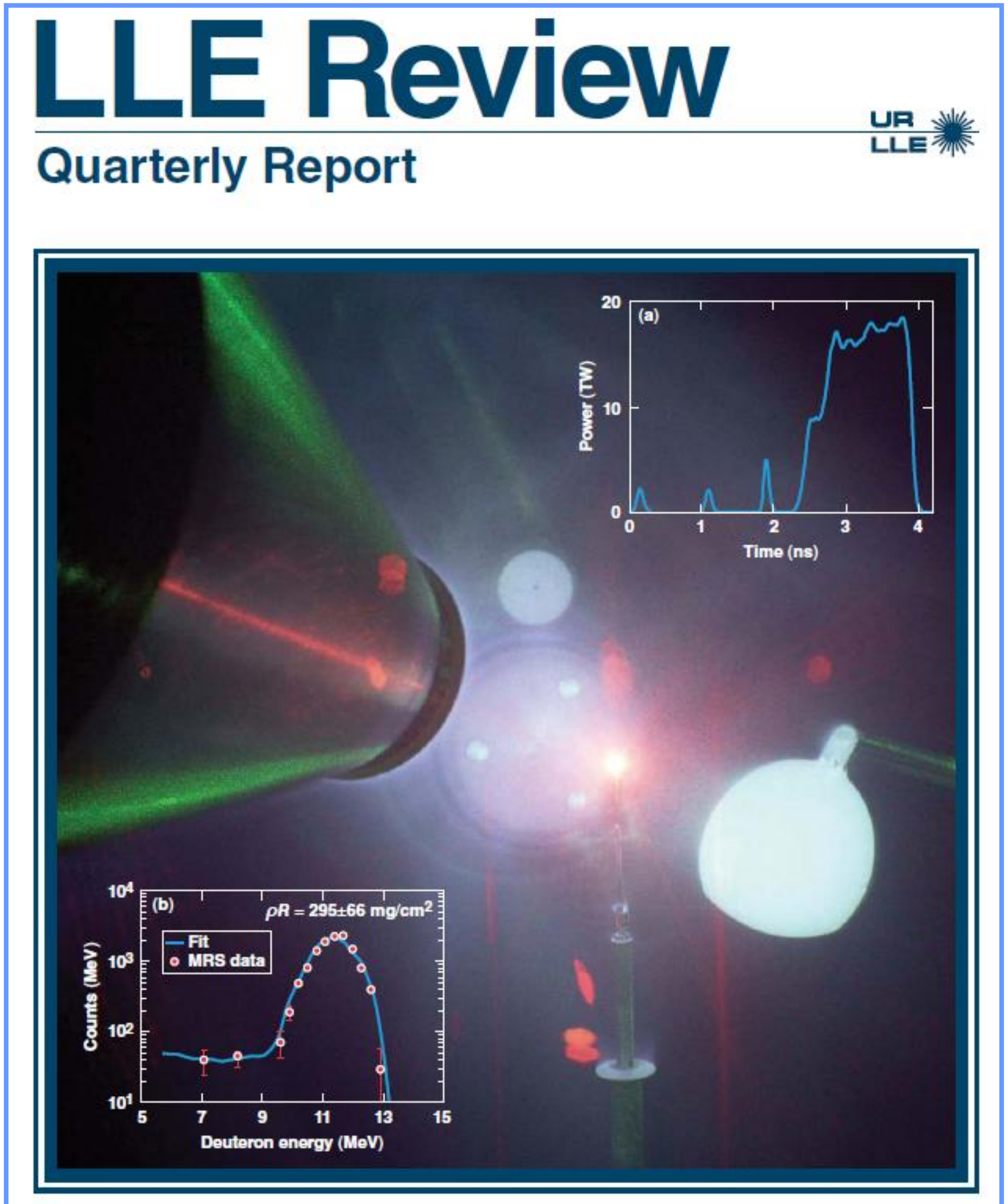
# The Magnetic Recoil Spectrometer (MRS) for diagnosing ρR in cryogenic DT implosions and for basic science experiments at OMEGA and the NIF





**Daniel Casey**


**18th High Temperature Plasma Diagnostics Conference**

Wildwood, NJ

May 16th – 20th, 2010

MIT Plasma Science & Fusion Center

# Collaborators

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PSFC MIT Plasma Science & Fusion Center  UR LLE  Sandia National Laboratories  GENESEO

Summary

# The MRS is being used to measure the ICF-neutron spectrum and to do basic science experiments at OMEGA

- The MRS at OMEGA is the only diagnostic that routinely diagnoses high-ρR (> 180 mg/cm$^2$) cryogenic DT implosions.
- Measurements of the astrophysical S-factor (or cross-section) for the T(t,2n)$^4$He reaction (TT-reaction) have been conducted for the first time using an ICF facility at energies inaccessible by conventional accelerator-based techniques.
- An MRS, which is currently being installed on the NIF, will play a critical role in guiding the National Ignition Campaign towards the demonstration of thermonuclear ignition and net energy gain.

# Outline

- Motivation
- MRS principle
- The MRS at OMEGA and the NIF
- Down-scattered neutron (DS-n) measurements
- TT-n Measurements at OMEGA
- Predicted performance of NIF MRS
- Conclusion

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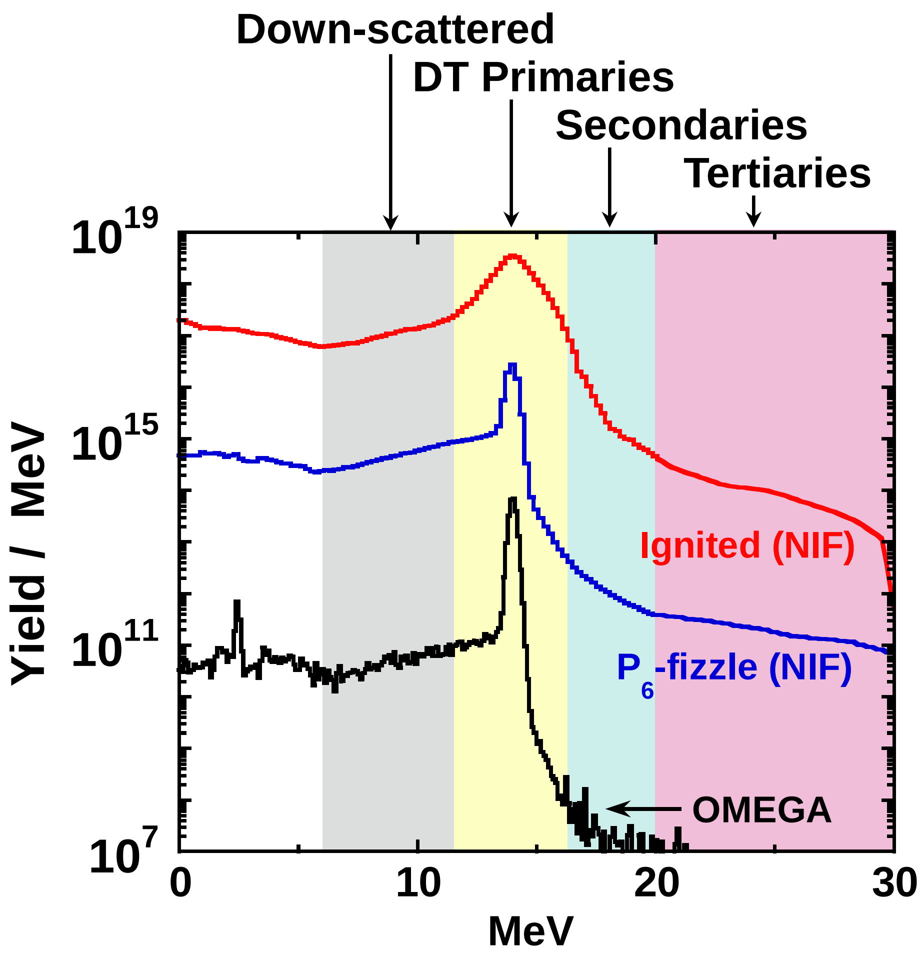
**Motivation**

# 1. To provide information about $\rho R$, $T_i$, $T_e$ and $Y_{1n}$ that will be integral for assessing failure modes




***From primaries ($Y_{1n}$):***

- $Y_{1n}$
- $T_i$ $\quad (T_i \propto \Delta E_D^2)$
- *Alpha-particle physics*

***From down-scattered ($Y_{ds}$):***

- $\rho R$ $\quad \left(\frac{Y_{ds}}{Y_{1n}} \propto \rho R\right)$

***From Secondaries ($Y_{2n}$):***

- $T_e$ $\quad \left(\frac{Y_{2n}}{Y_{1n}} \propto T_e^3\right)$

***From Tertiaries ($Y_{3n}$):***

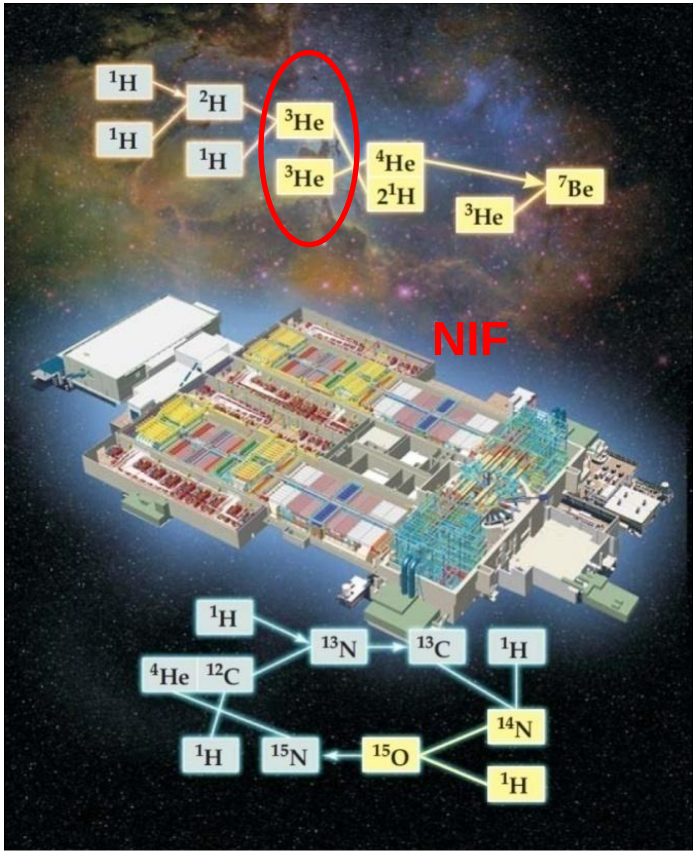
- $\rho R$ $\quad \left(\frac{Y_{3n}}{Y_{1n}} \propto \rho R\right)$



**J. Källne *et al.*, Phys. Rev. Letters 85, 1246 (2000).

Motivation

# 2. To perform basic science experiments by studying the $^3He(^3He,2p)^4He$ and $^3H(^3H,2n)^4He$ reactions




1. Measure the characteristics of the $^3H(^3H,2n)^4He$ reaction (an important mirror reaction to the $^3He(^3He,2p)^4He$ reaction that is relevant to the stellar nucleosynthesis).

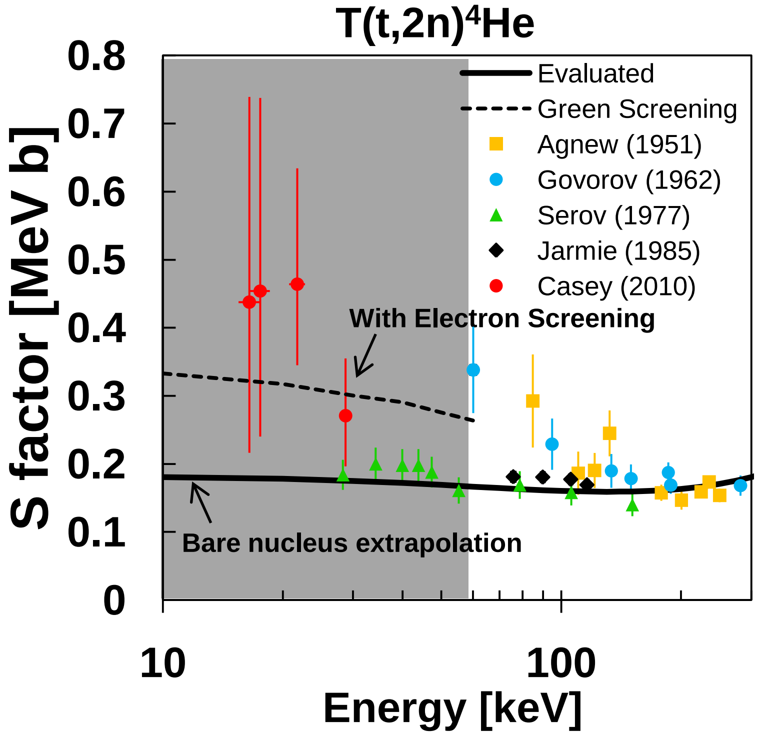
2. Measure $^3He(^3He,2p)^4He$ reaction at the NIF (this can be done by turning the MRS into a charged-particle spectrometer that can simultaneously measure the spectra of protons and $^4He$ ions).

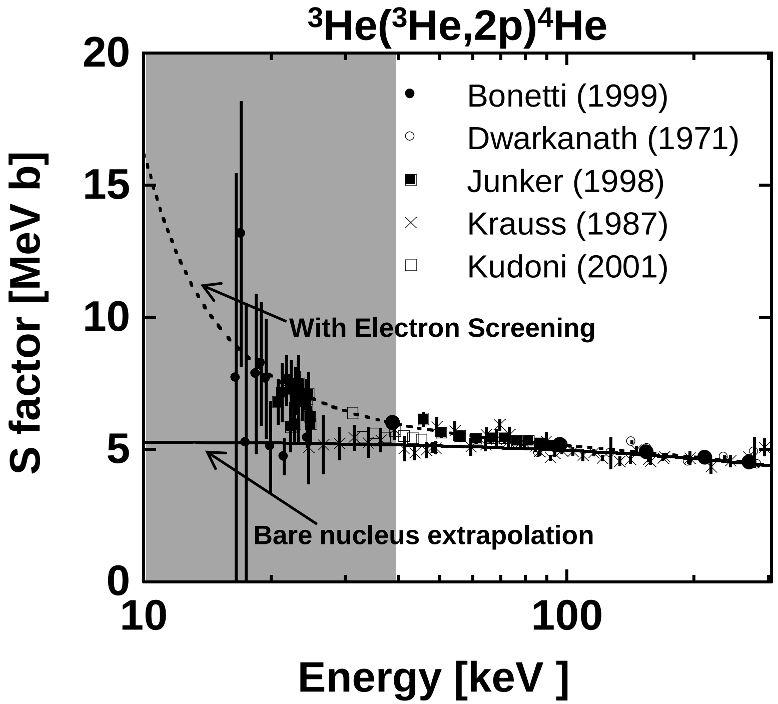


R.N. Boyd, L. Bernstein and C. Brune, Physics Today 62, August (2009).

# Using an ICF facility, the $^3He(^3He,2p)^4He$ and $T(t,2n)^4He$ reactions can be studied at energies inaccessible by conventional accelerator techniques

$$S_{factor} \propto \sigma$$




**ICF implosions produces weakly coupled plasmas**
**in which electron screening has no impact on the cross section**

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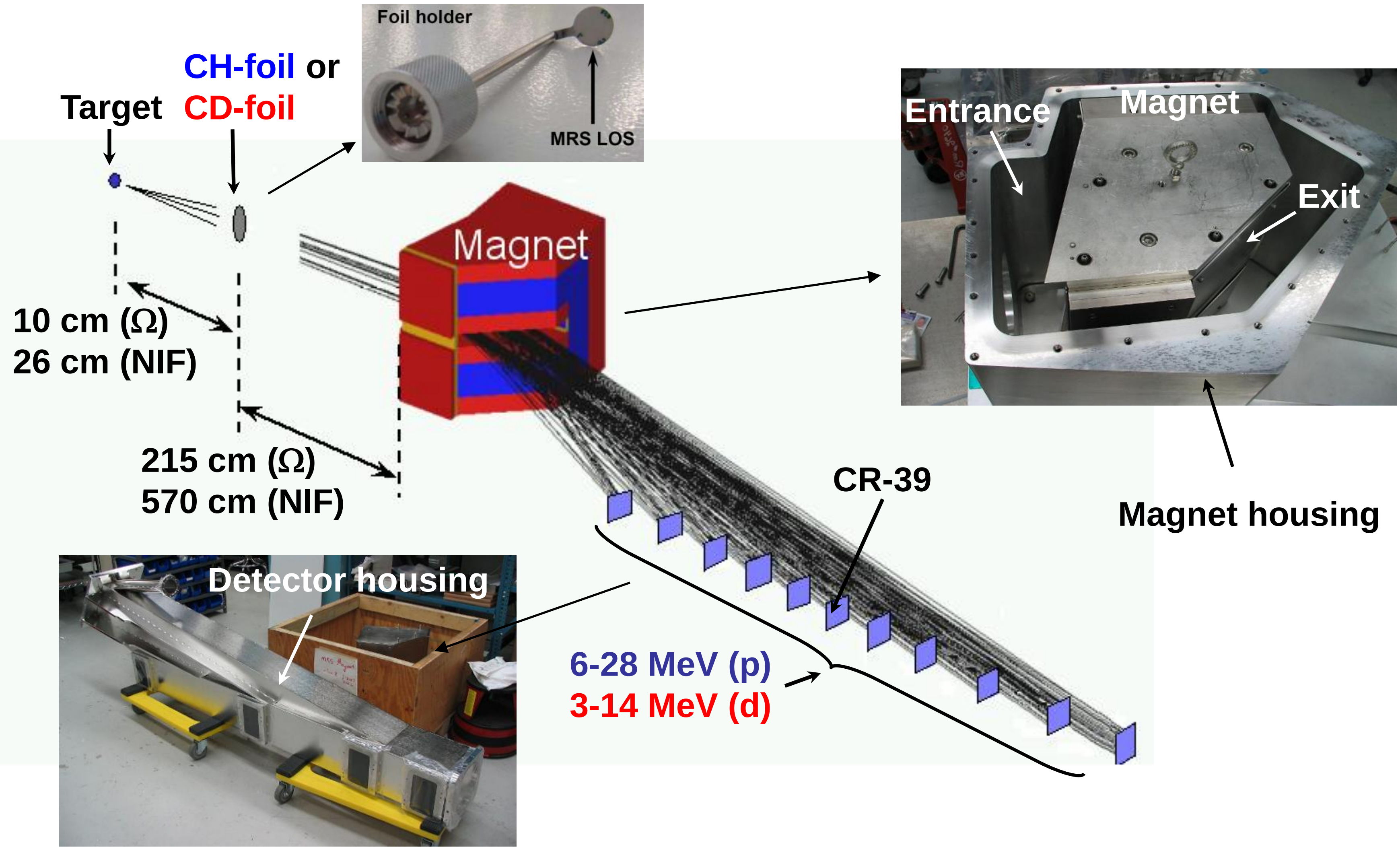
# The principle of the Magnetic Recoil Spectrometer (MRS)



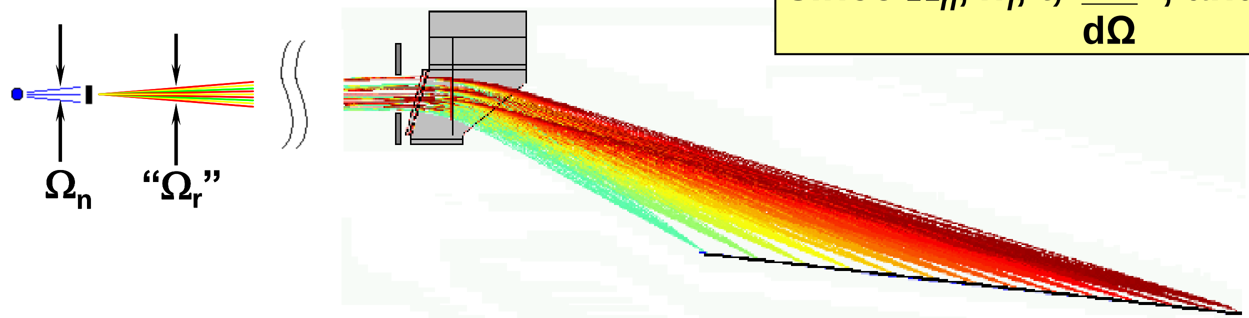

J.A. Frenje et al., Phys. Plasmas 16, 042704 (2009).

# MRS detection efficiency and energy resolution

- **The detection efficiency ($\varepsilon_{MRS}$) is defined as:**

$$\varepsilon_{MRS} = \frac{\Omega_n}{4\pi} \cdot n_i \cdot t \int^{"\Omega_r"} \frac{d\sigma}{d\Omega_{lab}} d\Omega$$

**Absolute yields are measured since $\Omega_n$, $n_i$, $t$, $\frac{d\sigma}{d\Omega}$, and $\Omega_r$ are known**

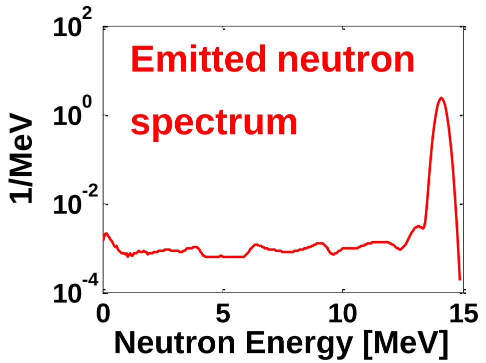


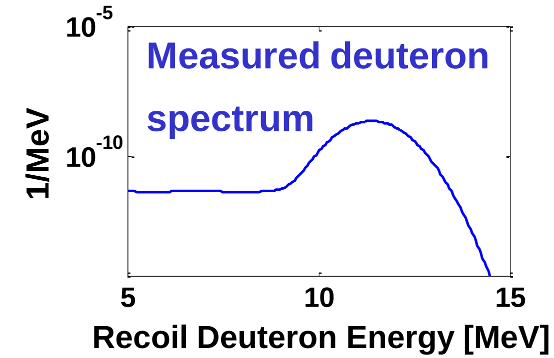

- **Resolution ($\Delta E_l$) is defined as:**

$$\Delta E_l \approx \sqrt{\Delta E_f^2 + \Delta E_k^2 + \Delta E_m^2}$$

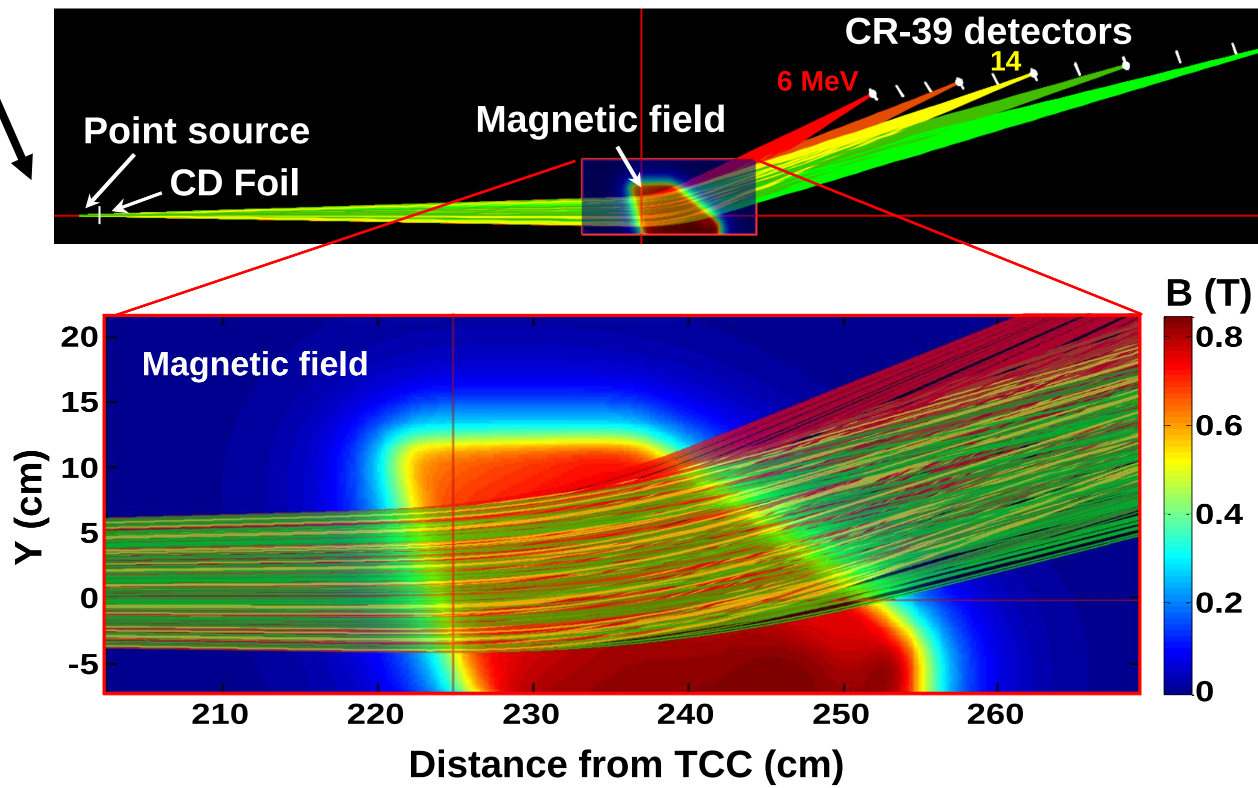
| | | | | |
|---|---|---|---|---|
| $\Delta E_f$ | = | **Energy loss in foil** | $\propto$ | **foil thickness** |
| $\Delta E_k$ | = | **Kinematic energy broadening** | $\propto$ | **foil and aperture sizes** |
| $\Delta E_m$ | = | **Optical energy broadening** | $\propto$ | **magnet performance** |

# The Monte Carlo code Geant4 is being used to model the full MRS detector response

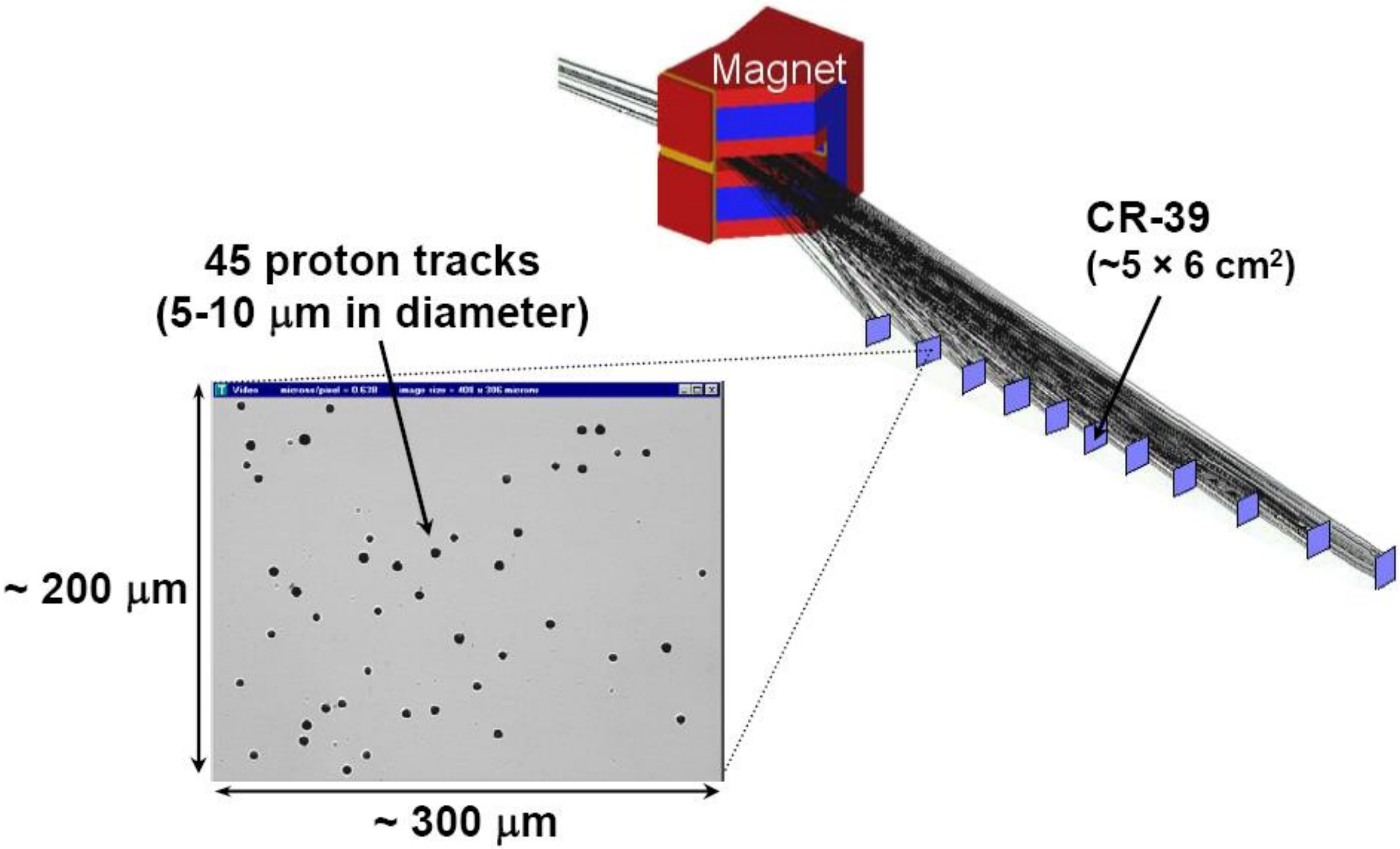



**MRS response function**

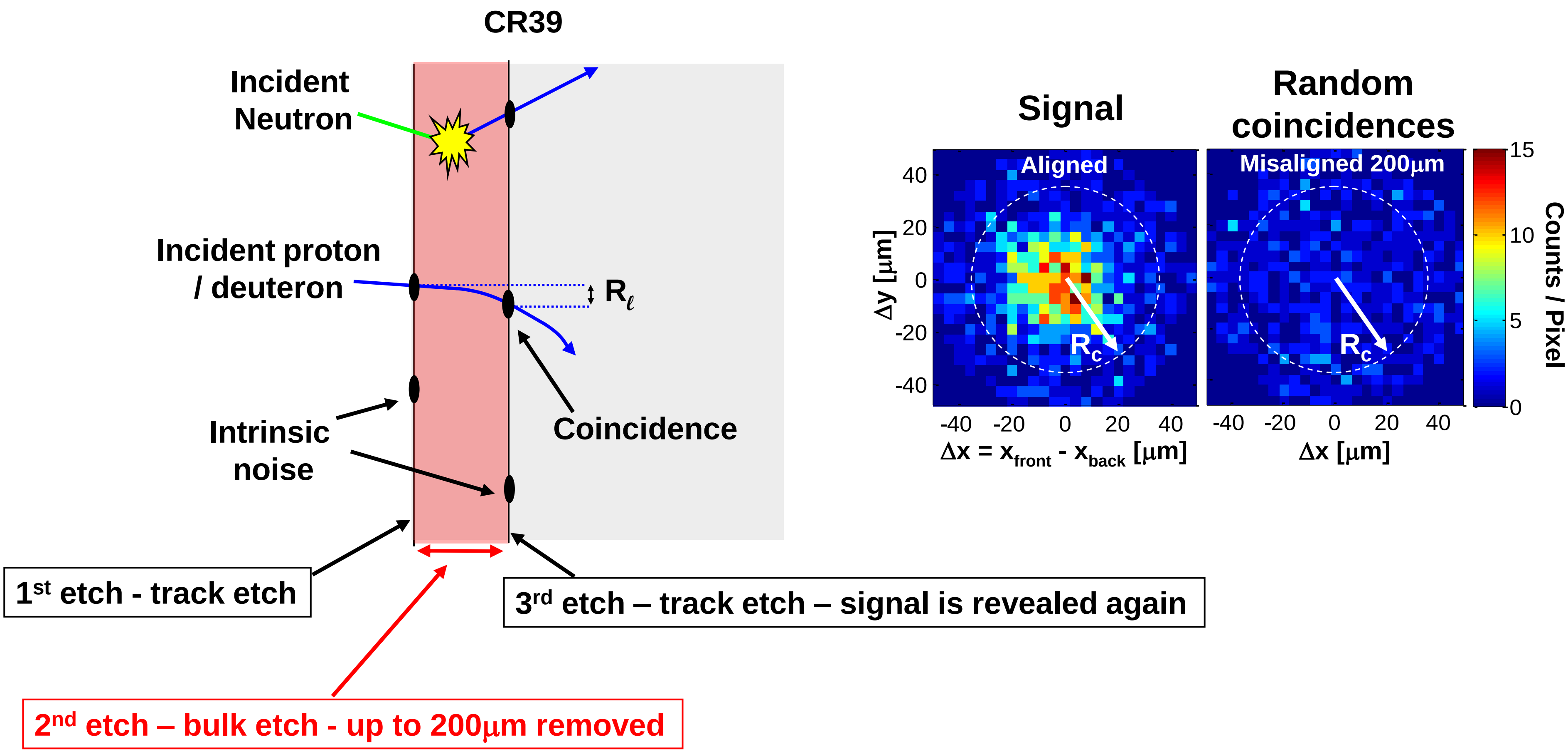


# The MRS uses CR-39 detectors to detect recoil protons and deuterons




- CR-39 detects the charged recoil particles with a 100% efficiency.
- CR-39 detects neutrons (bkgd) with an efficiency of $5 \times 10^{-5}$.

# The Coincidence Counting technique (CCT) reduces the CR-39 background for the MRS by orders of magnitude



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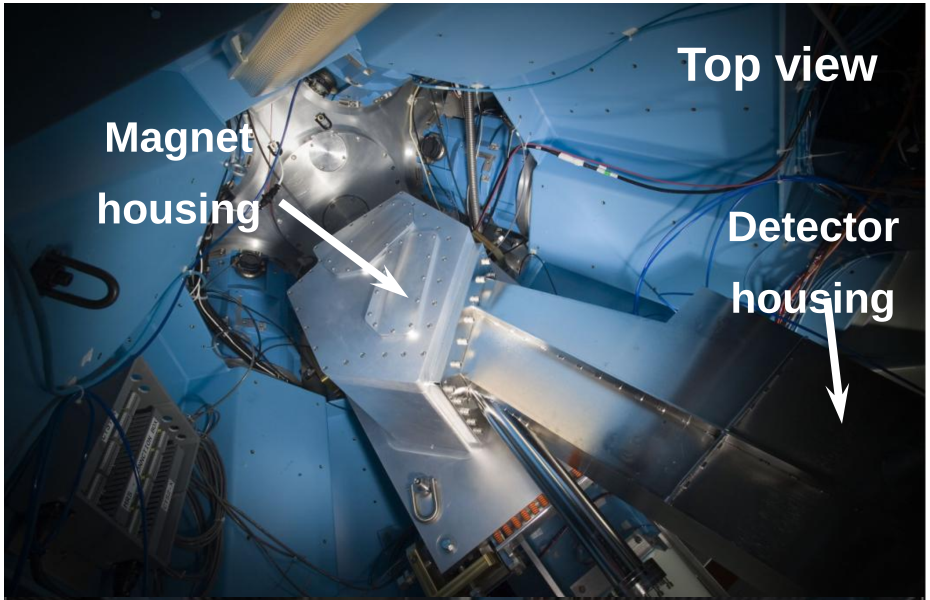
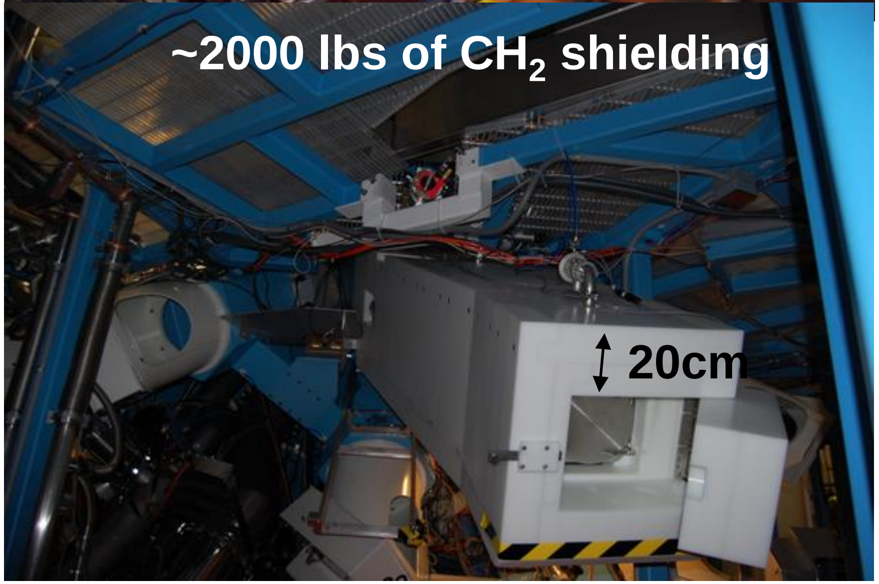
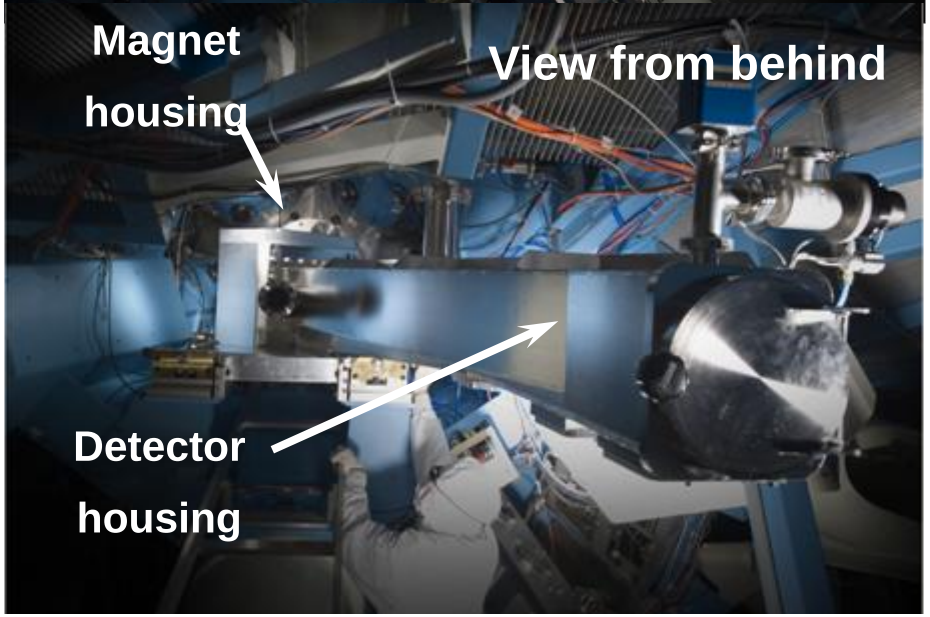
# The MRS on OMEGA was installed and fully commissioned in spring 2008

# The MRS on the NIF is being installed as we speak

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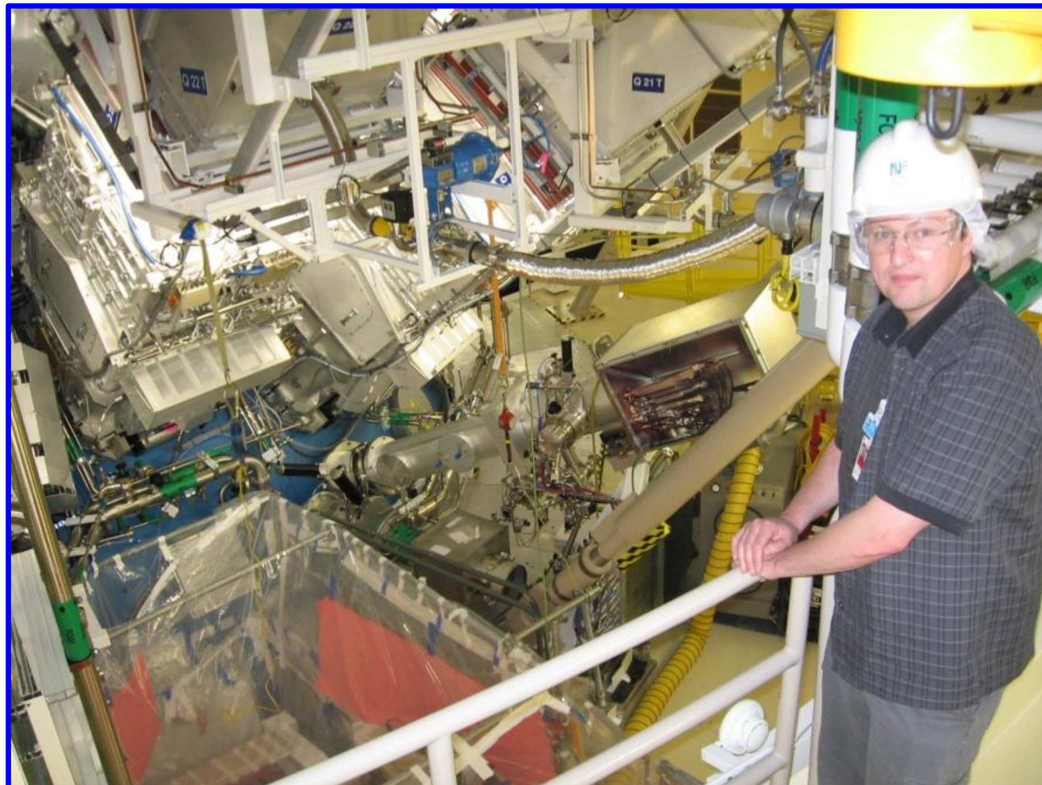

MRS Location

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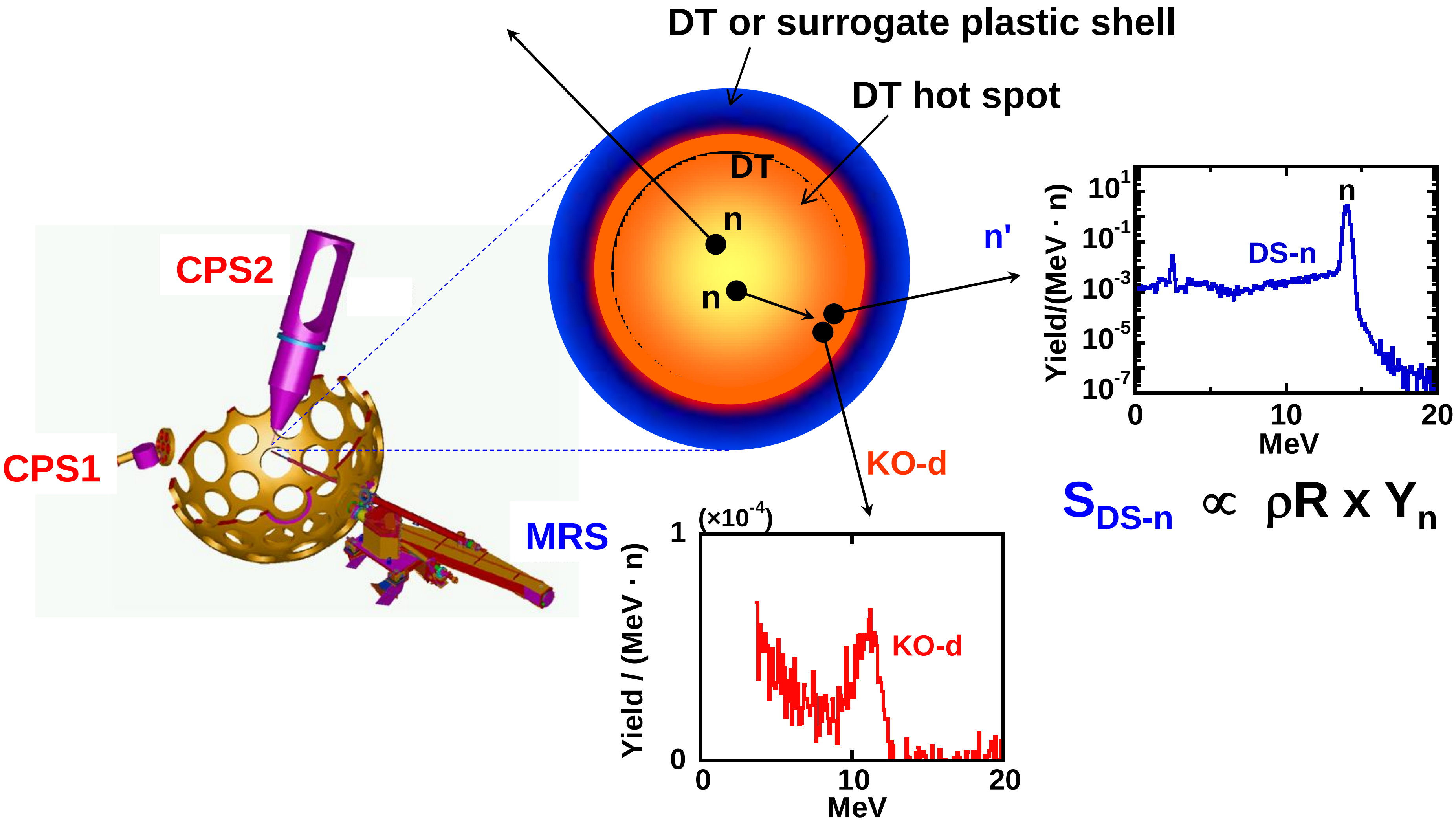
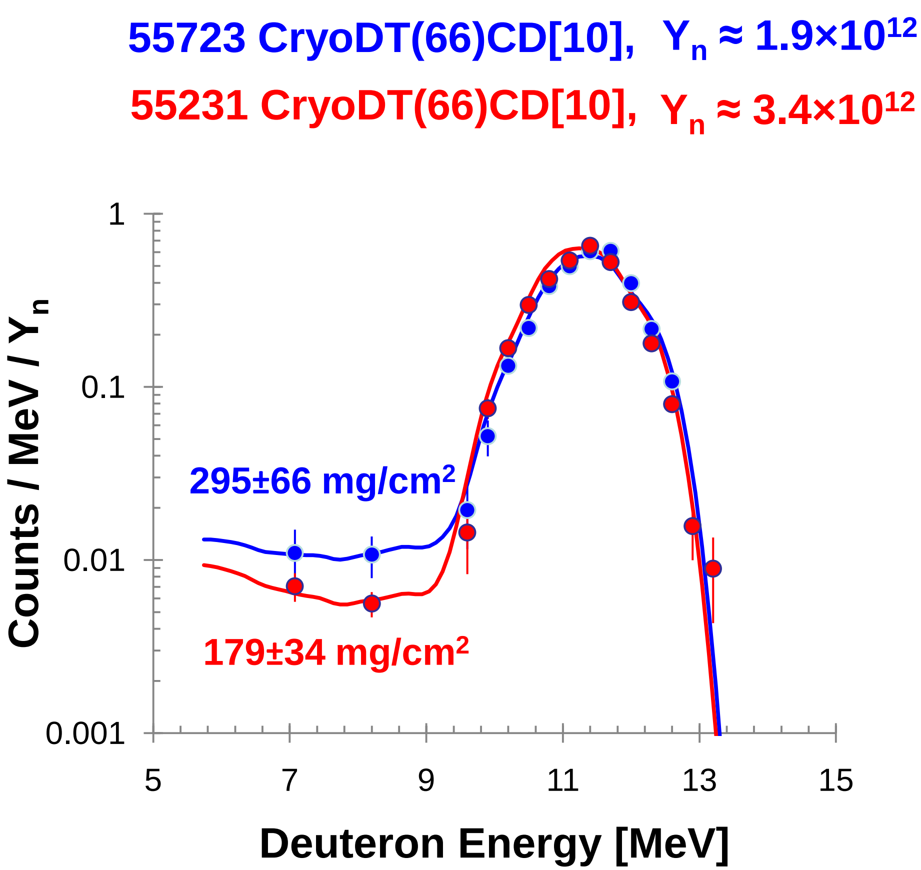
# Areal density (ρR) is inferred from knock-on deuterons (KO-d) and down-scattered neutrons (DS-n)

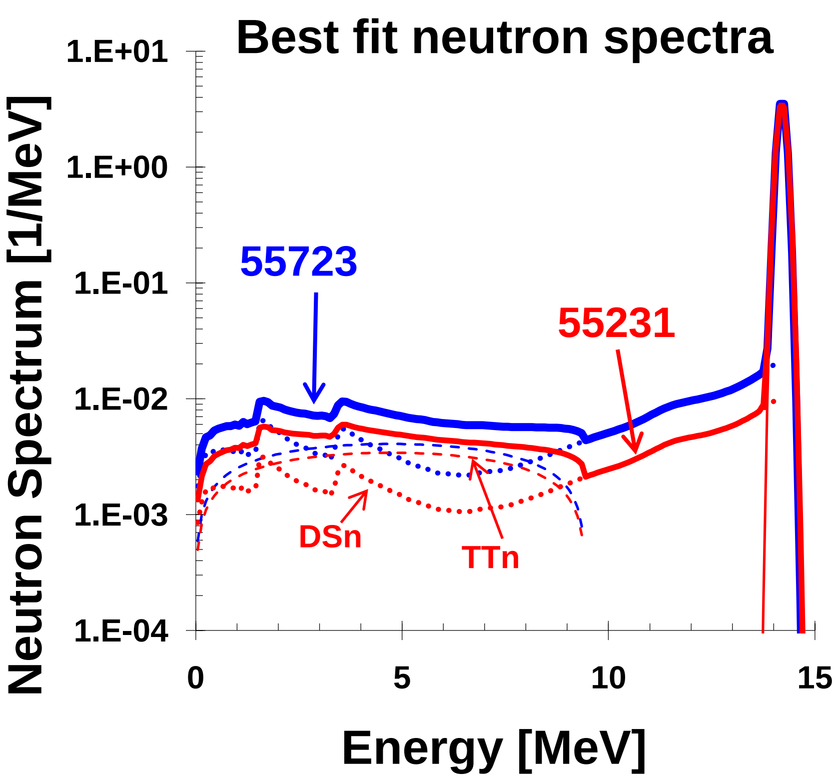



$S_{DS\text{-}n} \propto \rho R \times Y_n$

$S_{KO\text{-}d} \propto \rho R \times Y_n$

# The MRS regularly diagnoses ρR in cryogenic DT implosions at OMEGA including a recent implosion with ρR = 295 ± 66 mg/cm²



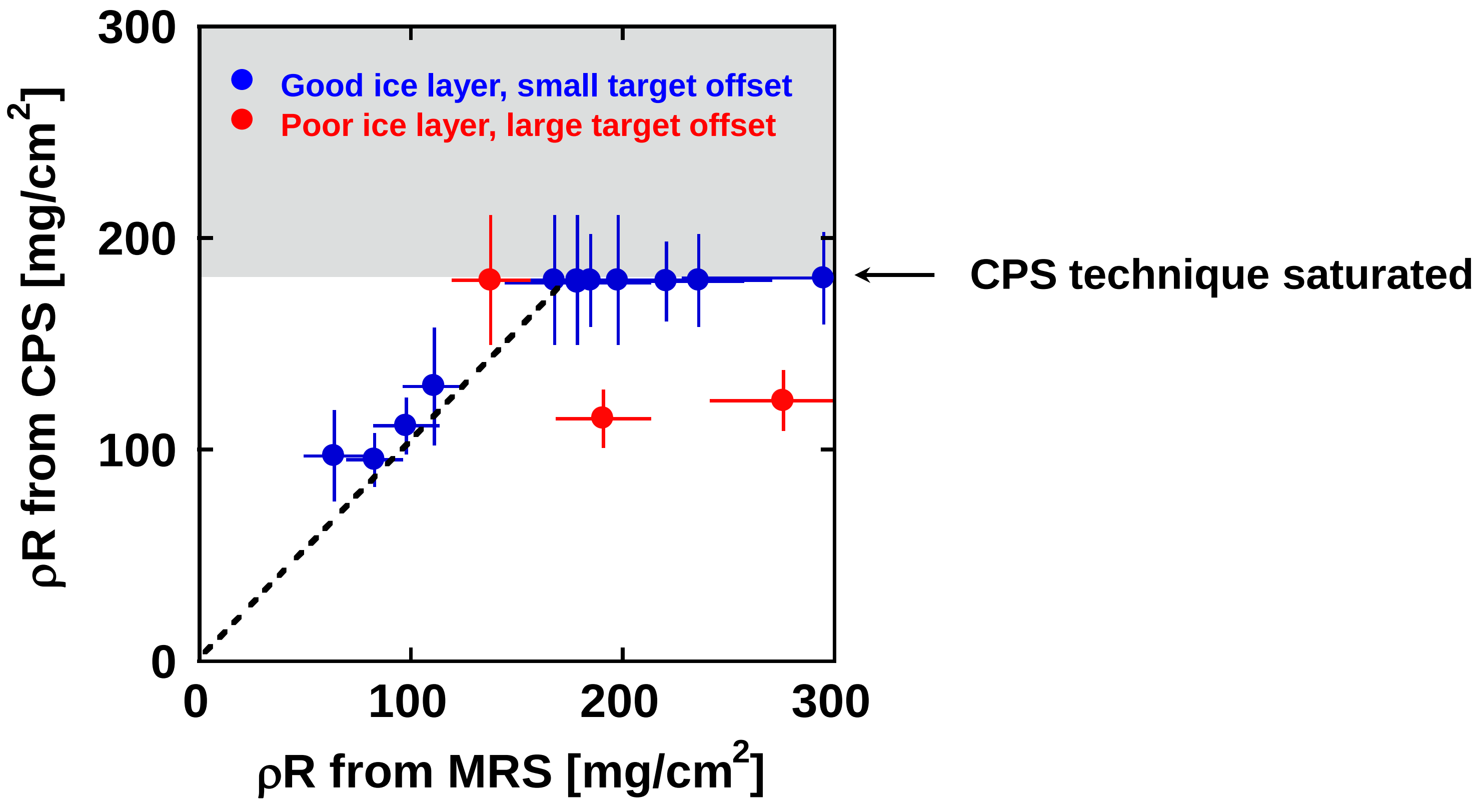




**Currently no other ρR diagnostic operates (>180mg/cm²)**


T. C. Sangster, - Phys. Plasmas 17, 056312 (2010).

J. A. Frenje, Phys. Plasmas 17, 056311 (2010).

# DS-n and KO-d measurements are in good agreement for symmetric implosions below the KO-d detection limit (<180mg/cm²)




J. A. Frenje, Phys. Plasmas 17, 056311 (2010).

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# Current theory predicts that the 2-body reaction channel accounts for <5% of the total TT-neutron emission (2-body + 3-body)

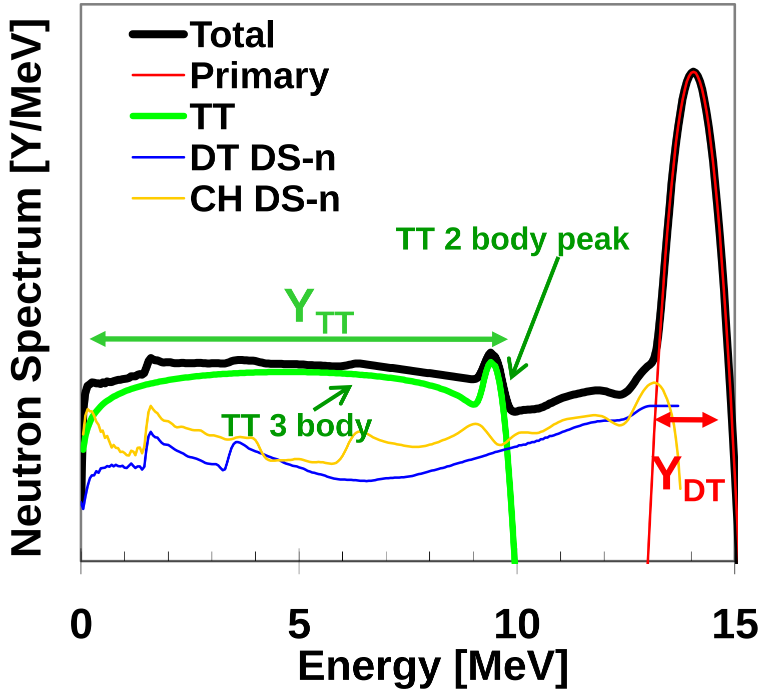
**Primary TT Neutrons**

**3 body reaction**

**T + T → α + n + n (0-9.5 MeV)**

**2 body reaction**

**T + T → *$He^5$ + n (8.7 MeV)**




C. Wong et al., Nucl. Phys. 71(1965)106, $E_{cm}$ = 250 keV -> $T(t,n)^5He$/total-n ~ 9%.

K. Allen et al., Phys. Rev. 82(1951)262, $E_{cm}$ = 110 keV -> $T(t,n)^5He$/total-n ~ 5%.

V. Glebov et al., Bull. Am. Phys.Soc.(2008) $E_G$~ 20 keV -> $T(t,n)^5He$/total-n ~ 0%.

# The TT S-factor can be measured directly from the ratio of the TT and DT yields at the Gamow energy

$$\sigma_{TT}(\varepsilon) = \frac{S_{TT}(\varepsilon)}{\varepsilon} e^{-\sqrt{\varepsilon_G/\varepsilon}}$$

**Electron screening correction f ~ 1.008**

$$<\sigma v> \propto A^{-1/3}\, T^{-2/3}\, f\, S\, e^{-3E_0/T}$$

**Gamow energy**

$$Y_{TT}/Y_{DT} \approx \frac{1}{2}\frac{n_T}{n_D}\frac{<\sigma v>_{TT}}{<\sigma v>_{DT}}$$

**Factor of ½ for TT reaction yield**

**is well known**

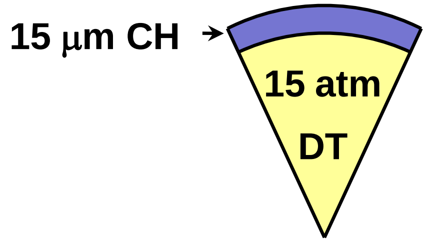
$$\Rightarrow \quad S_{TT} \propto \frac{Y_{TT}}{Y_{DT}} <\sigma v>_{DT}$$

**We can probe Gamow energies of ~8-40 keV at OMEGA**



***1D hydro simulations show approximately equal DT and TT burn profiles**

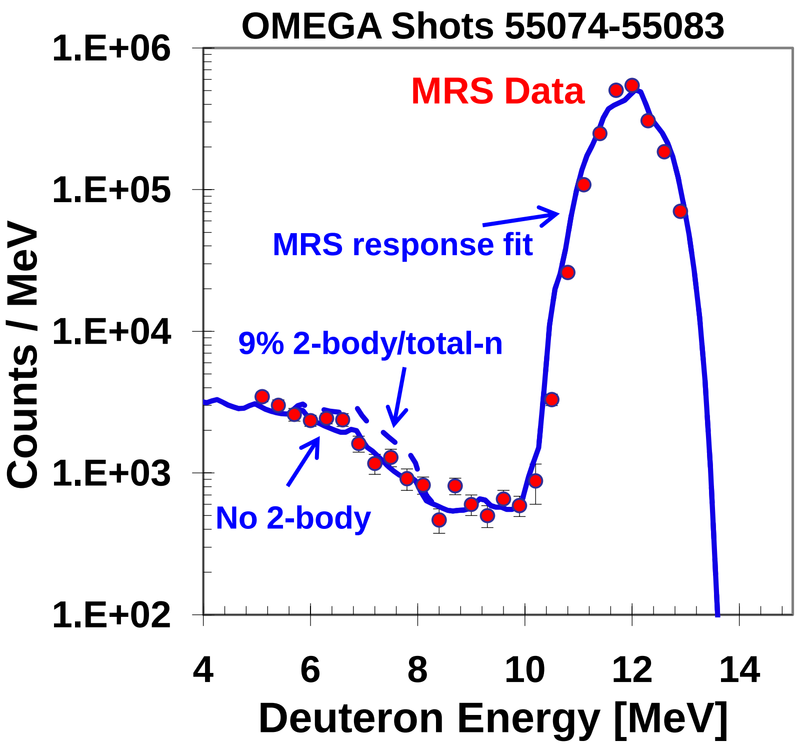
# The TT neutron spectrum was measured at a $T_i$ of 5 keV and analysis indicates the 2-body yield accounts for 1 ± 2 % of the total neutron emission

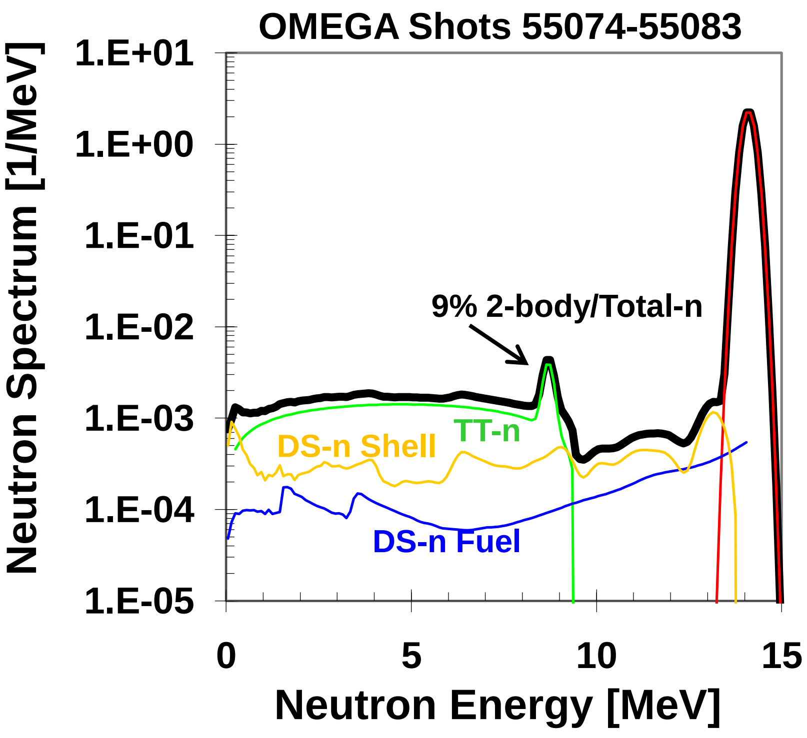



Integrated 9 shots $Y_n = 2\times10^{14}$

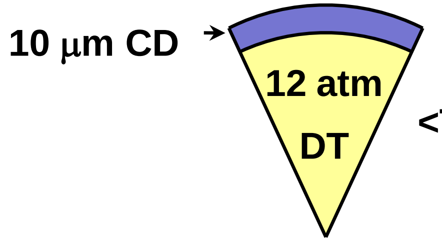
$\langle T_i \rangle n$ = 5.3 keV -> $E_0$ = 22 keV

$\rho R_{MRS}$ = 62 mg/cm²



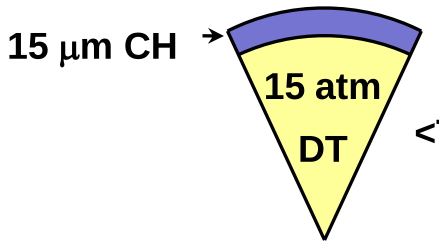
# This process was repeated for several sets of implosions and the 2-body reaction accounts for ~4% of the total TT neutrons at 16-30 keV




$Y_n = 3\times10^{14}$

$\langle T_i \rangle_n = 8.0$ keV

$E_0 = 29$ keV

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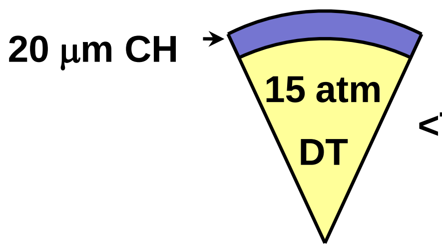
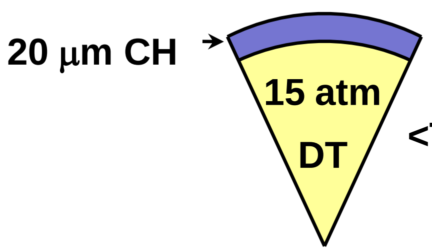



$Y_n = 4\times10^{14}$

$\langle T_i \rangle_n = 3.5$ keV

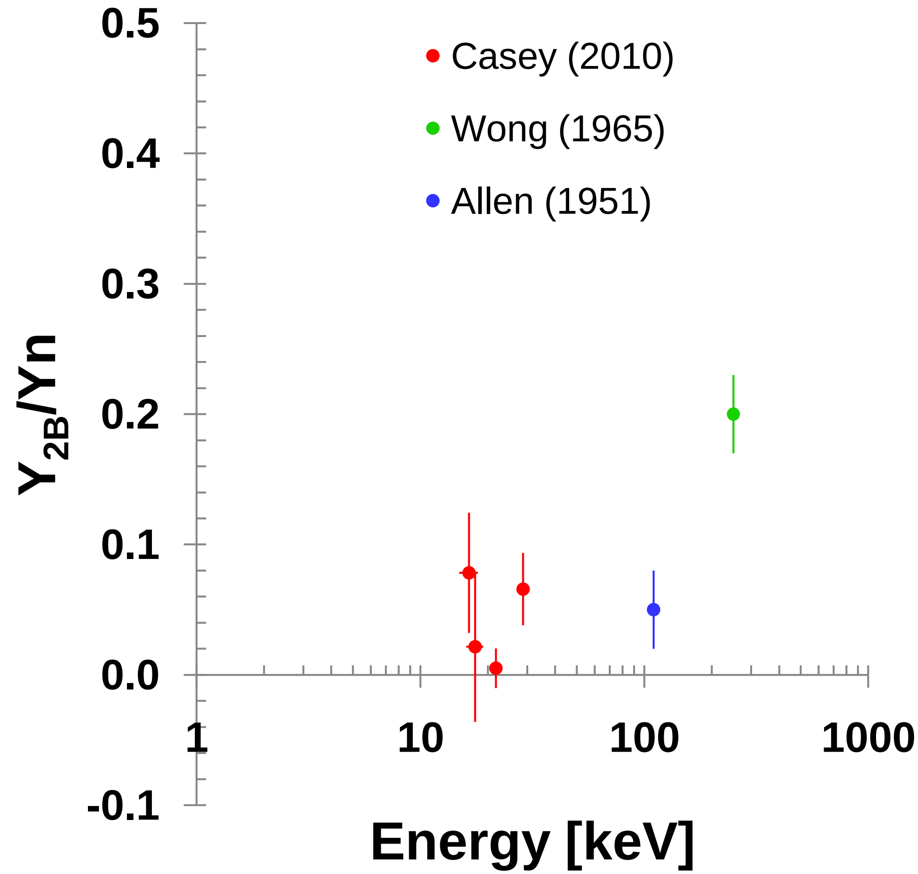
$E_0 = 16$ keV




$Y_n = 3\times10^{13}$

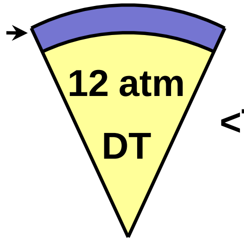
$\langle T_i \rangle_n = 3.8$ keV

$E_0 = 18$ keV



# The determined S-factors in the range 16-30 keV are higher than evaluated extrapolations but experimental errors are large

10 μm CD

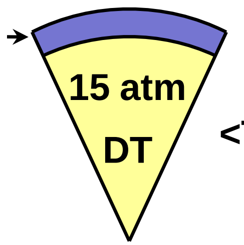



$Y_n = 3 \times 10^{14}$

$\langle T_i \rangle_n = 8.0$ keV

$E_0 = 29$ keV

15 μm CH

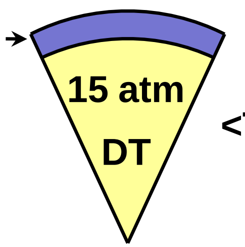



$Y_n = 2 \times 10^{14}$

$\langle T_i \rangle_n = 5.3$ keV

$E_0 = 22$ keV

20 μm CH

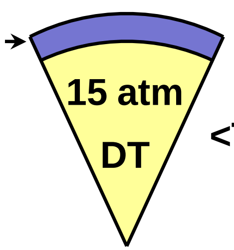



$Y_n = 4 \times 10^{14}$

$\langle T_i \rangle_n = 3.5$ keV

$E_0 = 16$ keV

20 μm CH




$Y_n = 3 \times 10^{13}$

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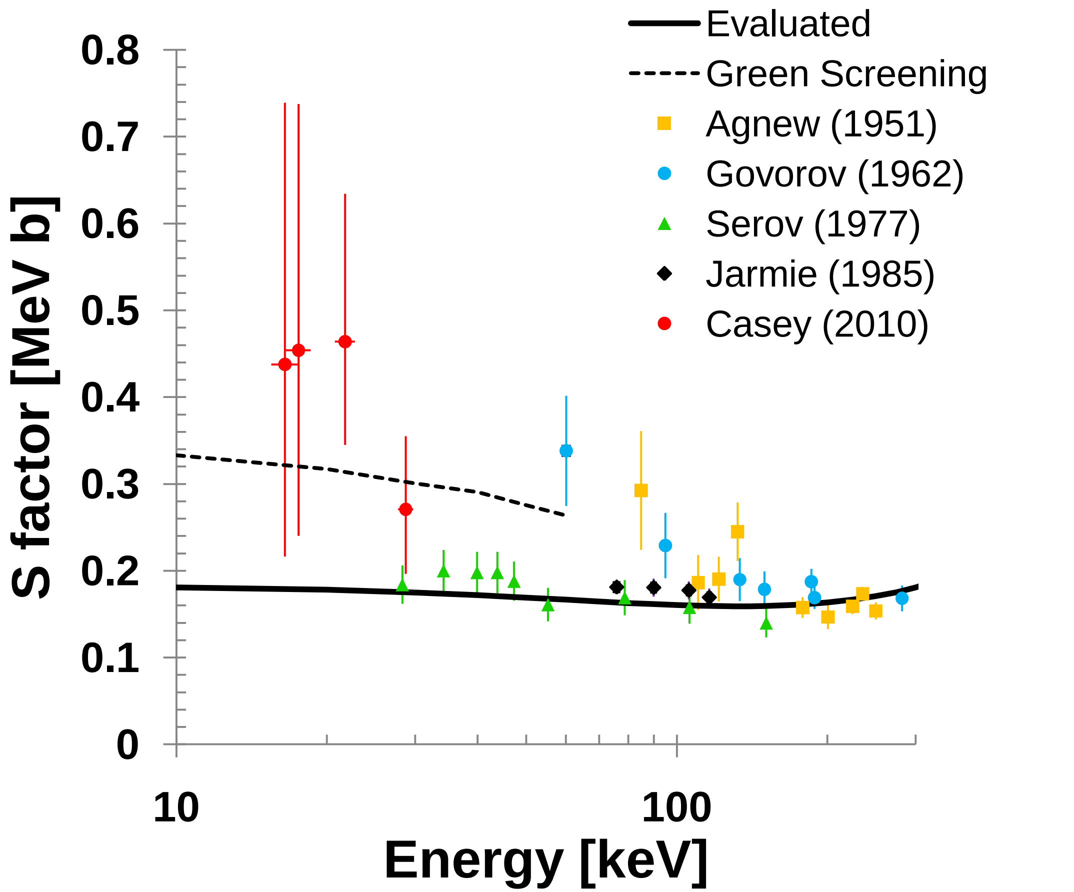
$E_0 = 18$ keV




**Could there be a near threshold resonance in the TT reaction, as there is one for DT and D3He?**

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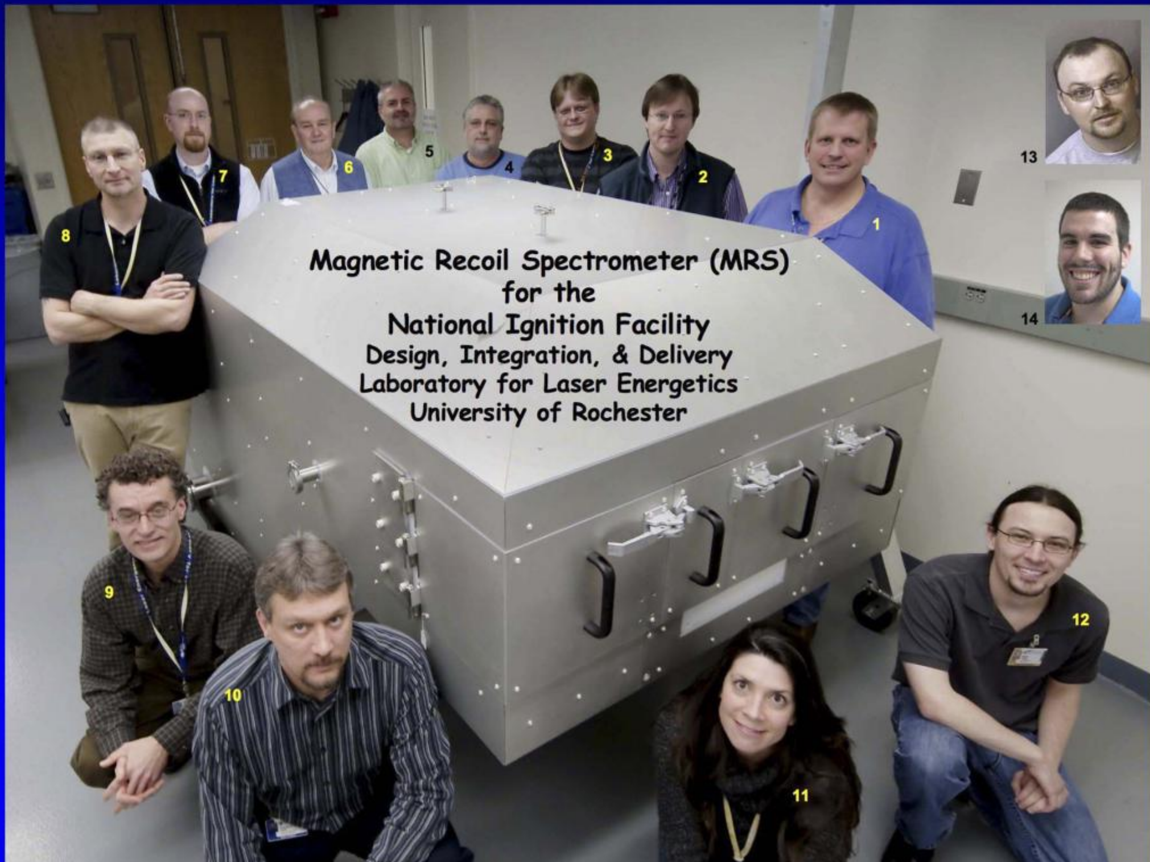


by eugene kowaluk, 16 February 2010

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8 Mark Romanofsky
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10 Tim Clark
11 Michelle Burke
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Tom Lewis

Chad Abbott

Chad Abbott

Tim Clark

Chad Abbott

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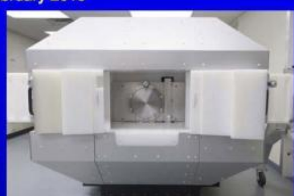
Chad Abbott

C Abbott, J Magoon, M Romanofsky



John Szczepanski, Chad Abbott

T Lewis, M Romanofsky, C Abbott, J Szczepanski

Mark Romanofsky, Ron Callari

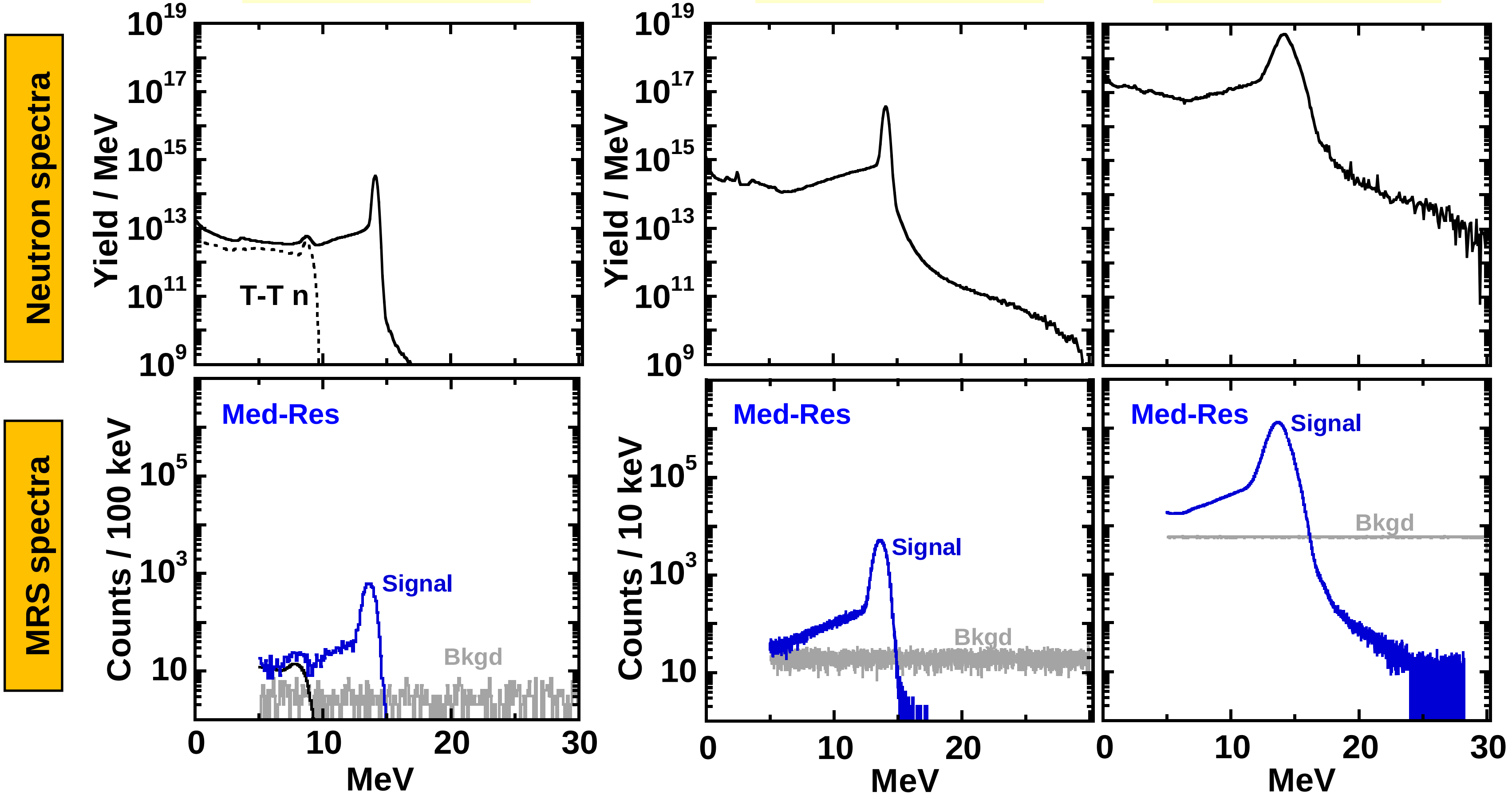
Johan Frenje, Rick Ashabranner (LLNL), Dan Casey

Chad Abbott, Tom Lewis, Fred Rister

On the way to LLNL

# OMEGA data and simulations indicate that the MRS will accurately diagnose THD and DT implosions at the NIF

| THD | P6 failure | Ignition |
|---|---|---|
| $Y1n = 2\times10^{14}$ | $Y1n = 2\times10^{16}$ | $Y1n = 8\times10^{18}$ |
| $\rho R = 2.1$ g/cm$^2$ | $\rho R = 2.0$ g/cm$^2$ | $\rho R = 1.4$ g/cm$^2$ |






J. A. Frenje, Phys. Plasmas 17, 056311 (2010).

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- **Measurements of the astrophysical S-factor (or cross-section) for the $T(t,2n)^4He$ reaction (TT-reaction) have been conducted for the first time using an ICF facility at energies inaccessible by conventional accelerator-based techniques.**

- **An MRS, which is currently being installed on the NIF, will play a critical role in guiding the National Ignition Campaign towards the demonstration of thermonuclear ignition and net energy gain.**