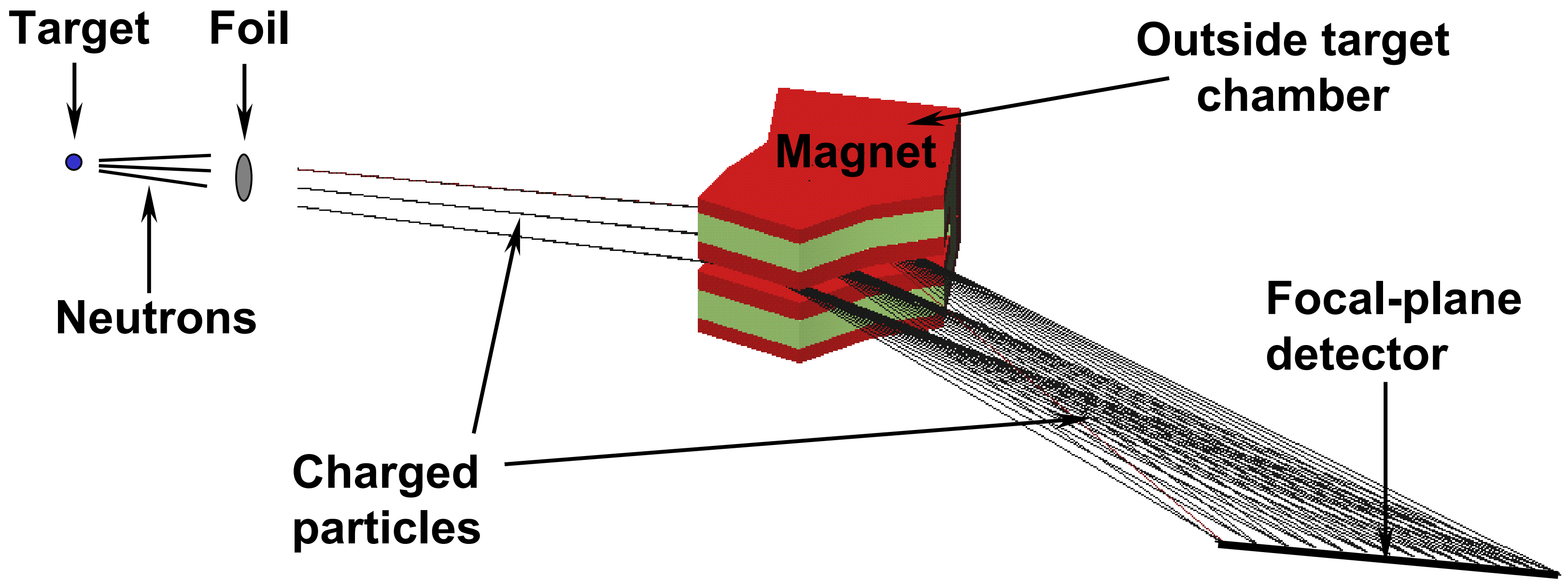
A Magnetic Recoil Spectrometer (MRS) for precise ρR_{fuel} and T_i measurements of warm and cryo targets at OMEGA and the NIF



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Abstract

A method for determining ρR_{fuel} of cryogenic deuterium-tritium plasmas involves measurement of the energy spectrum of elastically-scattered, primary neutrons. A spectrometer has been designed for doing this at OMEGA and the NIF, using scattered neutrons in the energy range 7-10 MeV to determine ρR_{fuel} and primary neutrons to measure T_i. The instrument utilizes a magnet and a conversion foil for production of charged particles. A large dynamic range ($>10^6$) will allow operation at yields as low as 10^{12}. This will allow ρR_{fuel} and T_i measurements of warm and cryogenic DT targets at OMEGA, and fizzle and ignited cryogenic DT targets at the NIF.

This work was supported in part by the US DoE (contract W-7405-ENG-48 with LLNL, grant DE-FG03-99DP00300 and Cooperative Agreement DE-FC03-92SF19460), LLE (subcontract P0410025G), and LLNL (subcontract B313975).

MRS strengths at OMEGA and the NIF

- ρR_{fuel} of warm, fizzle and ignited implosions can be measured at the NIF, and similarly for warm and cryo DT at OMEGA.

- Large dynamic range is achievable. ($Y_{1n} \sim 10^{12} – 10^{19}$)

- Flexible instrument:
  - Two different types of detectors can be used.
  - Recoils of either p or d can also be used.

- Authenticate the data through the primaries.

- A trade off can be made between high resolution and high efficiency, depending on exp.

- Large signal-to-background ratio for most applications.

- Wide-band spectrometer (6-24 MeV p); (3-12 MeV d).

- High-resolution spectrometer ($\Delta E_l/E = 1.8\%$).

ρR_{fuel} can be determined by measuring number of primary neutrons elastically scattered (Y_{scatt}) from fuel ions

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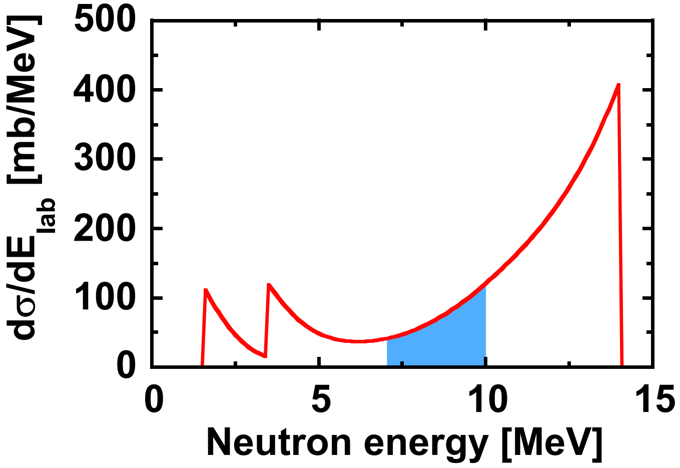
The relationship between ρR_{fuel} and Y_{scatt} is

$$\rho R_{fuel} = \frac{(2\gamma + 3)m_p}{(\gamma\sigma_d + \sigma_t)} \frac{Y_{scatt}}{Y_{1n}} \qquad (1)$$

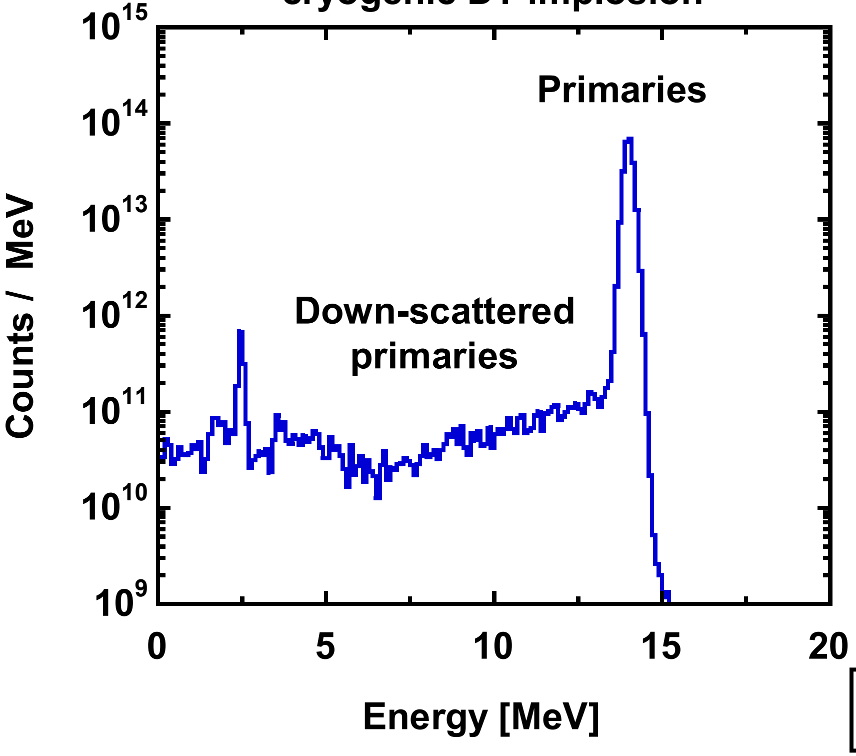
m_p = protons mass, $\gamma = n_d/n_t$, σ_d (σ_t) = elastic cross section for deuterons (tritons), and Y_{1n} is primary yield. For specificity, we'll focus on the energy range 7 to 10 MeV for the scattered neutrons); the total cross sections used in Eq. (1) must then be replaced by the effective cross sections for generating scattered neutrons in this energy range.



$$\boxed{\rho R_{fuel} \approx 40 \frac{Y_{scatt}}{Y_{1n}}} \qquad [\mathrm{g/cm^2}] \qquad (2)$$

Nature of relevant neutron spectra at OMEGA and NIF

To illustrate the nature of relevant spectra, and to provide a basis for evaluating the practical utility of the MRS on OMEGA and the NIF, following spectra were used in this work.



OMEGA

cryogenic DT implosion

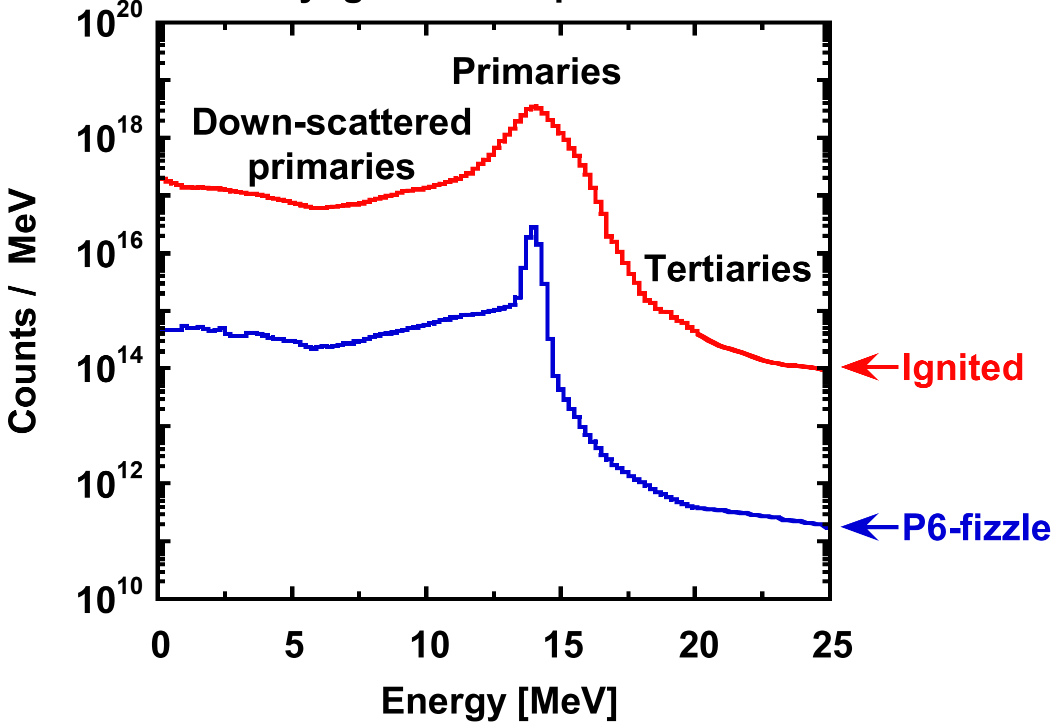
ρR_{fuel} = 128 mg/cm^2

Y_{1n} = 2.3×10^{13}

Y_{scatt} (7-10 MeV) = 1.3×10^{11}

Calculated by Steve Hatchett

Nature of relevant neutron spectra at OMEGA and NIF, continued



NIF

cryogenic DT implosions

Ignited

ρR_{fuel} = 1850 mg/cm^2

Y_{1n} = 7.4×10^{18}

Y_{scatt} (7-10 MeV) = 3.2×10^{17}

P6-fizzle

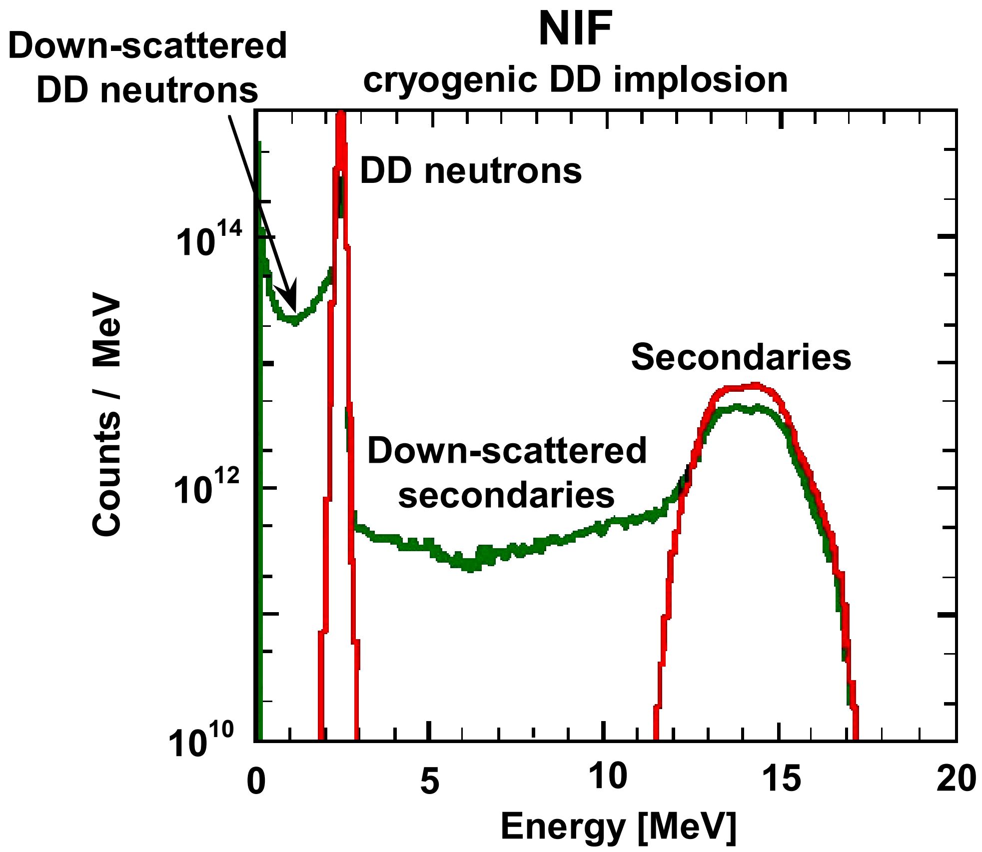
ρR_{fuel} ~ 2000 mg/cm^2

Y_{1n} = 2.1×10^{16}

Y_{scatt} (7-10 MeV) = 1.3×10^{15}

Calculated by Steve Haan

Nature of relevant neutron spectra at OMEGA and NIF, continued



ρR_{fuel} = 1500 mg/cm^2

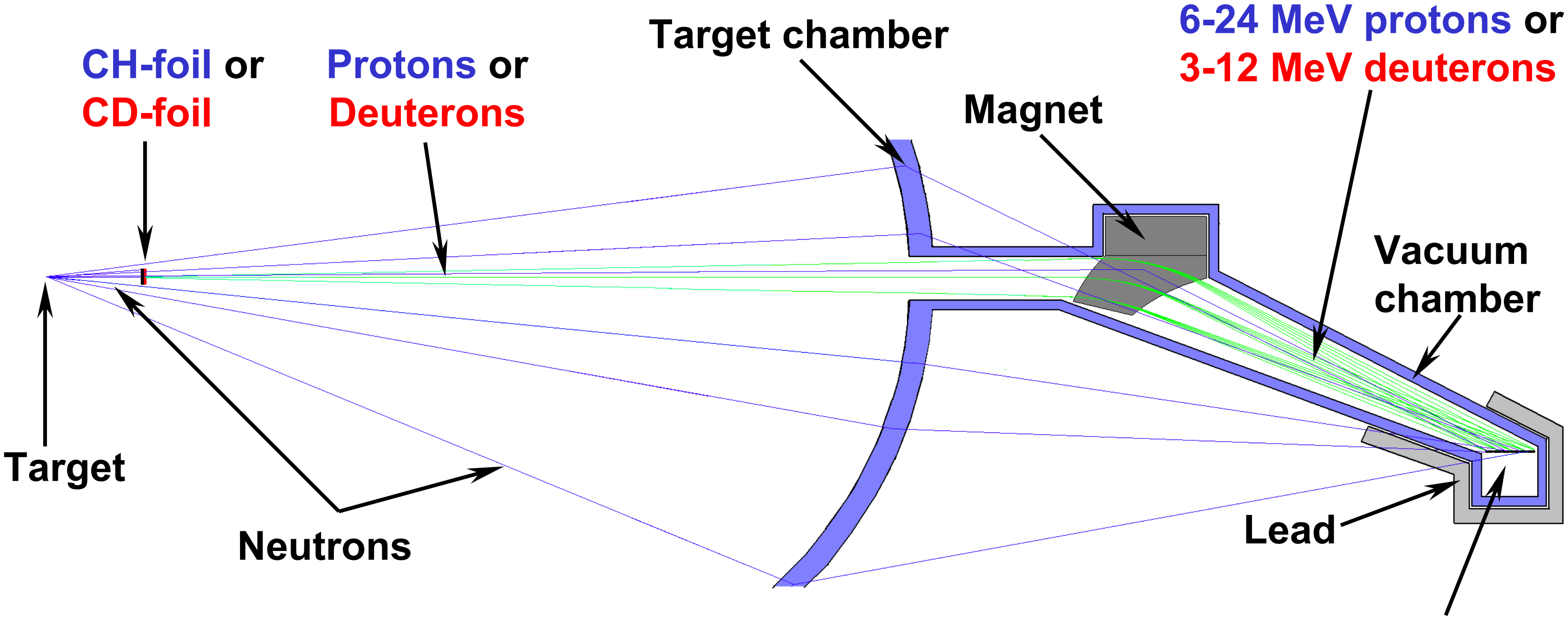
$Y_{1n} = 2\times10^{14}$

$Y_{2n} = 2\times10^{13}$

Y_{scatt} (7-10 MeV) = 1.2×10^{12}

Calculated by Steve Hatchett

MRS principle



CH-foil or
CD-foil

Protons or
Deuterons

Target chamber

Magnet

6-24 MeV protons or
3-12 MeV deuterons

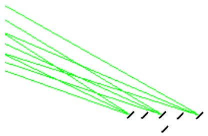
Vacuum
chamber

Target

Neutrons

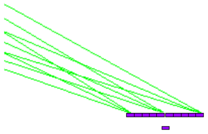
Lead

Coincidence
CR-39



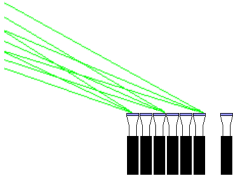
and

CVD-strip
detectors



or

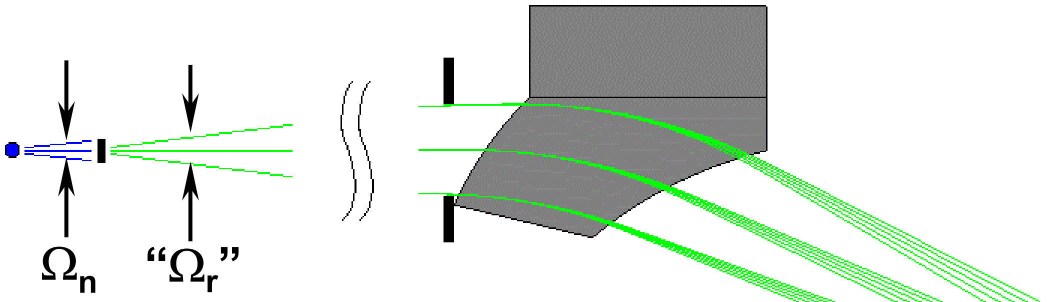
Current-mode
scintillators



MRS principle - Detection efficiency (ε_n)

- The detection efficiency can be expressed as

$$\varepsilon_n \propto \Omega_n \int^{"\Omega_r"} \frac{d\sigma}{d\Omega_{lab}} d\Omega$$



- Maximum differential cross section at forward scattering angles, focusing aspects and large aperture significantly enhances ε_n.

MRS principle - Resolution (ΔE_I)

- Resolution (ΔE_I) of the spectrometer is defined as the energy distribution at the focal plane when viewing a fluence of mono-energetic neutrons. The resolution can be written as

$$\Delta E_I \approx \sqrt{\Delta E_f^2 + \Delta E_k^2 + \Delta E_s^2}$$

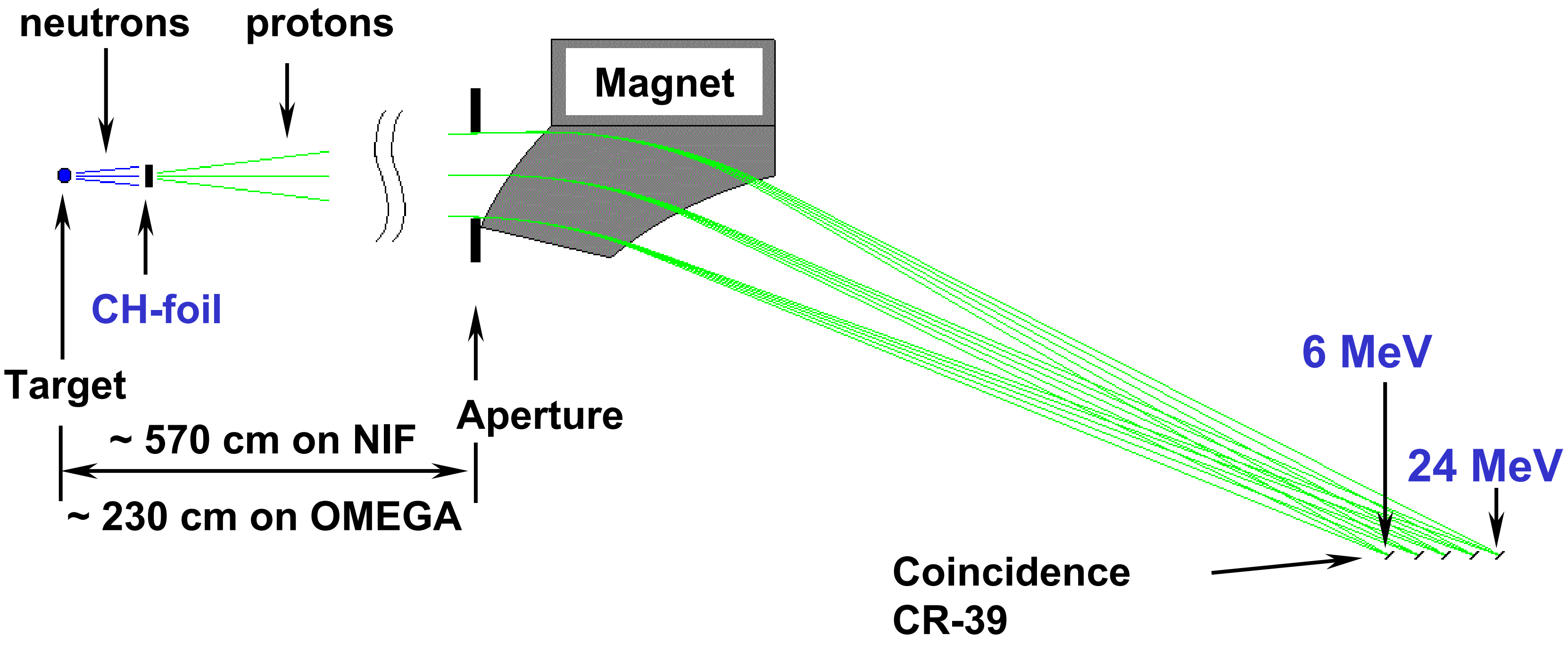
ΔE_f = Energy loss in foil $\propto$ foil thickness

ΔE_k = Kinematic energy broadening $\propto$ foil and aperture size

ΔE_s = Ion optical energy broadening $\propto$ magnet performance

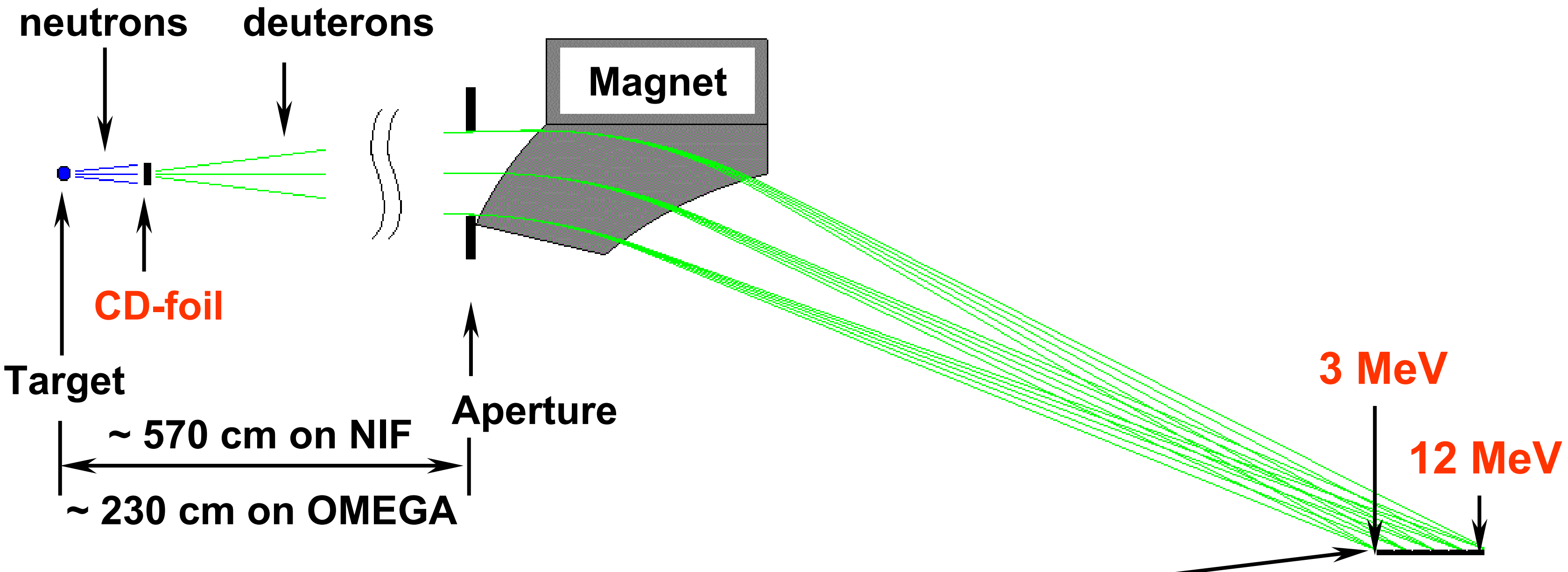
Design philosophy

Initial and potentially the final implementation (ρR_{fuel} and T_i)



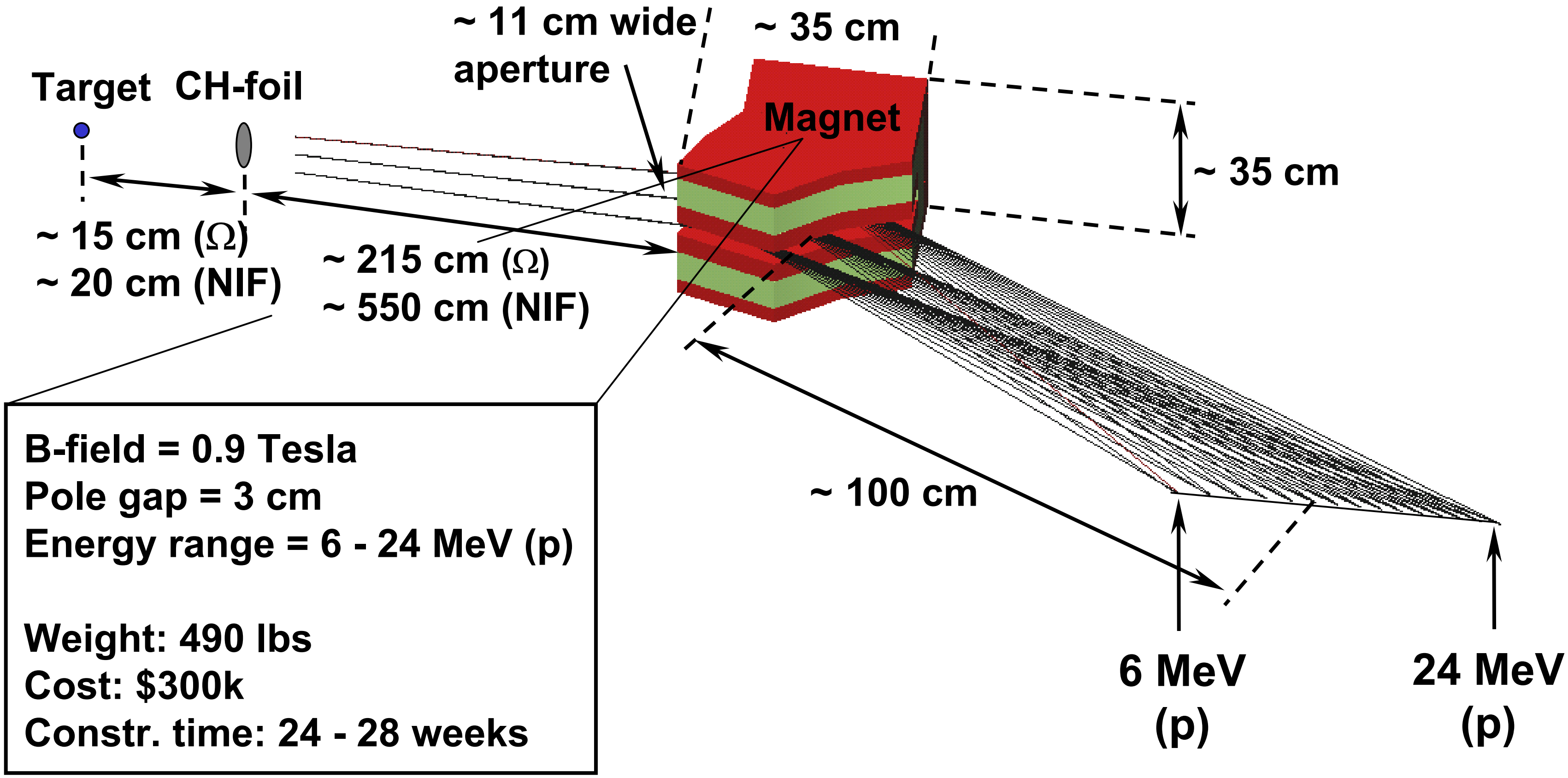
Design philosophy

Potential upgrade
(ρR_{fuel})



1. Coincidence CR-39
2. CVD detectors or Current-mode scintillators

Design of the MRS at OMEGA and the NIF



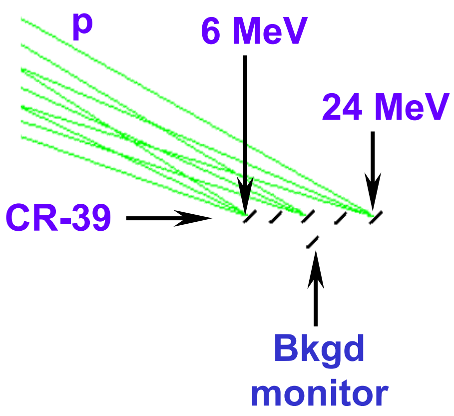
B-field = 0.9 Tesla
Pole gap = 3 cm
Energy range = 6 - 24 MeV (p)

Weight: 490 lbs
Cost: $300k
Constr. time: 24 - 28 weeks

J. A. Frenje et al., Rev. Sci. Instrum. 72 (2001) 854.

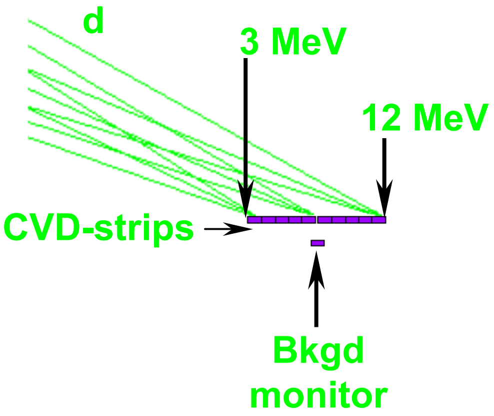
We will develop coincidence CR-39 and one of two electronic detector systems

Coincidence CR-39



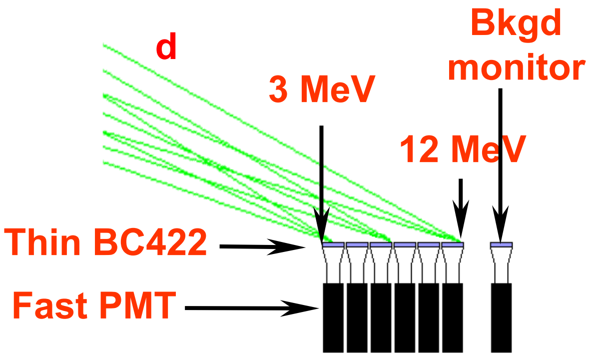
p
6 MeV
24 MeV
CR-39
Bkgd monitor

CVD-strip detectors



d
3 MeV
12 MeV
CVD-strips
Bkgd monitor

Current-mode scintillators



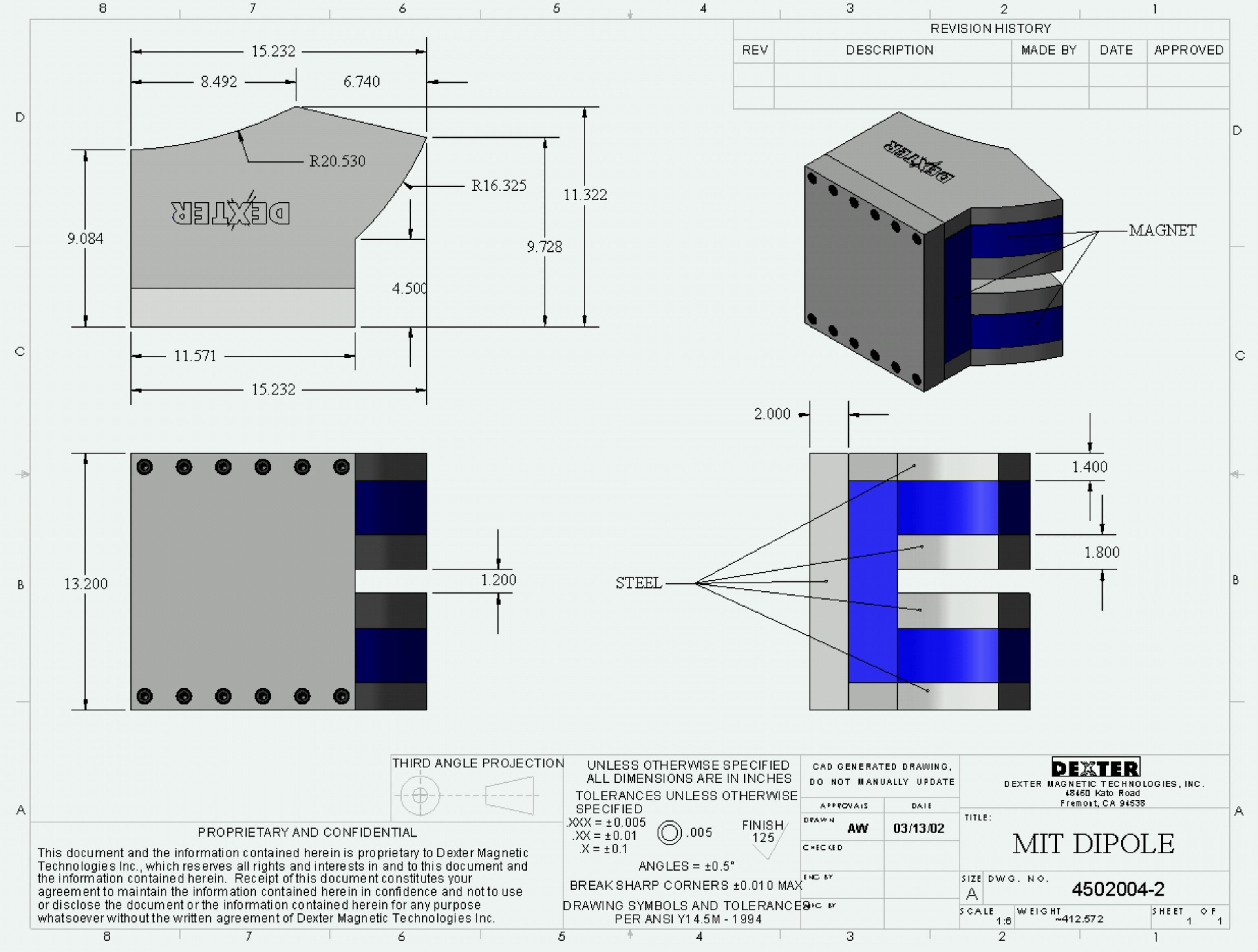
d
3 MeV
12 MeV
Bkgd monitor
Thin BC422
Fast PMT

We will develop coincidence CR-39 and one of two electronic detector systems

Detector	Advantages	Disadvantages
Coincidence CR-39**	Totally insensitive to EMP, X-rays & γ-rays Shielding not required Robust technology	9-12 hour turn around
CVD-strip detector	Large dynamic range Fast Insensitive to γ’s Radiation hardened	Sensitive to EMP
Current-mode scintillator	Fast Well-known technology	Sensitive to γ’ Sensitive to EMP

** At Vulcan, only CR-39, radiochromic film, and film can be reliably used.

MRS-conceptual design



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.XX = ±0.01
.X = ±0.1
.005
FINISH 125
ANGLES = ±0.5°
BREAK SHARP CORNERS ±0.010 MAX
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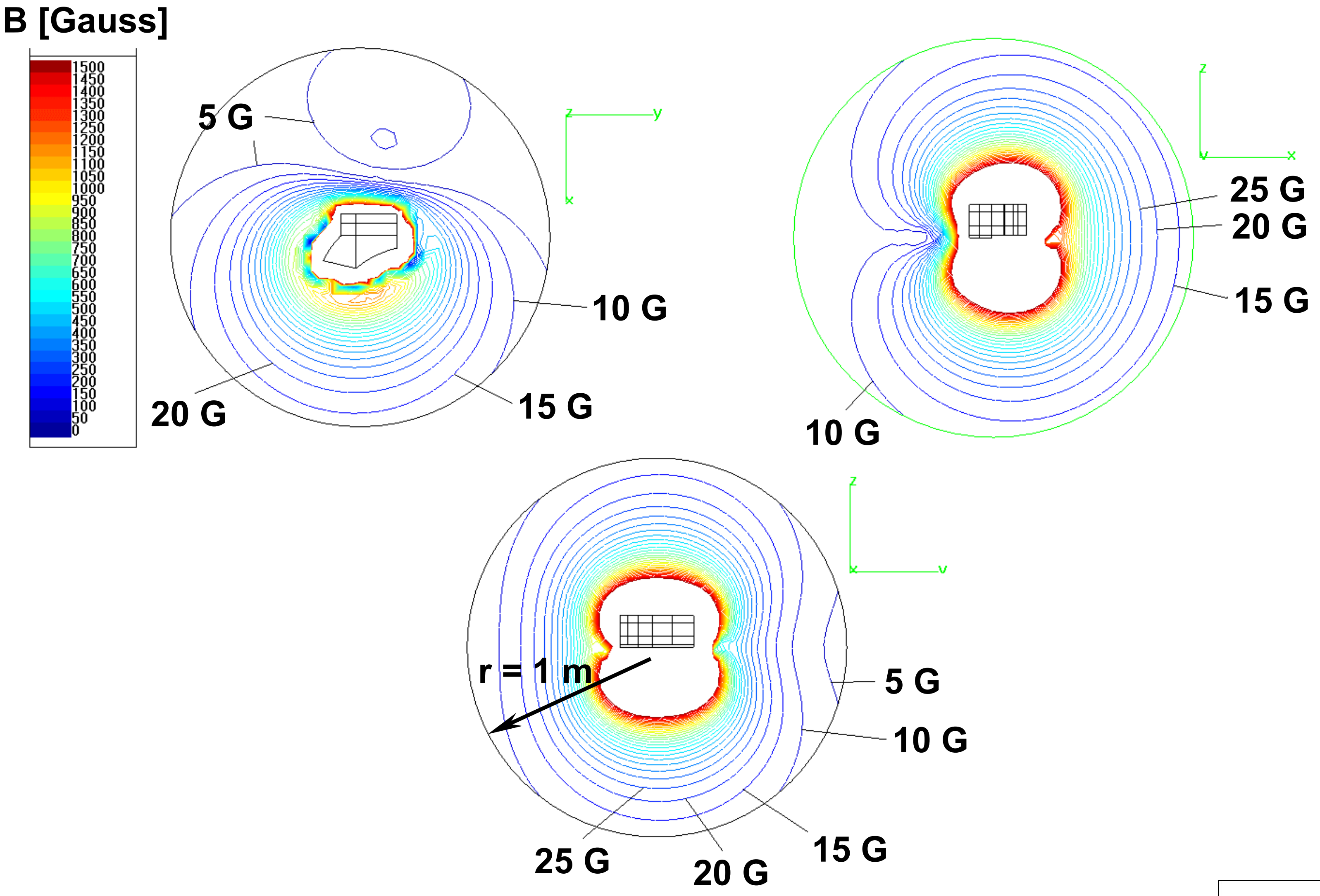
SHEET 1 OF 1

External B-fields from MRS are negligible

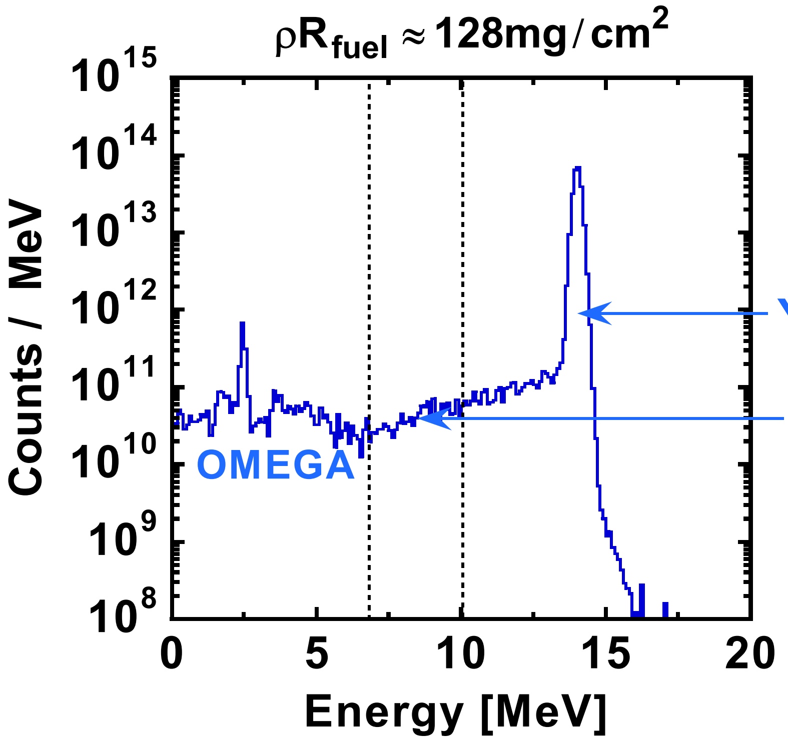


Performance of MRS at OMEGA and the NIF

Facility	Type of measurement	Foil	ε_n	ΔE_l [keV]
OMEGA	ρR_{fuel} & T_i	CH	5×10^{-10}	250
"	ρR_{fuel} & T_i	"	6×10^{-9}	3000
"	ρR_{fuel}	CD	8×10^{-10}	250
"	ρR_{fuel}	"	1×10^{-8}	3000

At the NIF, ε_n is about one order of magnitude smaller for the same ΔE_l.

Predicted signal (S) for ρR_{fuel} measurements of a cryo DT target at OMEGA



Calculated by Steve Hatchett

$Y_{1n} = 2\times10^{13}$

$Y_n = 1.3\times10^{11}$

$\varepsilon_n = 10^{-8}$

$\Rightarrow$ Signal ~ 2600

- How many photons are produced in the thin BC422 scintillator (0.25 mm thick) by these 2600 fully stopped deuterons?

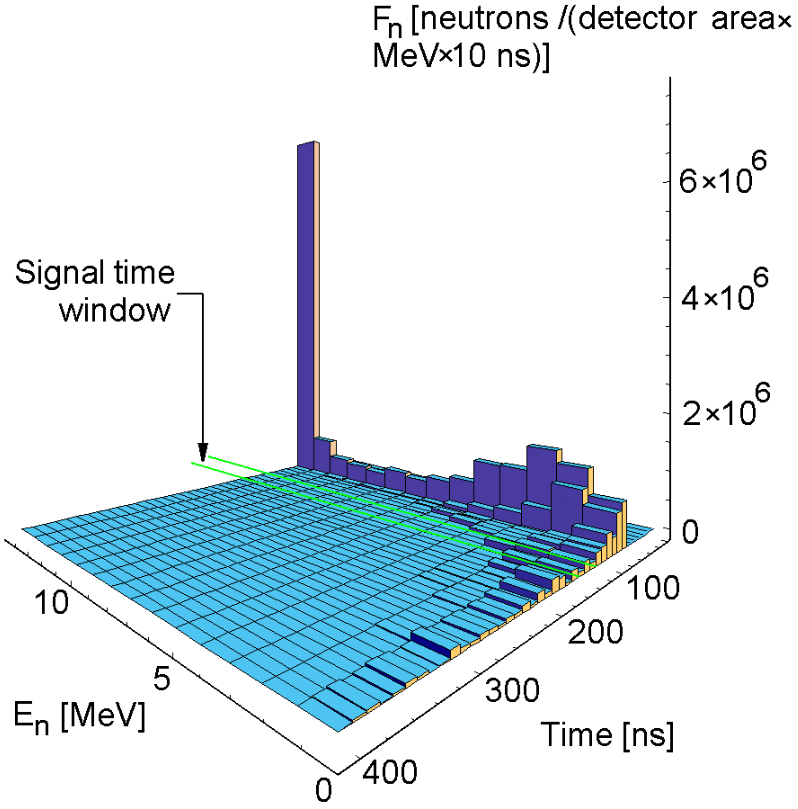
$$S \sim \frac{2600 \times 2\ \mathrm{MeV_{ee}}}{100\ \mathrm{eV/photon}} \sim 5 \times 10^{7}\ \text{photons}$$

Predicted Background (B) for ρR_{fuel} measurements of a cryo DT target at OMEGA

Background (B)

- Neutron transport codes COG and TART2000 were used to predict neutron flux and spectrum at detector.

- About 5×10^5 neutrons (E_n = 0 - 4 MeV) pass the detector in the signal time window (which is about 55 – 81 ns after the primary neutrons hit the detector.



Calculated by Greg Schmid

Predicted S/B ratio for ρR_{fuel} measurements of a cryo DT target on OMEGA

- About 1800 neutrons interact with the scintillator.
- A benchmarked Monte Carlo code predicted total number of produced photons by modeling scintillator geometry and response to the neutrons.

$$B \sim \frac{1800 \times 0.2\ \mathrm{MeV_{ee}}}{100\ \mathrm{eV/photon}} \sim 3.6\times10^{6}\ \text{photons}$$

$$\Rightarrow \quad \boxed{S/B \sim \frac{5\times10^{7}}{3.6\times10^{6}} \sim 14}$$

$$\boxed{\frac{S}{B} \propto \frac{\rho R_{fuel} \times Y_{1n}}{Y_{1n}} = \rho R_{fuel}}$$

Predicted signal-to-background (S/B) ratio for the different measurements at OMEGA and the NIF

Implosion	ρR_{fuel} [mg/cm^2]	Facility	S/B (CR-39)	S/B (BC422)
Warm DT	~ 30*	OMEGA	~ 14	~ 9
Cryo DT	~ 128	OMEGA	~ 27	~ 14
Warm DT	~ 30*	NIF	~ 6	~ 9
Cryo DT P2-fizzle (9×10^{14})	~ 1500	NIF	~ 112	~ 170
Cryo DT P6-fizzle (9×10^{14})	~ 2000	NIF	~ 113	~ 220
Ignited (9×10^{14})	~ 1850	NIF	~ 79	~ 205
Cryo D_2	~ 1500	NIF	~ 2	~ 200

The remaining detected background can be separately characterized…

- by moving the foil out of the spectrometer line of sight.

- by background monitors beside the focal plane detector.

Accuracy analysis of ρR_{fuel} measurements using the MRS at OMEGA

The <u>relative statistical uncertainty</u> in the number of measured signal events (S), which are generated by down-scattered neutrons, can be expressed as

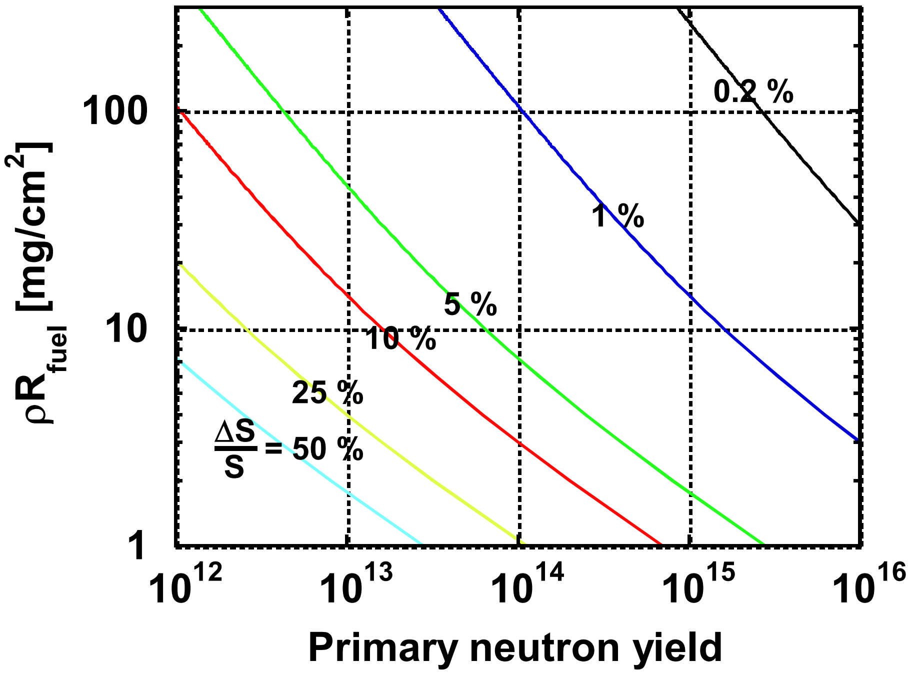
$$\frac{\Delta S}{S} = \sqrt{\frac{\rho R_{fuel} + 6}{10^{-12} \rho R_{fuel}^{2} Y_{1n}}} \qquad (2)^{**}$$

when operating the MRS at ΔE_I=3000 keV. ρR_{fuel} is given in mg/cm^2. Eq. (2) can be rewritten as

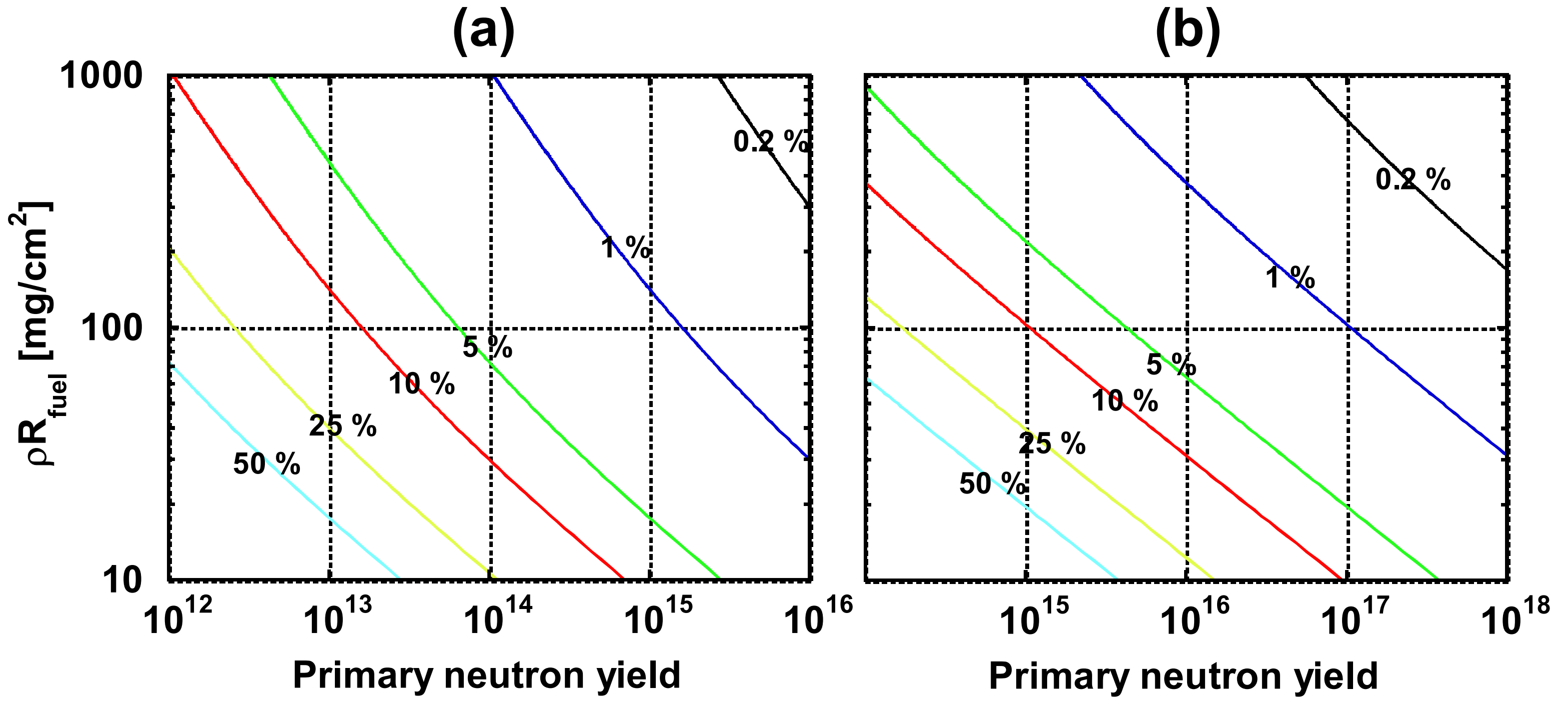
$$\rho R_{fuel} = \frac{1}{2 \times 10^{-12} Y_{1n} \left(\frac{\Delta S}{S}\right)^{2}} + \sqrt{\frac{1}{\left(2 \times 10^{-12} Y_{1n} \left(\frac{\Delta S}{S}\right)^{2}\right)^{2}} + \frac{6}{2 \times 10^{-12} Y_{1n} \left(\frac{\Delta S}{S}\right)^{2}}} \qquad (3)$$

** Eq. (2) assumes that S/B scales linearly with ρR_{fuel}, which is the case for electronic detection.

ρR_{fuel} vs Yield at OMEGA for different $\Delta S/S$ when operating the MRS at ΔE_l = 3000 keV

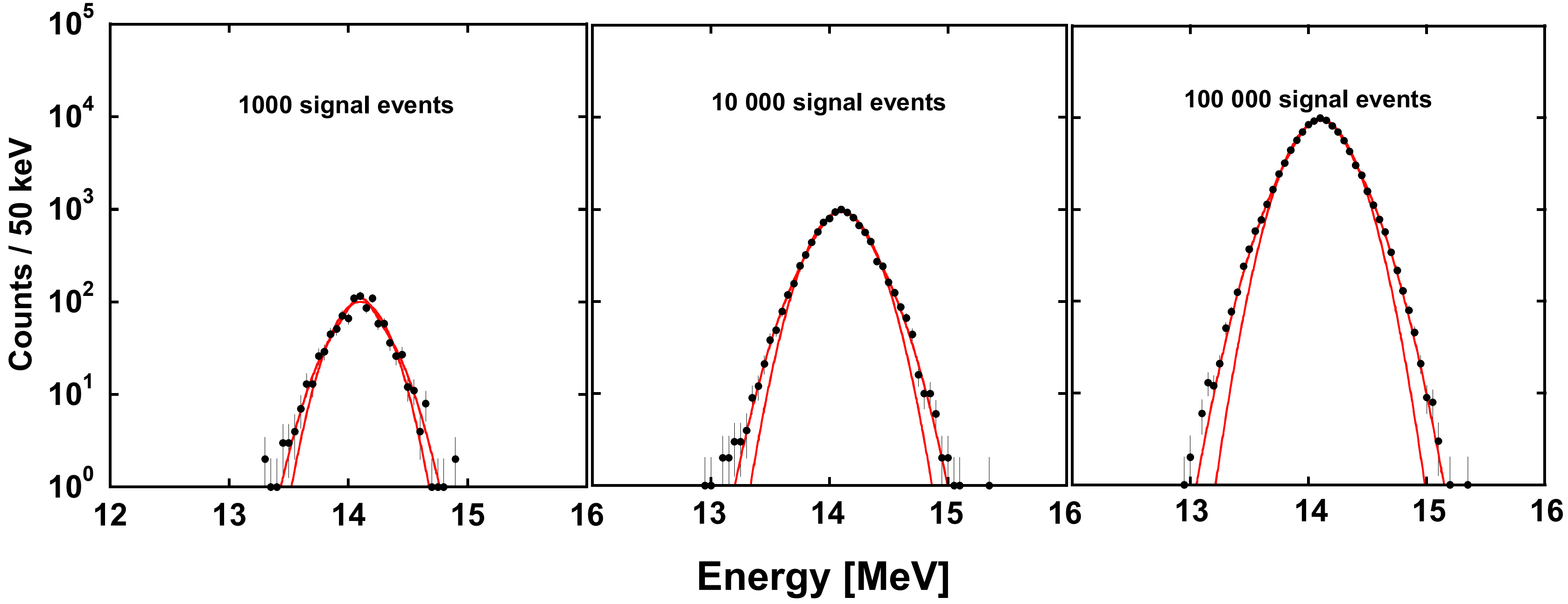


ρR_{fuel} vs Yield at NIF for different ΔS/S when operating the MRS at ΔE_l = 3000 keV (a), and ΔE_l = 250 keV (b)



Using the CH-foil, the MRS can measure deviations from Maxwellian distributions when operated at ΔE_l = 250 keV

A hot spot at 10 keV and surrounding cold plasma at 2 keV was assumed. (A model was used which resulted in comparable yields from the two regions.)



T_i measurement is affected by ΔE_I, ΔE_D and number of counts in spectrum

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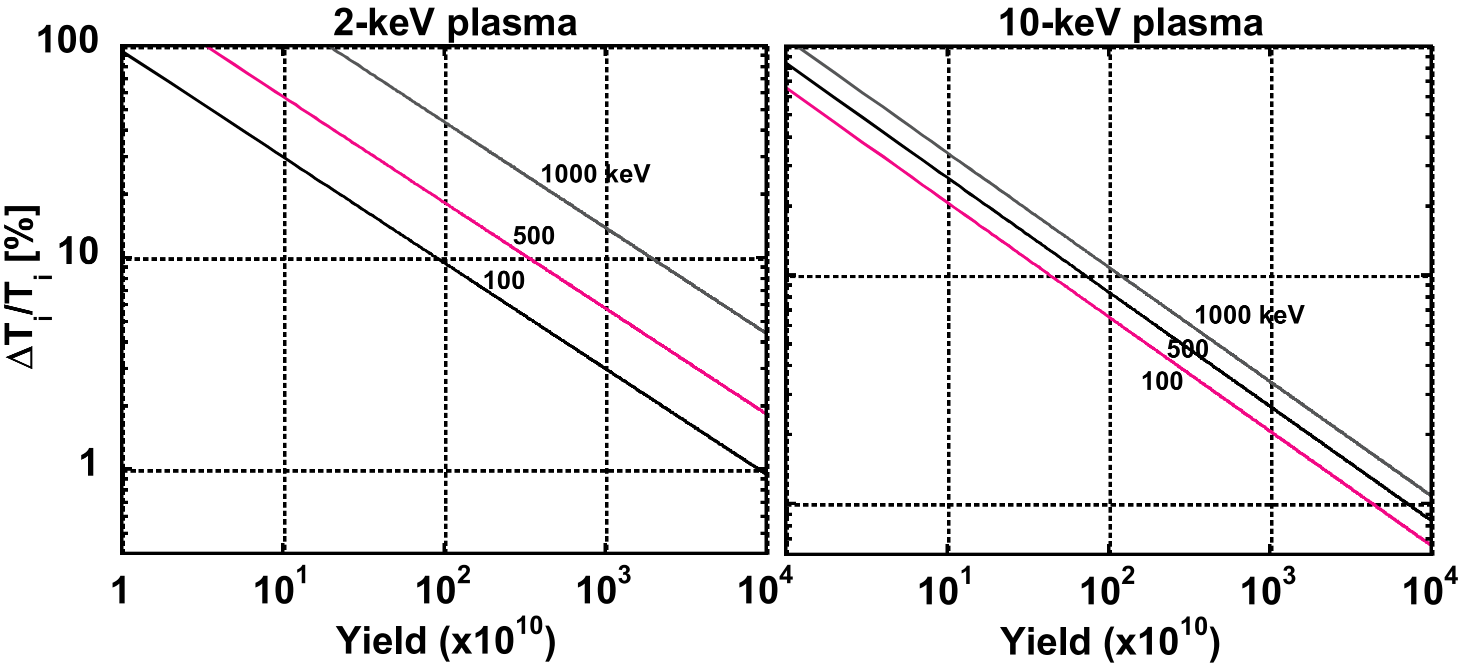
The relative statistical uncertainty in the T_i measurement can be expressed as

$$\frac{\Delta T_i}{T_i} = \left[1 + \left(\frac{\Delta E_I}{\Delta E_D}\right)^2\right]\sqrt{\frac{2}{N}} \qquad (1)\ ^{**}$$

ΔE_I is the instrumental response function, ΔE_D is the Doppler broadening, and N is the number of counts in the spectrum.

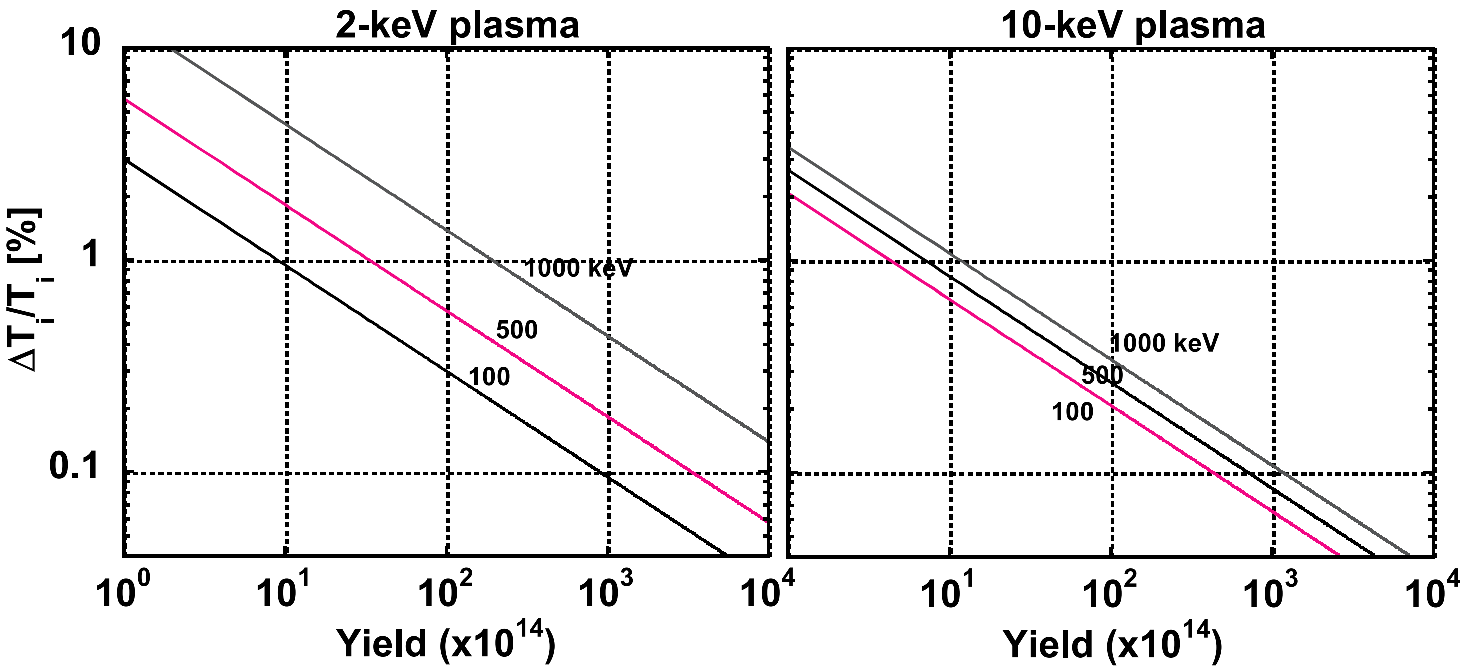
** Eq. (1) assumes that the spectrometer response function is characterized very well, ie, $\Delta(\Delta E_I) = 0$. The equation also assumes that background is negligibly small.

$\Delta T_i/T_i$ vs Yield at OMEGA for different ΔE_I



$$\frac{\Delta T_i}{T_i} = \left[1 + \left(\frac{\Delta E_I}{\Delta E_D}\right)^2\right] \sqrt{\frac{2}{\underbrace{3.3 \times 10^{-10}\, Yield\, \frac{\Delta E_D}{100\, keV}}_{= N}}}$$

$\Delta T_i/T_i$ vs Yield at the NIF for different ΔE_I



$$\frac{\Delta T_i}{T_i} = \left[1 + \left(\frac{\Delta E_I}{\Delta E_D}\right)^2\right] \underbrace{\sqrt{\frac{2}{3.3 \times 10^{-11} Yield \, \dfrac{\Delta E_D}{100 keV}}}}_{= \mathrm{N}}$$