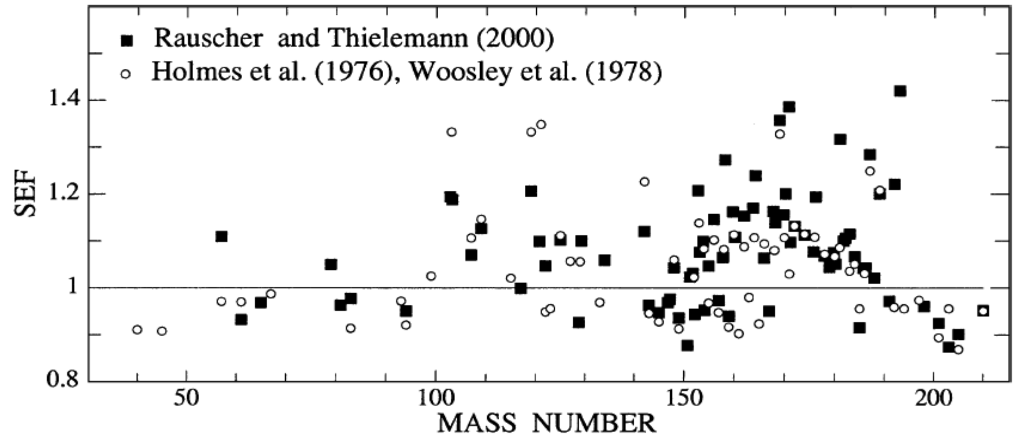
L. Bernstein, LLNL

Many important* s-process branch point nuclei have HEDP-populated low-lying excited states

S-process (n,γ) enhancement due to excited states*

$$SEF(kT) = \frac{\sigma_{HEDP}}{\sigma_{GS}} = \frac{\sum_{i=0}^{\infty}(2J_i+1)\sigma(E_x=E_i)e^{-E_i/kT}}{\sigma_{GS}\sum_{i=0}^{\infty}(2J_i+1)e^{-E_i/kT}}$$

*Bao & Kappeler At. Dat. Nucl. Dat. Tables **76,** 70–154 (2000)



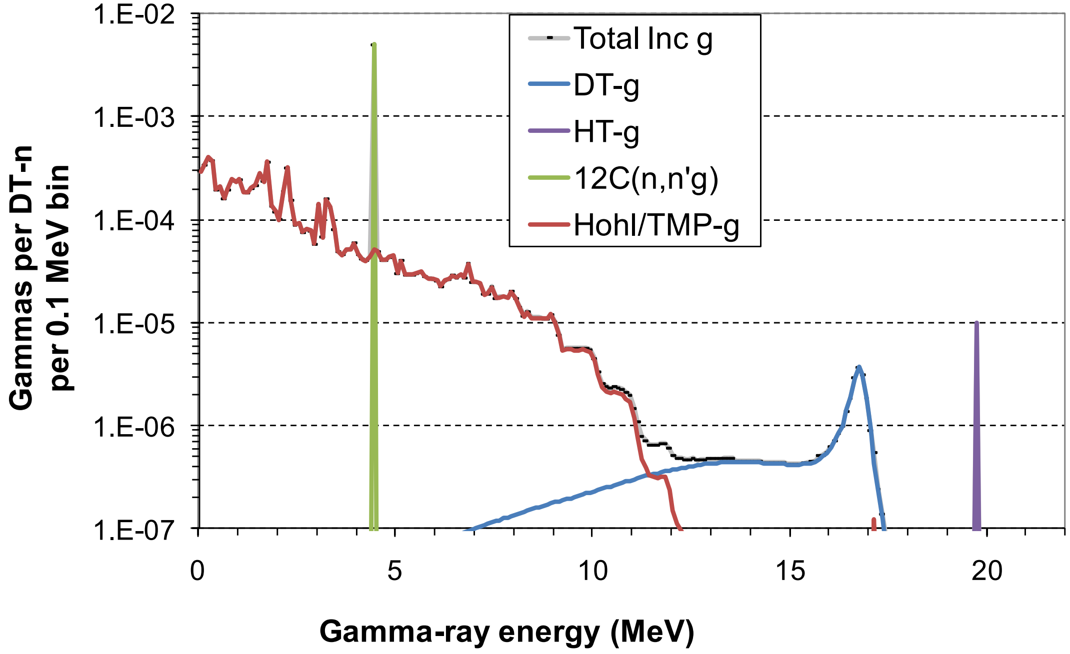
Branch Point	Gnd State J^{π}	1^{st} Exc. State E_x (keV)	1^{st} Exc. State J^{π}
^{79}Se	**7/2^{+}**	**95.77**	**1/2^{-}**
^{85}Kr	9/2^{+}	304.871	1/2^{-}
^{147}Pm	**7/2^{+}**	**91.1**	**5/2^{+}**
^{151}Sm	**5/2^{-}**	**4.821**	**3/2^{-}**
^{163}Ho	**7/2^{-}**	**100.03**	**9/2^{-}**
^{170}Tm	**1^{-}**	**38.7139**	**2^{-}**
^{171}Tm	**1/2^{+}**	**5.0361**	**3/2^{+}**
^{179}Ta	**7/2^{+}**	**30.7**	**9/2^{+}**
^{204}Tl	2^{-}	414.1	4^{-}
^{205}Pb	5/2^{-}	703.3	7/2^{-}
^{185}W	**3/2^{-}**	**23.547**	**1/2^{-}**

NIF (or LMJ) are the *only* places where (n,γ) might be measured on ground+excited states

L. Bernstein, LLNL

Gamma spectrum at NIF provides a wealth of information

NIC



HEDP

Reaction	Gamma-ray Energy (MeV)	Cross-section
Alpha-particle Physics		
9Be(γ, nγ)12C	5.7	~ 50 mb
Aneutronic Fuel		
D(p,γ)3He	5.5	~ 10 nb
D(3He,γ)5Li	16.4	~ 1 μb
Stellar Nucleosynthesis		
12C(γ,γ)16O	7.12	1 – 10 nb

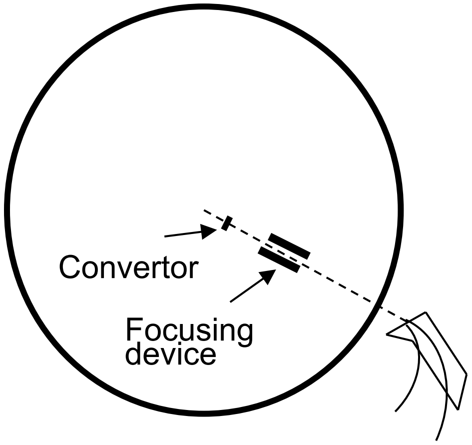
- GRH is useful to infer spectral information, but better resolution is required.

Y. Kim, LANL

Gamma Compton Spectrometer (GCS) Design

NIF GCS design goals:

- broad-energy-range (1-20 MeV)
- high sensitivity (NIF Yields > 10^{14} DT-n to isolate HTg)
- modest energy resolution (1-2 MeV)
- modest temporal resolution (~1 ns)
- high signal to background ratio

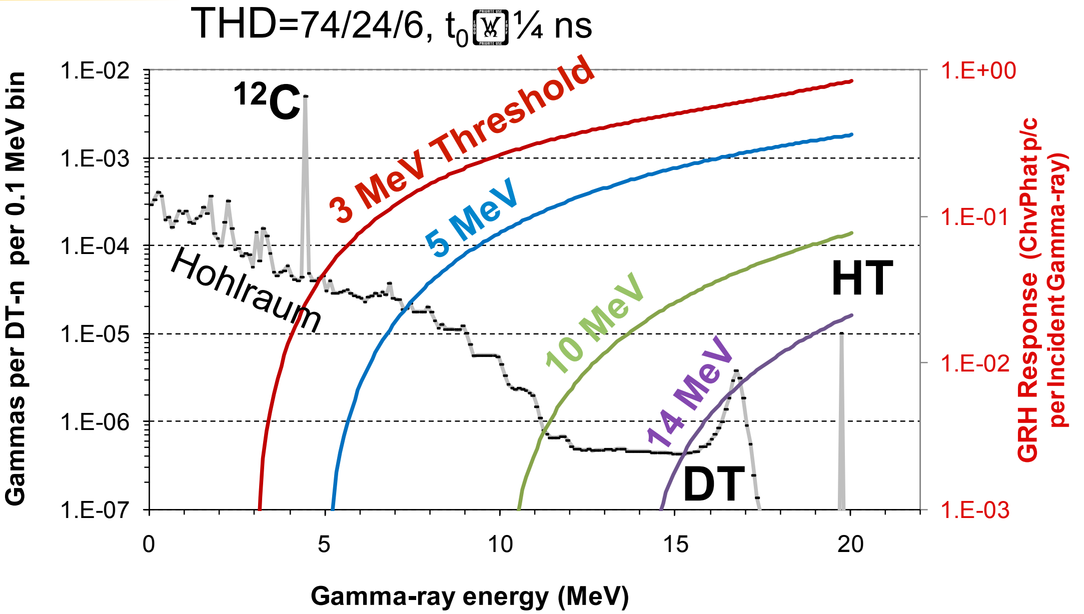


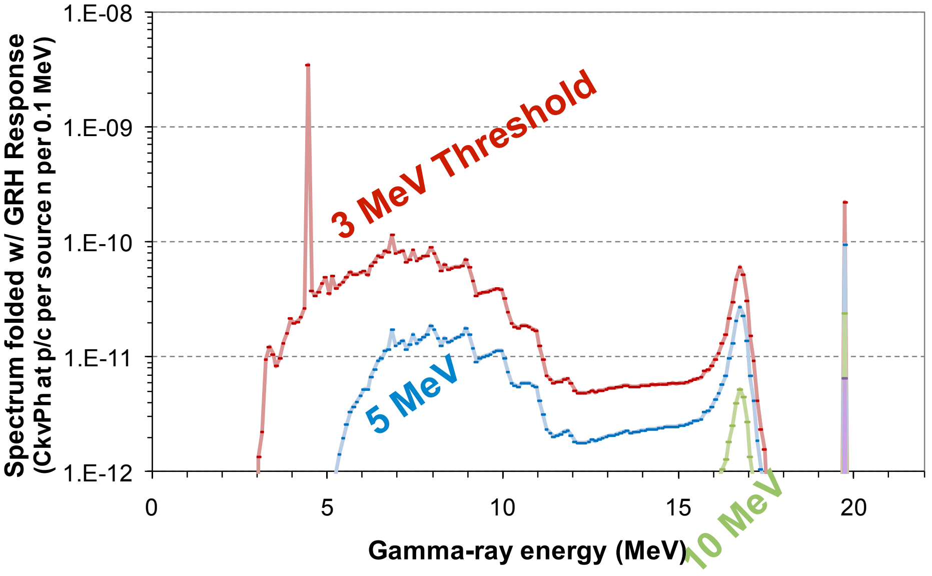
Preliminary Concept:

- electromagnet & detector array attached outside NIF chamber.
- two modes of operation:
    1) Chamber-mounted converter foil for high-yield (> 10^{16} DT-n)
    2) DIM-mounted converter foil & electron optics for low-yield (<10^{16} DT-n).

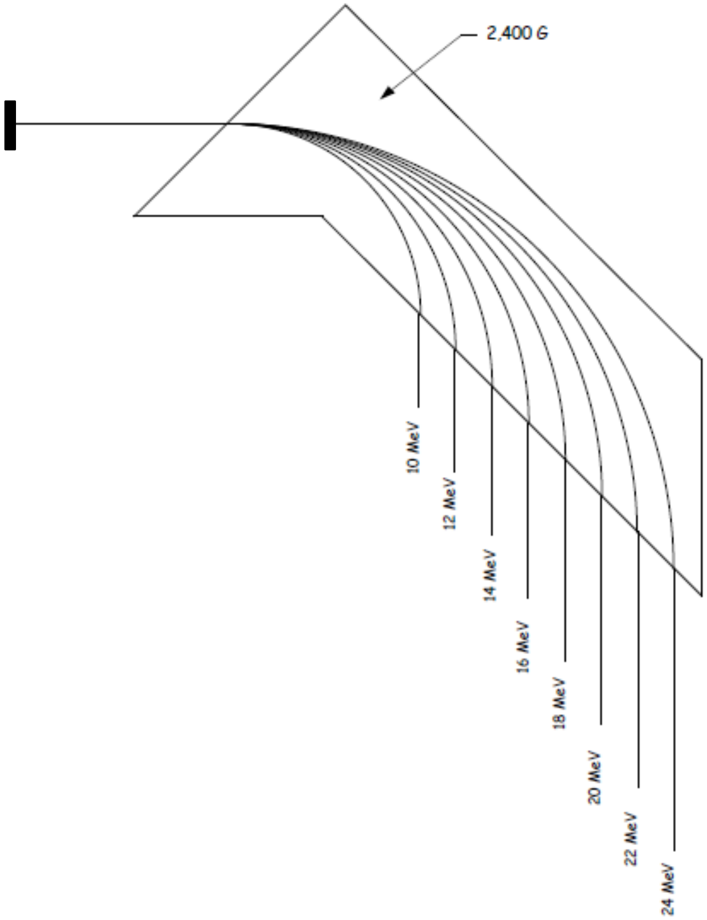
GRH is useful as a 4-channel, energy-thresholded spectrometer. However, a true energy-resolving spectrometer is highly desired.

- **“Prompt” ⊠-rays of interest from indirectly-driven, THD:**
  - **16.75 MeV DT fusion ⊠-ray**
    - ➢Total DT Yield
  - **19.8 MeV HT fusion ⊠-ray**
    - ➢Hot Spot H/D ratio?
  - **4.44 MeV ^{12}C(n,n’) ⊠-ray**
    - ➢Ablator rhoR
  - **Hohlraum/TMP n-⊠ continuum**
    - ➢Effective n-to-g convertor for low yield BT determination





LANL built WHEBY 25 years ago. Design and Calibration data is still useful to GCS



WHEBY 10-24

Components	Parameters	Data
Design goal	**Energy range (MeV)**	**10-24**
	Momentum resolution (%)	1-2
	Time resolution (ps)	100
Magnet	B-field (G)	2400, uniform
	Size (cm)	57×26×13
	Weight (lbs)	300
Converter	Material	Be
	Diameter (cm)	0.8
	Thickness (cm)	0.2
Detector	Photoconductive	GaAs

Y. Kim, LANL

T. Hilsabeck, GA

NIF needs a Total DT Yield measurement during high rhoR implosions

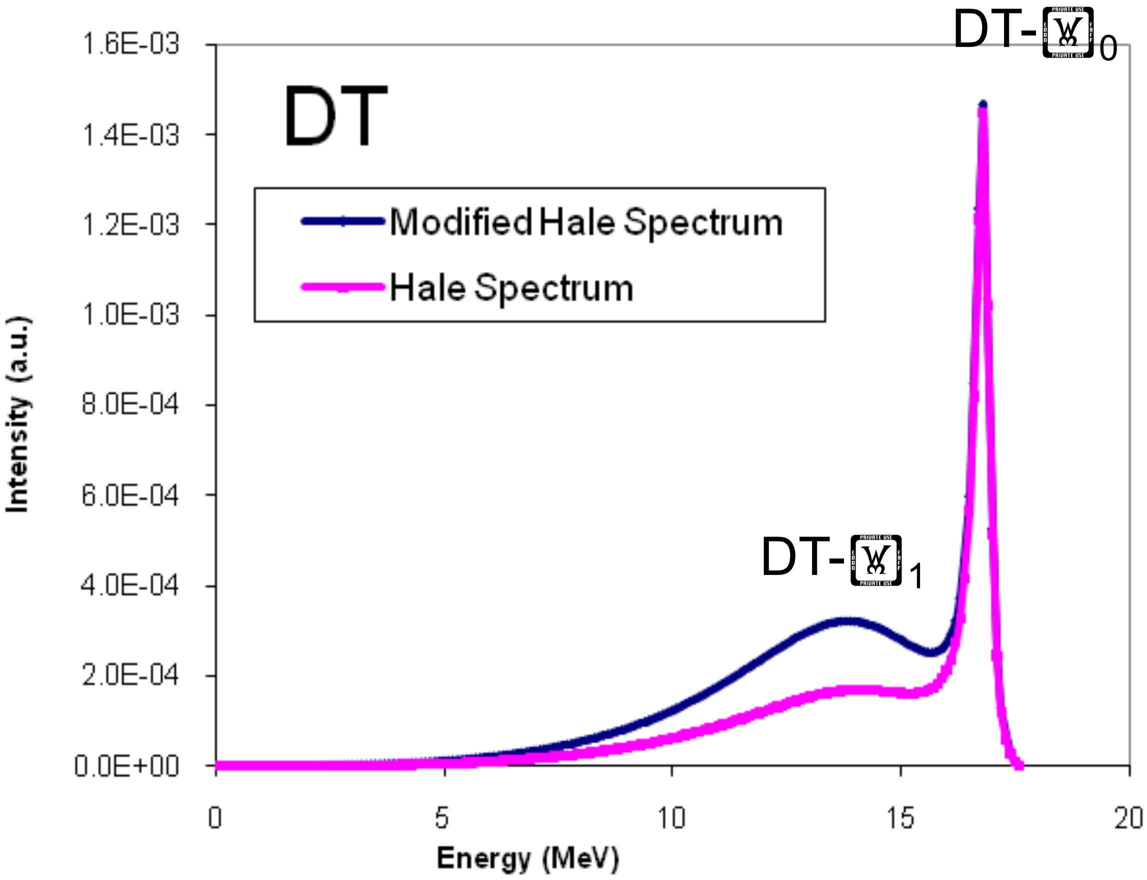
- Existing yield measurements compromised by:
  - Yn: neutron downscattering
  - GRH: presence of HT-γ
- DTγ_0-rays could provide Total DT yield (=$Y_{DT\gamma 0}/BR_{\gamma 0}$)
  - Negligible DT-γ down-scattering (unlike DT-n)
  - Either need to know BR & have a good absolute calibration
  - Or, perform in-situ calibrations using DT Expl Pshr (γR [illegible] 0)

$$\mathrm{TDSF} = 1 - \frac{Y_{DTn}(13-15\ \mathrm{MeV})}{Y_{DT_{\gamma 0}} / BR_{\gamma 0}}$$

Separation of DT-□$_0$ and DT-□$_1$ resolves 5He nuclear status issue and impacts on BR□

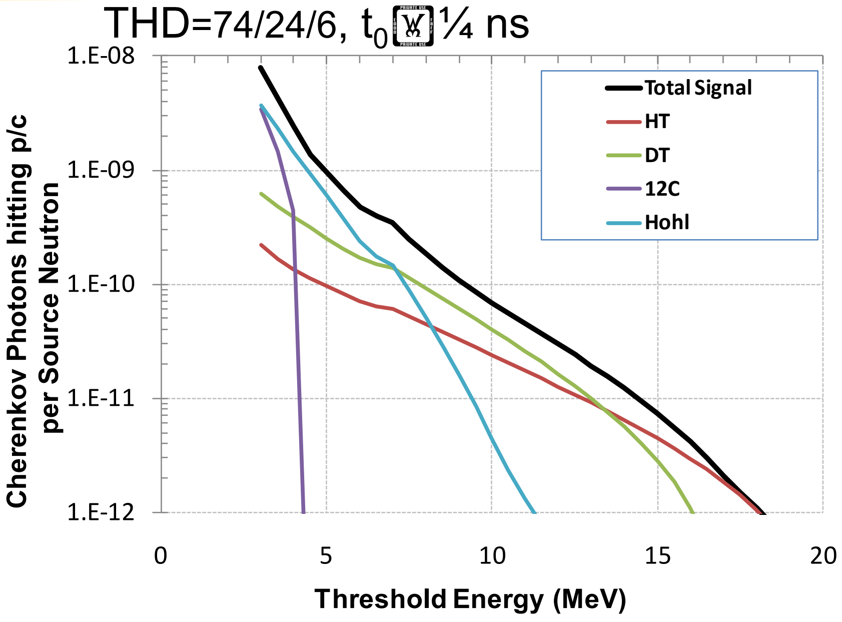
G. Hale (2006)

C. Horsfield (2010)

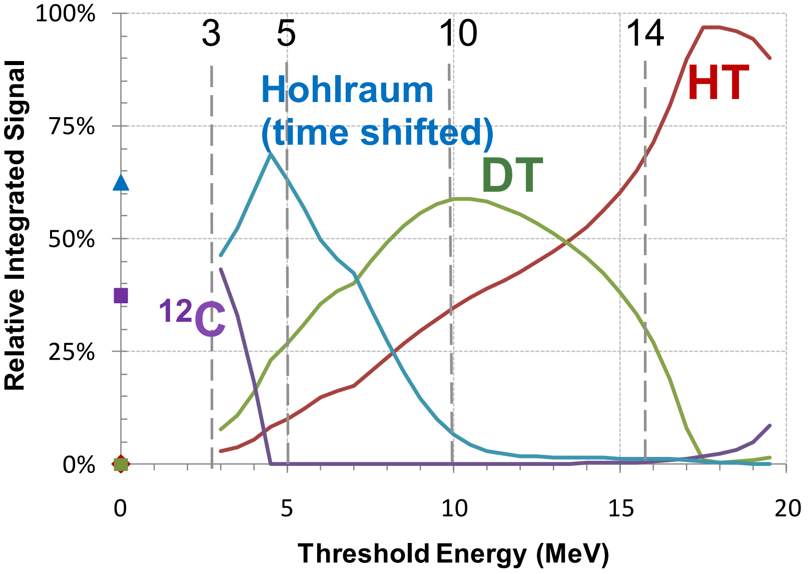


GRH is a 4-channel, Time-resolved, Energy-thresholded, Gamma-Ray Spectrometer

- **"Prompt" γ-rays of interest from indirectly-driven, THD:**
  - 19.8 MeV HT fusion γ-ray
  - 16.75 MeV DT fusion γ-ray
  - 4.44 MeV $^{12}C(n,n')$ γ-ray
  - Hohlraum/TMP n-γ continuum



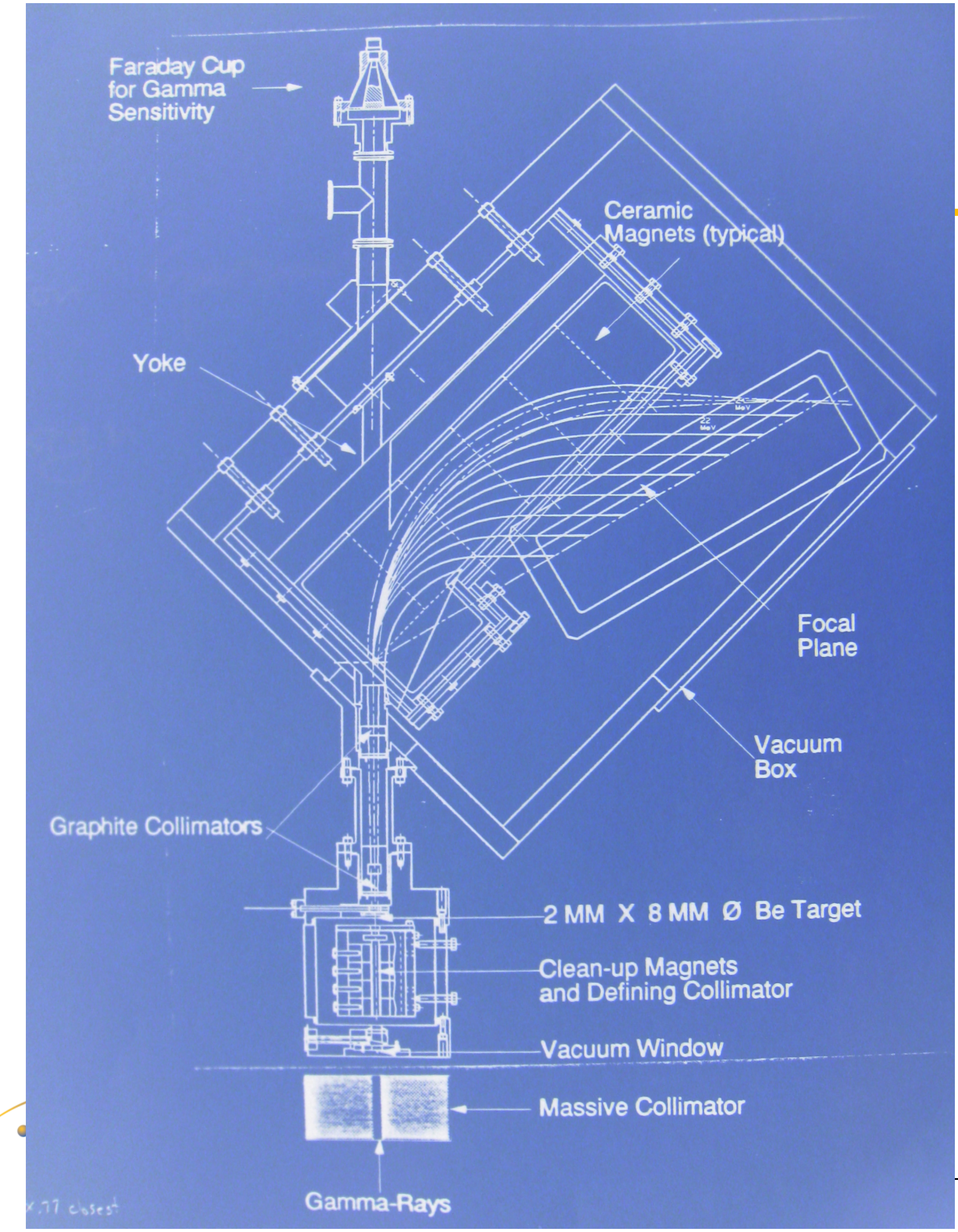
- **Relative abundances inferred from multiple threshold measurements on each shot**
  - <1% of total prompt γ-rays are from fusion (DT + HT)
  - This is why we need a threshold detector !
  - >90% of GRH signal is from fusion γ-rays at 10 MeV threshold



Outline

- **Why do we need GCS?**
- **<u>How it works?</u>**
  - Review of LANL’s previous WHEBY
  - Broad-energy GCS
- **Technical challenges at NIF**
  - Shielding against hard radiation background
  - Improving detector sensitivity
- **Summary**

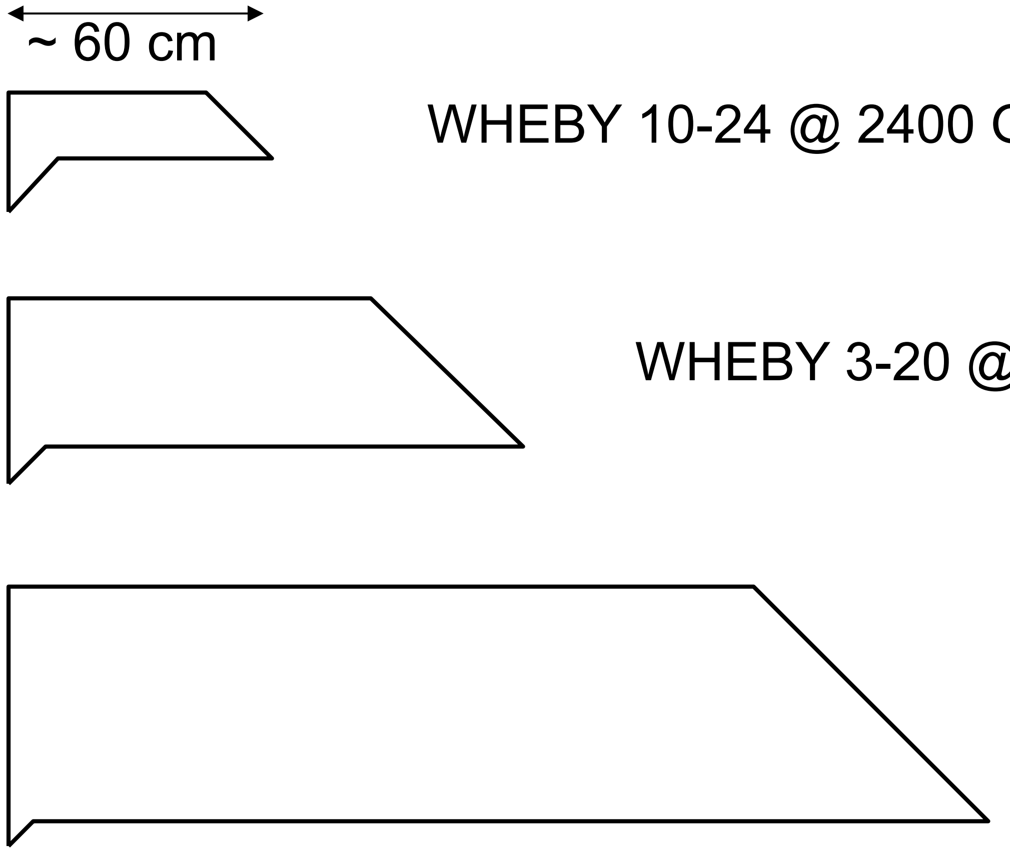
WHEBY 10-24



- Design ideas from previous work

  - clean-up magnet
  - collimator made of graphite
  - beam dump
  - vacuum box
  - calibration data

Magnet Size would need to get Bigger to catch Low Energy Gamma



~ 60 cm

WHEBY 10-24 @ 2400 G

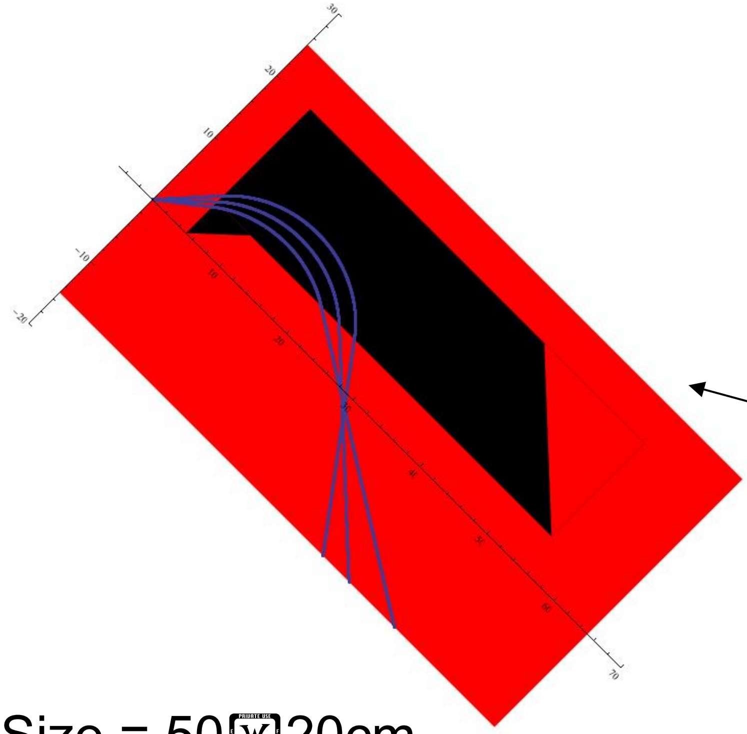
WHEBY 3-20 @ 1000 G

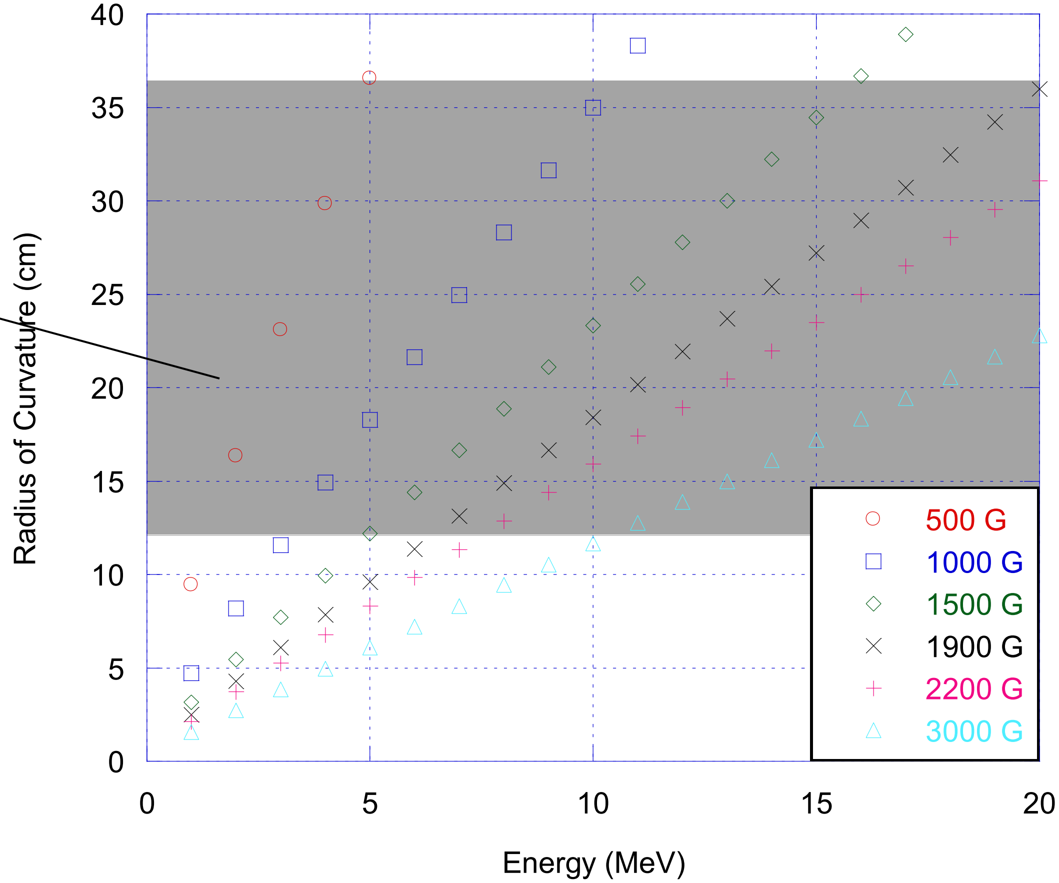
WHEBY 1-20 @ 500 G

~ 2 meter

Electromagnet is the way to have broad-energy range with a compact system

$$B\rho\,[kG\cdot cm] = 3.3356\cdot\sqrt{2m_o c^2 E_k + E_k^2}$$





Size = 50×20cm
2 MeV lines @500G

Outline

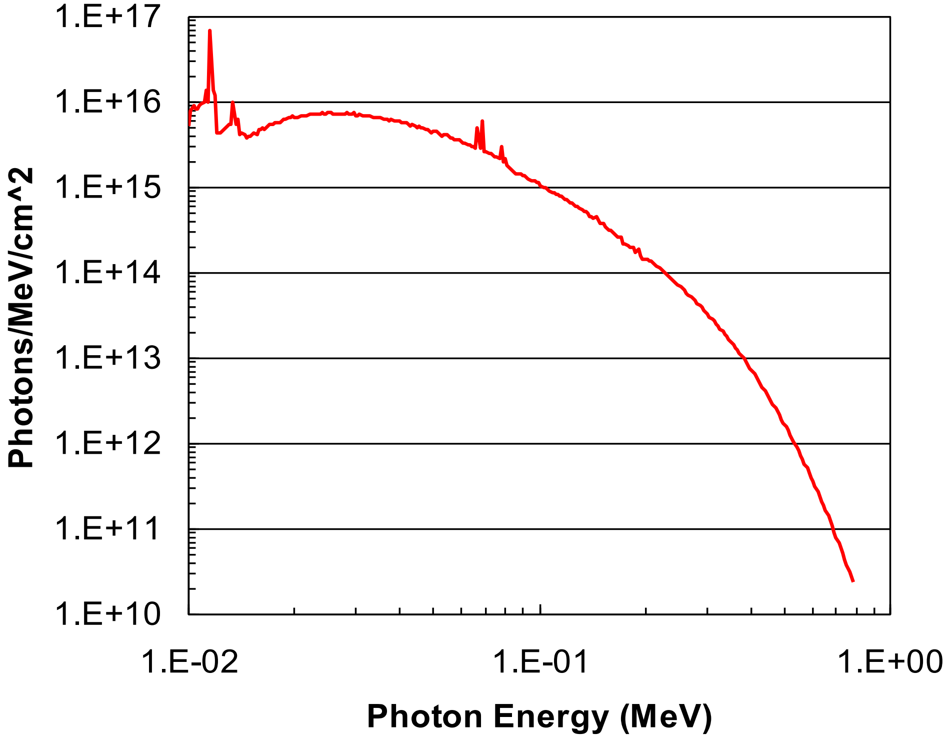
- **Why do we need GCS?**
- **How it works?**
  - Review of LANL’s WHEBY
  - Broad-energy GCS
- **Technical challenges at NIF**
  - Shielding against hard radiation background
  - Improving detector sensitivity
- **Summary**

Technical Challenges: Indirect-drive creates a challenging hard x-ray background for close-in detectors

- ~100 kJ Hard x-rays from LPI-induced, hot-electron Bremsstrahlung
  - ~1e7x more energy than the ~10 mJ of DT fusion gamma-ray energy from a 1e14 DTn shot
- Ave Energy ~50 keV, but extends up to ~MeV
- Significant shielding needed!

Shielding requirement
& NIF interference
will be reduced by locating GCS
outside target chamber

X-ray spectrum due to conversion of 33% of laser energy (1.8 MJ) into hot electrons



11th International Conference on Radiation Shielding
Hesham Khater, Sandra Brereton, and Mike Singh
LLNL-PRES-402778
April 17, 2008

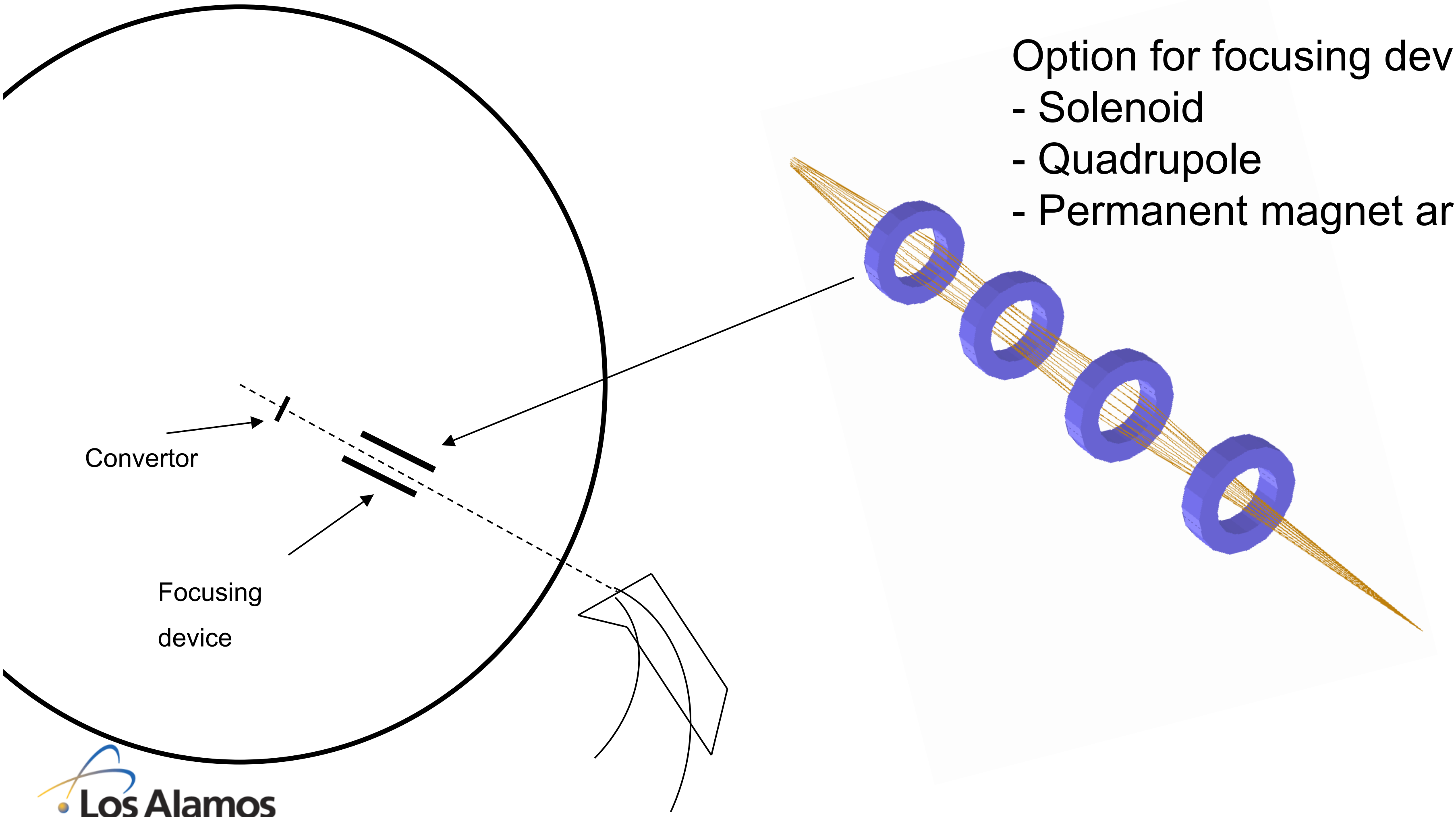
Estimated Sensitivity at 1.5 MeV Resolution = Yn ~ 5×10^{15}

- Minimum neutron yield (Yn_min) estimation

$$Y_{n\_\min}\cdot BR_{\gamma}\cdot\Omega\cdot\eta_{\gamma e}(\psi,t_c)\cdot\eta_{mag}=100\ \text{electrons}$$

Branching ratio [BR_{γ}]	5e-5	
Solid angle[Ω]	5e-7	Converter diameter =1.7 cm, distance from TCC = 600 cm
γ-to-e conversion efficiency[$\eta_{\gamma e}$]	1e-3	Converter thickness = 1 cm
Magnet efficiency[η_{mag}]	0.8	
Min Yield[Yn_min]	5e15	

If we place magnet outside chamber, how can we improve efficiency?
Converter & focusing device in close to target can improve detector sensitivity



Option for focusing device
- Solenoid
- Quadrupole
- Permanent magnet array

Summary

- **We need GCS to support NIC and beyond, *e.g.*, gamma-based yield measurement**
- **Using existing WHEBY knowledge, design & calibration work previously demonstrated.**
- **Electromagnet design enables energy ranges of 1-20 MeV**
- **NIF background shielding will be simplified by locating magnet outside chamber**
  - Detection efficiency may require enhancement
  - Converter & focusing device in close to target can improve detector sensitivity