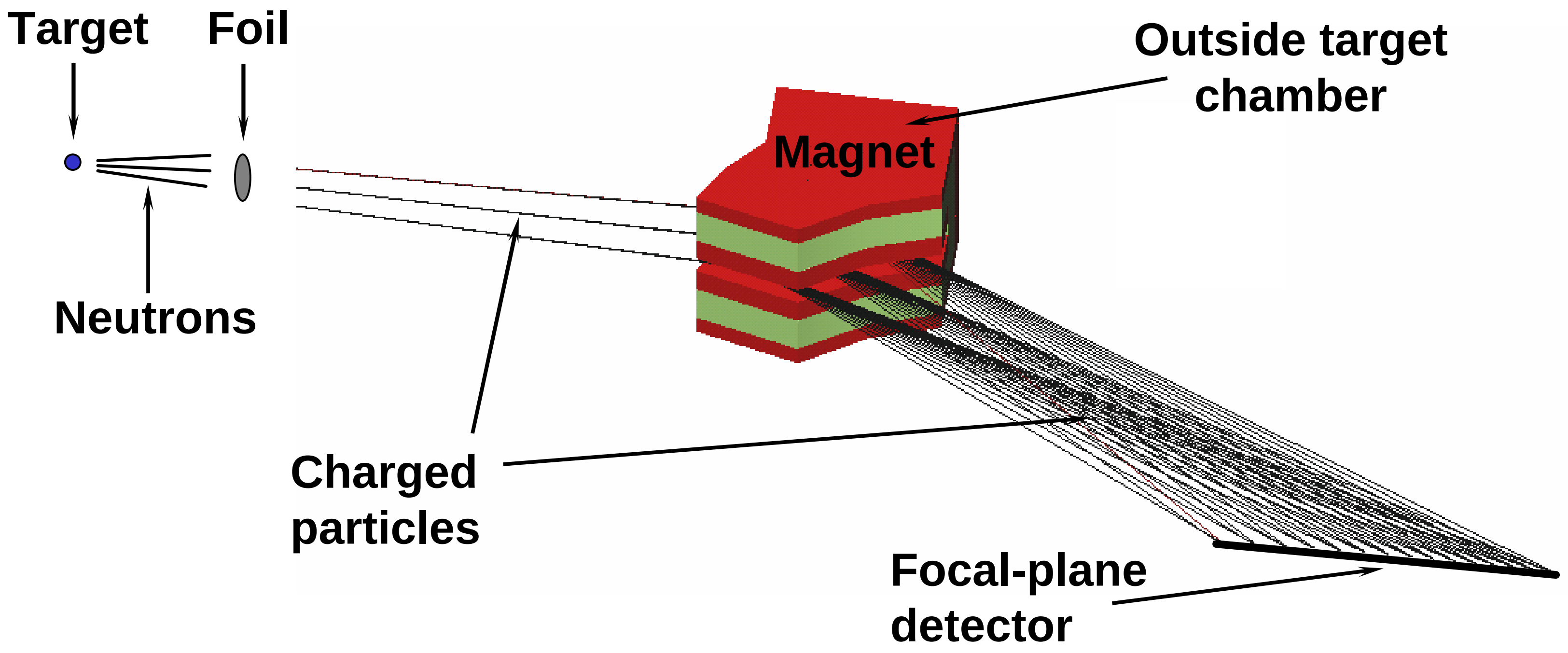
Introduction

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

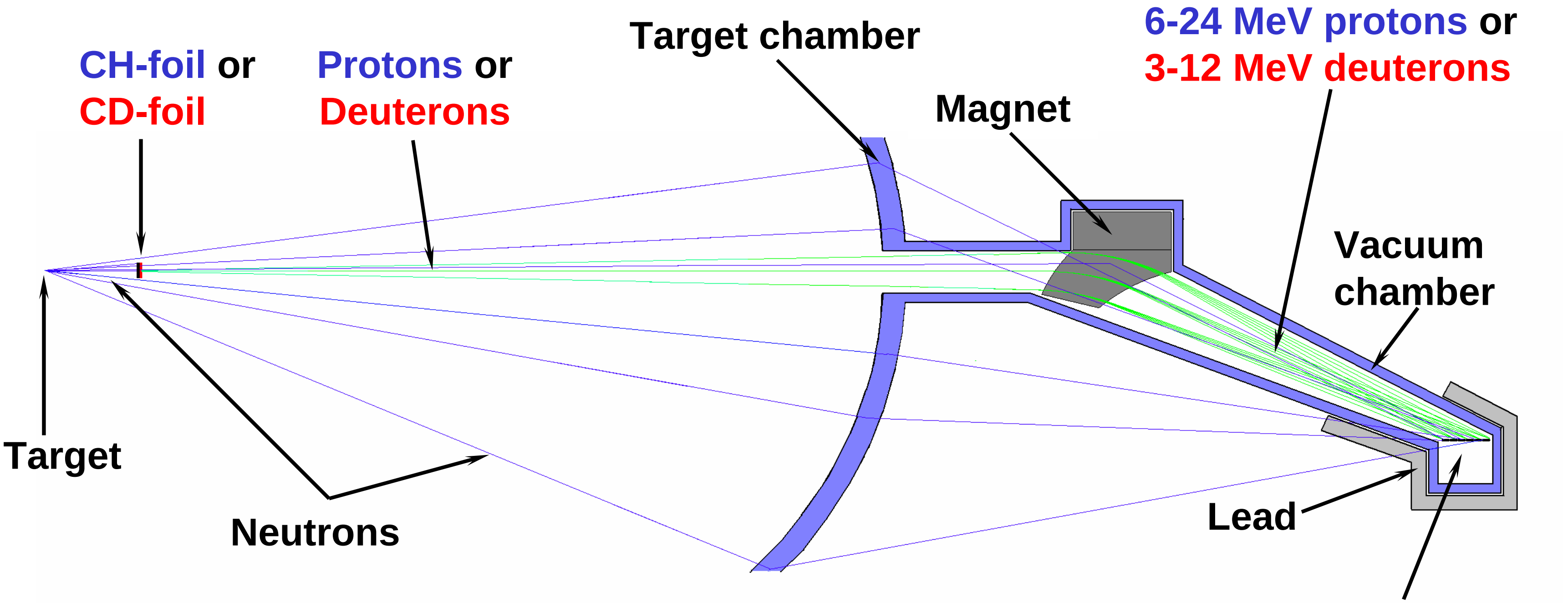
A method to determine ρR_{fuel} of cryogenic deuterium-tritium (DT) plasmas is to measure the energy spectrum and yield of elastically scattered primary neutrons. Minimizing the effect of the background is critical for successful implementation, and to accomplish this, a novel spectrometer for measurements of neutrons has been designed for OMEGA and the NIF. From scattered neutrons in the energy range (7-10 MeV), the ρR_{fuel} will be measured; from primary neutrons, T_i measurements will be performed besides final characterization of the spectrometer. The instrument is based on a magnetic spectrometer with a conversion foil for production of charged particles at nearly forward scattered angles. In its initial, and perhaps final, phase of implementation, a thin CH-foil in combination with CR-39 track detectors positioned in the focal plane of the spectrometer will be used to detect recoil protons, produced by 14.1-MeV primary neutrons, with high spatial resolution. The CR-39, operated in coincidence mode, will facilitate a highly accurate ρR_{fuel} and T_i measurements, and accurate energy calibration of the system. In the later implementation, current mode detectors, such as CVD-strip detectors or scintillators, might be used for detection of deuteron recoils for ρR_{fuel} measurements. The spectrometer has a large dynamic range ($>10^6$), and can operate at yields as low as 10^{12}. This will allow ρR_{fuel} measurements of warm and cryo DT targets at OMEGA, and fizzle and ignited cryo DT targets at the NIF. Using LASNEX and neutron transport calculations, the signal-to-noise (S/N) ratio is estimated to be of the order 100 for measurements of cryo DT targets at OMEGA and the NIF, irrespective detection scheme.

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.
- ρR_{fuel} asymmetries can be potentially measured on NIF.
- Large dynamic range is achievable. ($Y_{1n} \sim 10^{12} – 10^{19}$)
- Flexible instrument: - 2 different types of detectors can be used advantageously.
  - Recoils of either p or d can also be used advantageously.
- Authenticate the data through the primaries.
- A trade off can be made between high resolution and high efficiency, depending on exp.
- Large signal-to-noise ($S/N \sim 100$) ratio for most applications.
- Wide-band spectrometer (6-24 MeV p); (3-12 MeV d).
- High-resolution spectrometer ($\Delta E_l/E = 1.8\%$).
- Accurately measure T_i ($\Delta T_i = \pm 30$ eV).
- Background spectra can be separately characterized.
- The MRS is outside target chamber, which makes mechanical interface straight forward.
- For CR-39 detection, shielding is not required.

MRS principle

MRS principle



CH-foil or
CD-foil

Protons or
Deuterons

Target chamber

Magnet

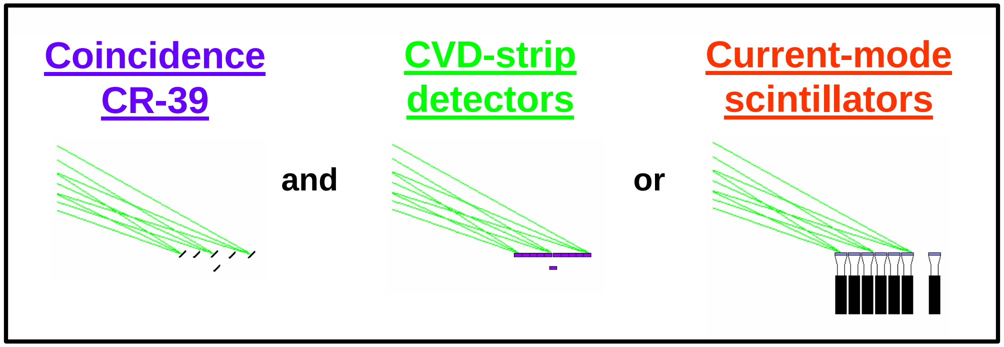
6-24 MeV protons or
3-12 MeV deuterons

Vacuum
chamber

Target

Neutrons

Lead



Coincidence
CR-39

and

CVD-strip
detectors

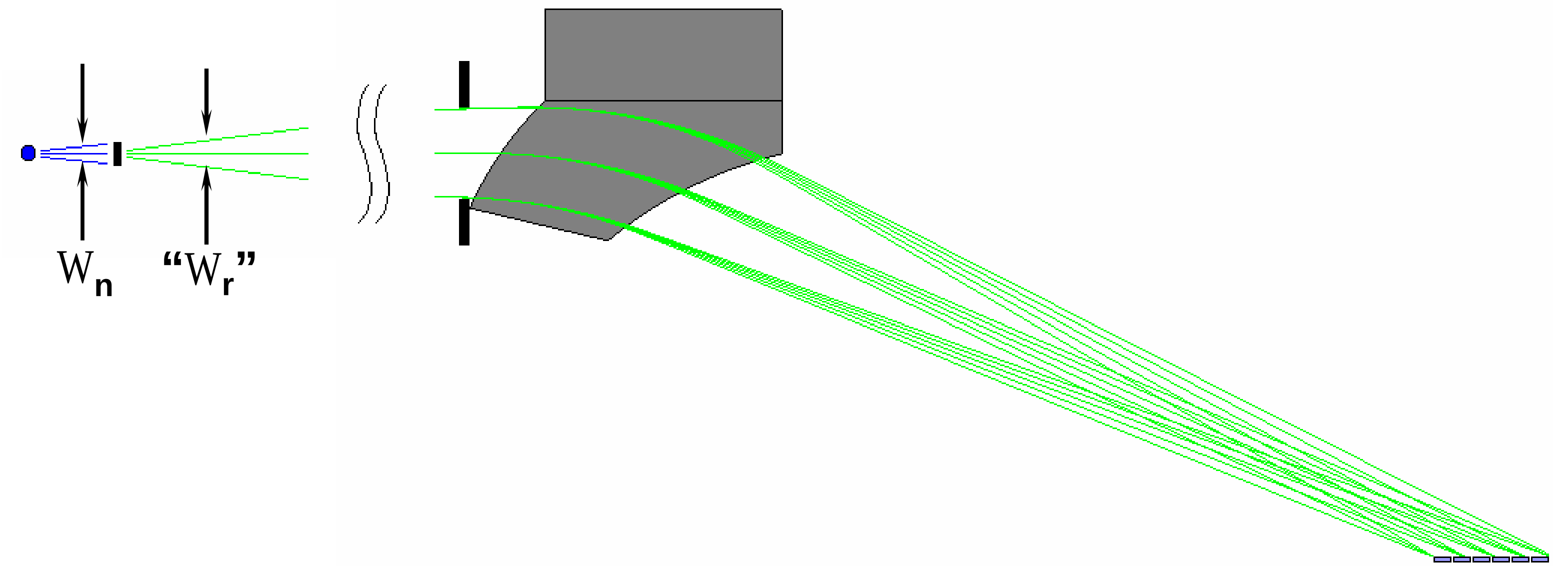
or

Current-mode
scintillators

MRS principle - Detection efficiency (ε_n)

- **The detection efficiency can be expressed as**

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



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

MRS principle - Resolution (DE_l)

- **Resolution (DE_l) 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**

$$\mathrm{D}\mathbf{E_l} » \sqrt{\mathrm{D}\mathbf{E_f^2} + \mathrm{D}\mathbf{E_k^2} + \mathrm{D}\mathbf{E_s^2}}$$

DE_f = **Energy loss in foil** µ **foil thickness**

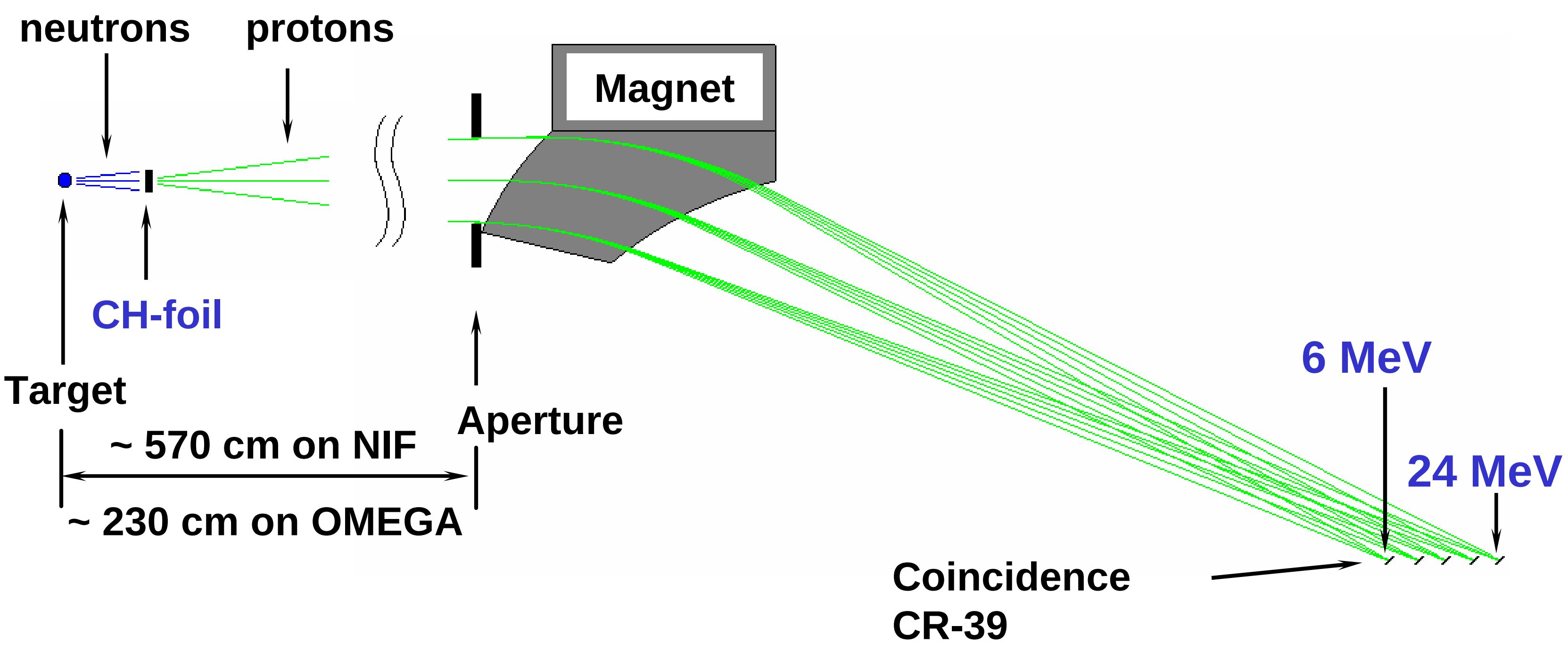
DE_k = **Kinematic energy broadening** µ **foil and aperture size**

DE_s = **Ion optical energy broadening** µ **magnet performance**

MRS design

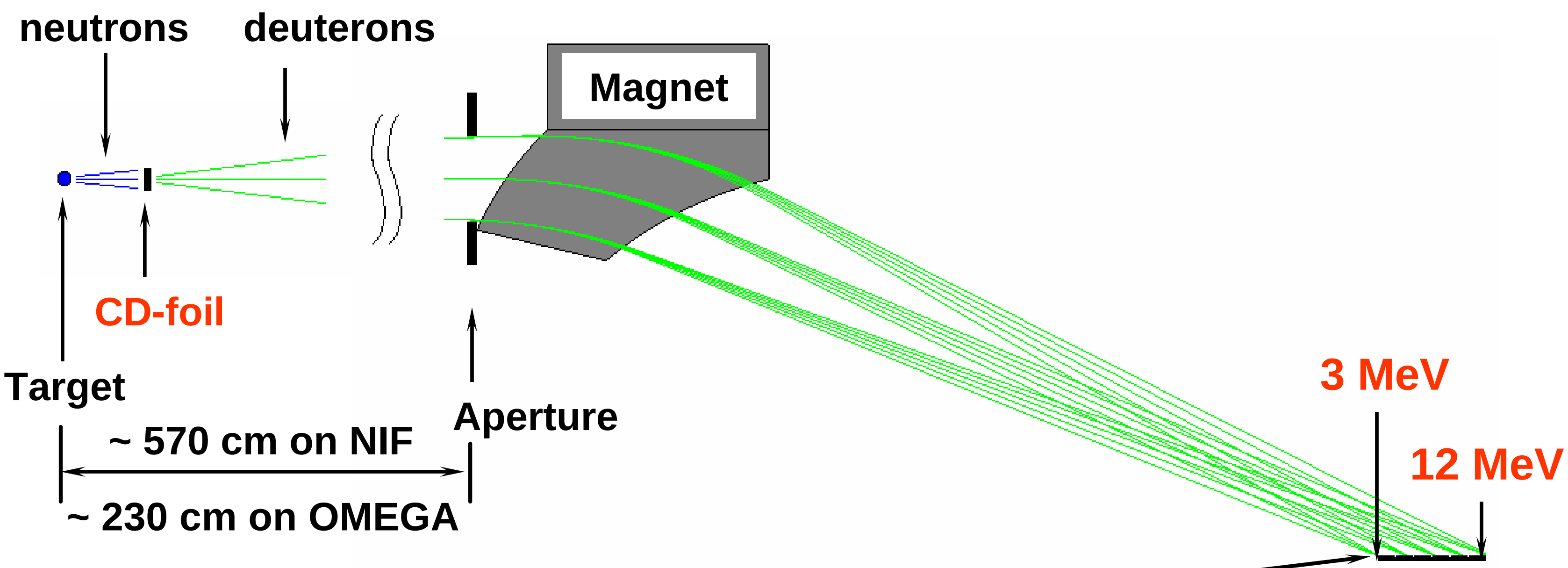
Design philosophy

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



Design philosophy

Potential upgrade
(ρR_{fuel})



neutrons

deuterons

Magnet

CD-foil

Target

Aperture

~ 570 cm on NIF

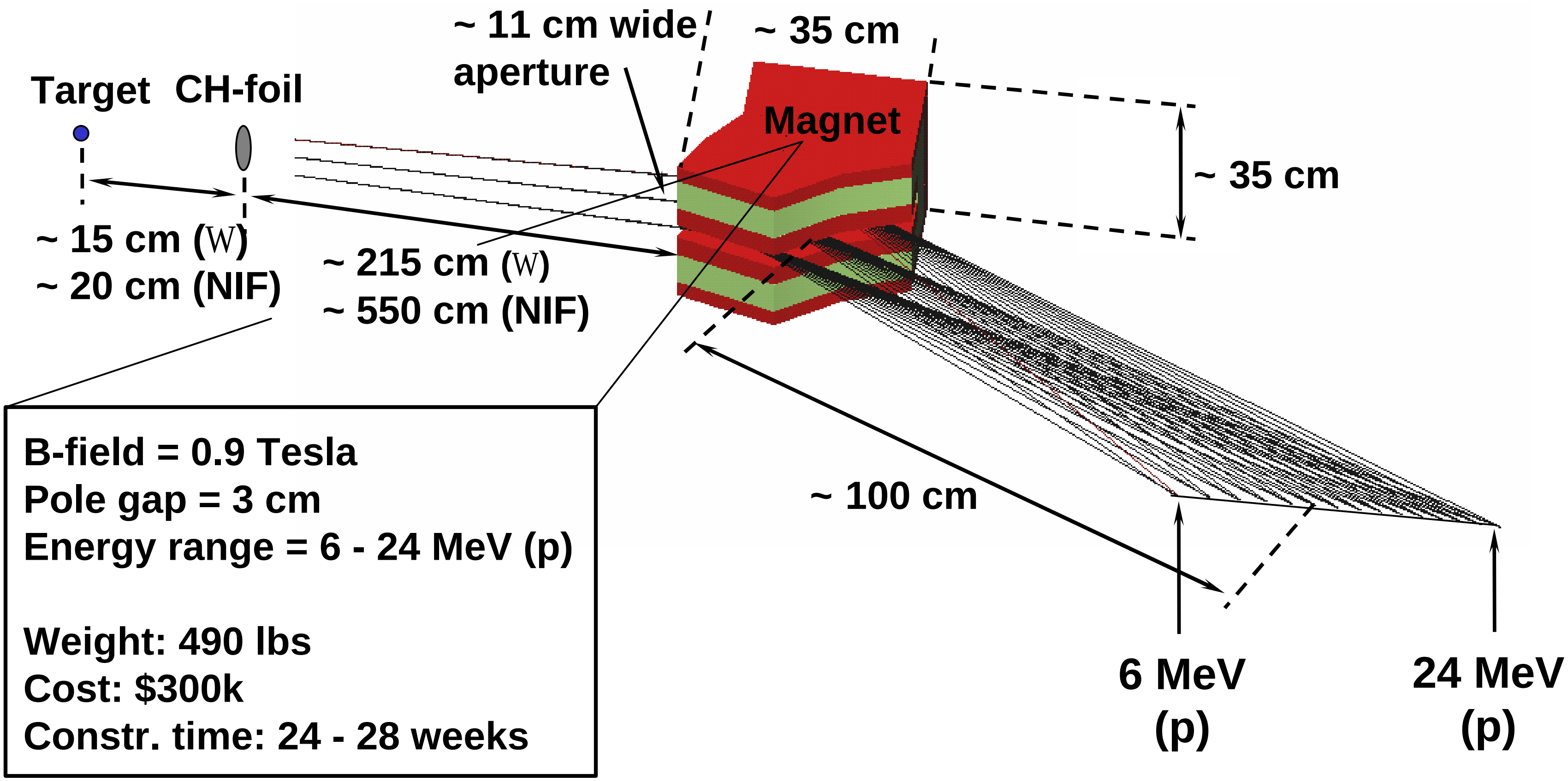
~ 230 cm on OMEGA

3 MeV

12 MeV

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

Design of the MRS at OMEGA and the NIF



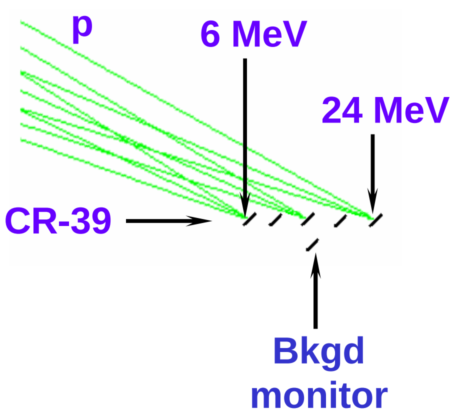
B-field = 0.9 Tesla
Pole gap = 3 cm
Energy range = 6 - 24 MeV (p)

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

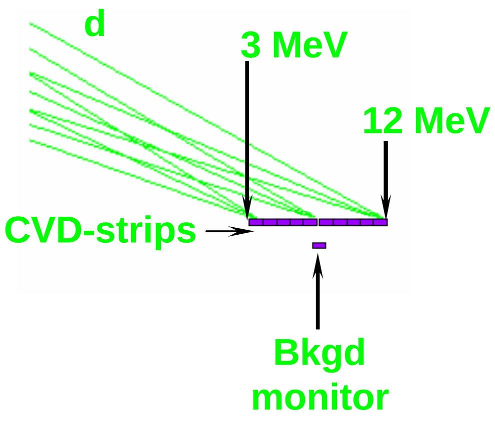
J. A. Frenje et al., Rev. Sci. Instrum. 72 (2001) 854.

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

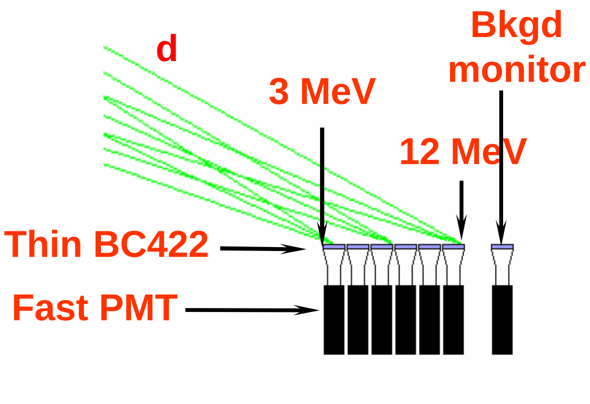
Coincidence CR-39



CVD-strip detectors



Current-mode scintillators



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 & g-rays Shielding not required Robust technology	9-12 hour turn around
CVD-strip detector	Large dynamic range Fast Insensitive to g's Radiation hardened	Sensitive to EMP
Current-mode scintillator	Fast Well-known technology	Sensitive to g' Sensitive to EMP

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

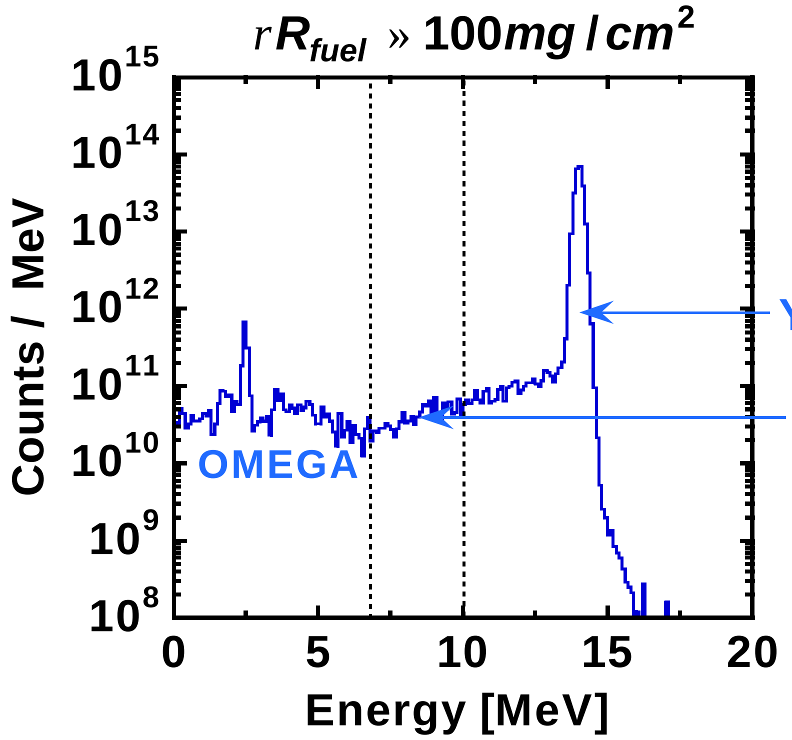
MRS performance

Performance of MRS at OMEGA and the NIF

Facility	Type of measurement	Foil	e_n	DE_l [keV]
OMEGA	rR_{fuel} & T_i	CH	5×10^{-10}	250
“	rR_{fuel} & T_i	“	6×10^{-9}	3000
“	rR_{fuel}	CD	8×10^{-10}	250
“	rR_{fuel}	“	1×10^{-8}	3000

At the NIF, e_n is about one order of magnitude smaller for the same DE_l.

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



$Y_{1n} = 10^{13}$

$Y_n = 10^{11}$

$e_n = 10^{-8}$

Þ Signal ~ 1000

Calculated by Steve Hatchett

- How many photons are produced in the thin BC422 scintillator (0.25 mm thick) by these 1000 fully stopped deuterons?

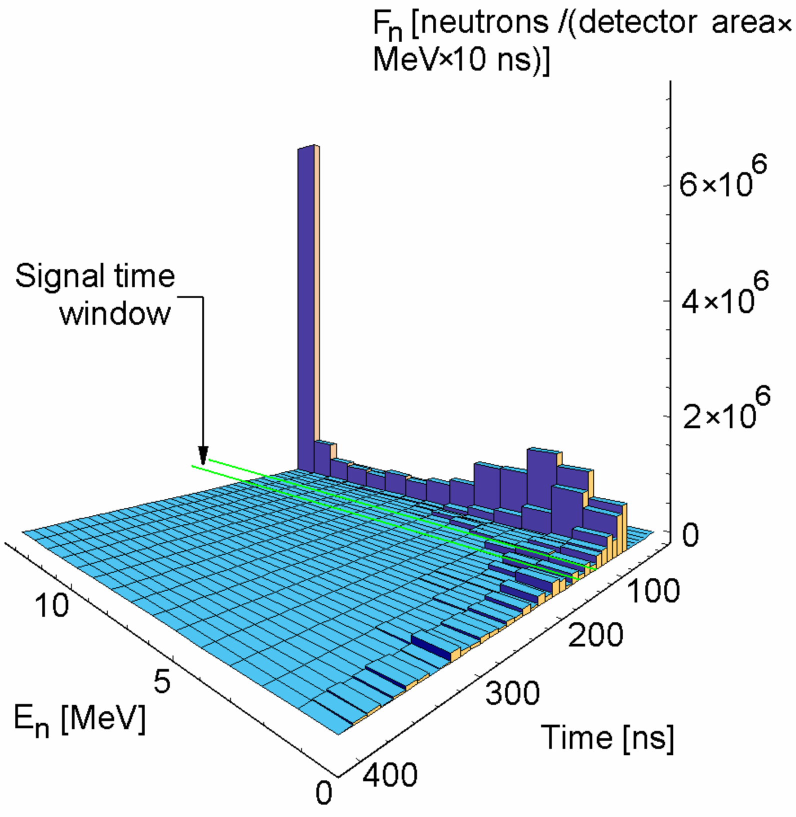
$$S \sim \frac{1000 \times 2\ \mathrm{MeV}_{ee}}{100\ \mathrm{eV/photon}} \sim 2 \times 10^{7}\ \text{photons}$$

Predicted Noise (N) for rR_{fuel} measurements of a cryo DT target at OMEGA

Noise (N)

- **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/N ratio for rR_{fuel} measurements of a cryo DT target on OMEGA

- About 1200 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.

$$N \sim \frac{1200 \times 0.1\ \text{MeV}_{ee}}{100\ \text{eV/photon}} \sim 1\times10^{6}\ \text{photons}$$

$$\text{Þ} \quad \boxed{S/N \sim \frac{2\times10^{7}}{1\times10^{6}} \sim 20}$$

$$\boxed{\frac{S}{N}\ \text{µ}\ \frac{rR_{fuel}\ \text{´}\ Y_{1n}}{Y_{1n}} = rR_{fuel} \quad \text{Þ} \quad \text{At NIF, S/N} \sim 200}$$

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

Implosion	rR_{fuel} [mg/cm^2]	Facility	S/N (CR-39)	S/N (BC422)
Warm DT	~ 10	OMEGA	~ 40	~ 2
Cryo DT	~ 100	OMEGA	~ 400	~ 20
Cryo DT fizzle (9x10^{14})	~ 1000	NIF	~ 160	~ 200
Cryo D_2	~ 1000	NIF	~ 1600	~ 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.

$r R_{fuel}$ measurements

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

The number of measured signal events (S), which are generated by down-scattered neutrons, is linearly proportional to ρR_{fuel}, and the <u>relative statistical uncertainty in S</u> can be expressed as

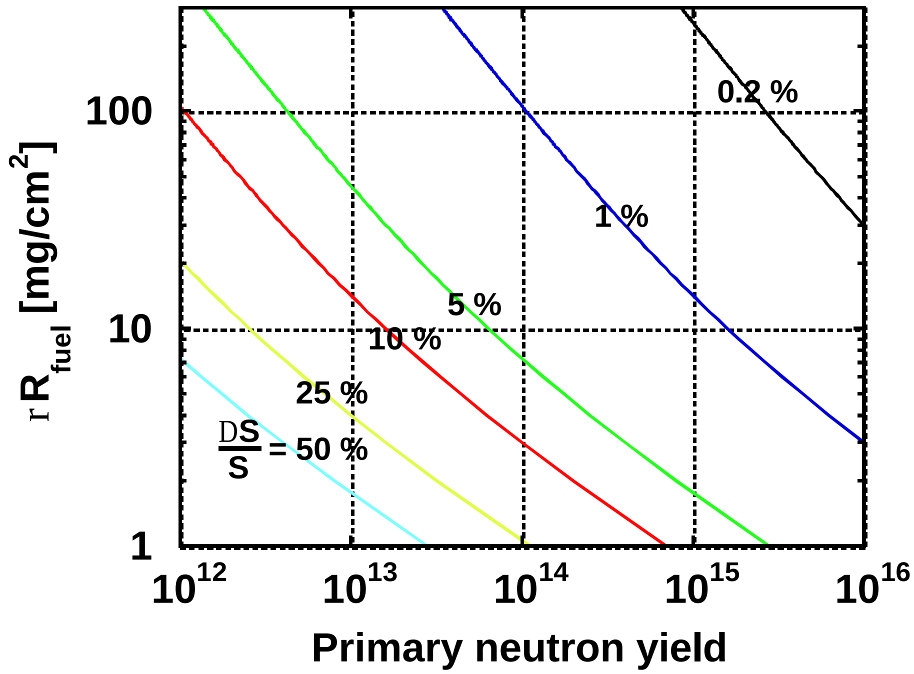
$$\frac{\Delta S}{S} = \sqrt{\frac{\rho R_{fuel} + 6}{10^{-12}\,\rho R_{fuel}^{2}\,Y_{1n}}} \qquad \text{(2)**}$$

when operating the MRS at ΔE_l=3000 keV. ρR_{fuel} is given in mg/cm². Eq. (2) can be rewritten as

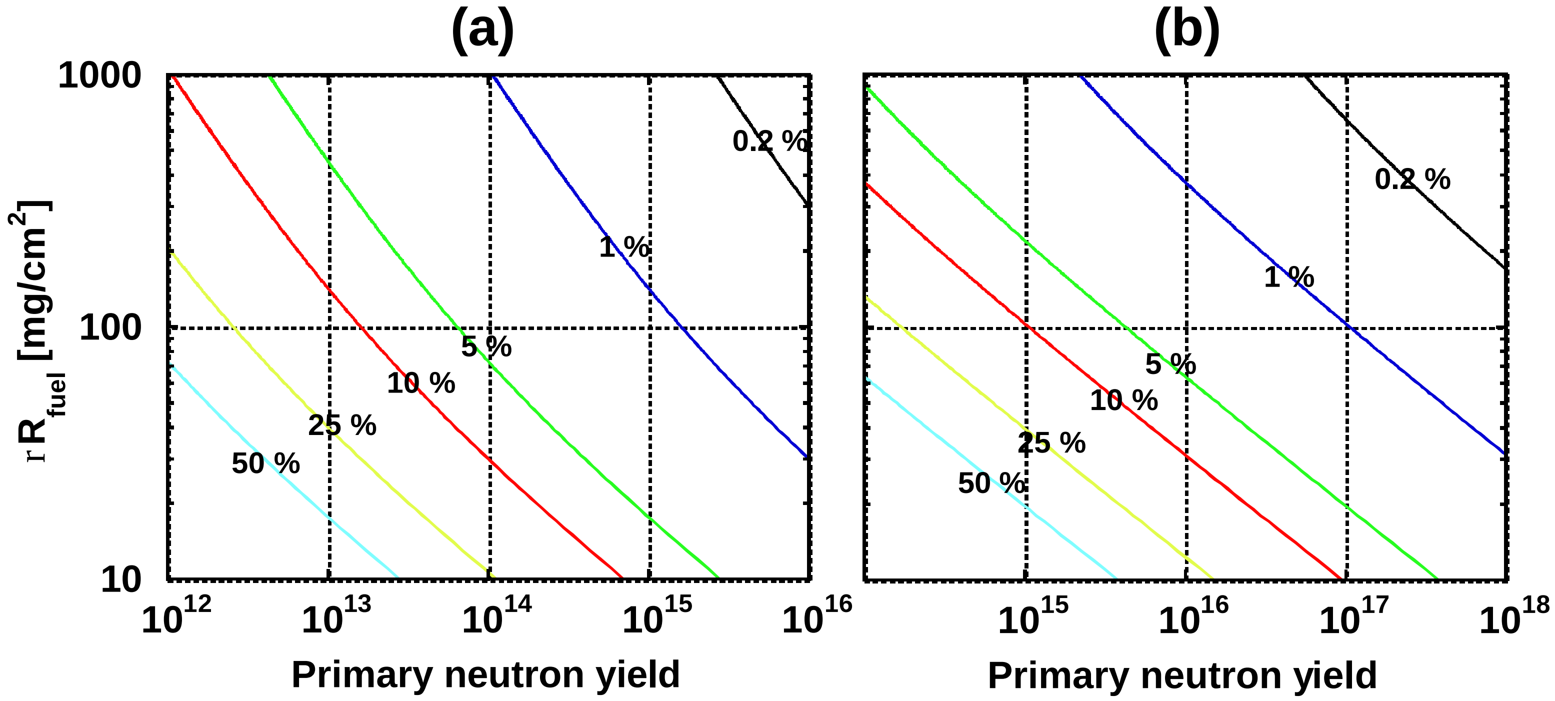
$$\rho R_{fuel} = \frac{1}{2\times 10^{-12}\,Y_{1n}\left(\frac{\Delta S}{S}\right)^{2}} + \sqrt{\left(\frac{1}{2\times 10^{-12}\,Y_{1n}\left(\frac{\Delta S}{S}\right)^{2}}\right)^{2} + \frac{6}{2\times 10^{-12}\,Y_{1n}\left(\frac{\Delta S}{S}\right)^{2}}} \qquad \text{(3)}$$

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

rR_{fuel} vs Yield at OMEGA for different DS/S when operating the MRS at DE_l = 3000 keV



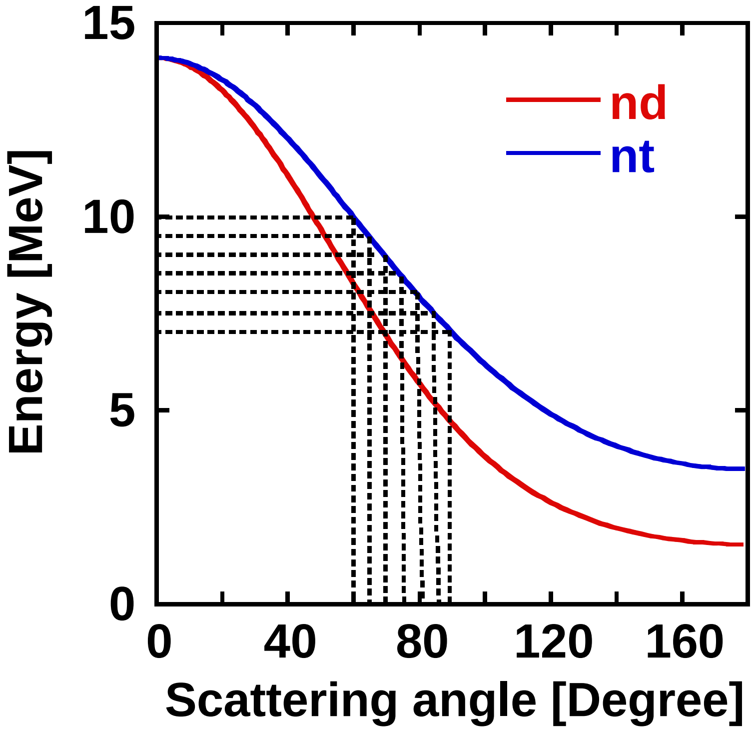
$r R_{fuel}$ vs Yield at NIF for different DS/S when operating the MRS at DE_l = 3000 keV (a), and DE_l = 250 keV (b)

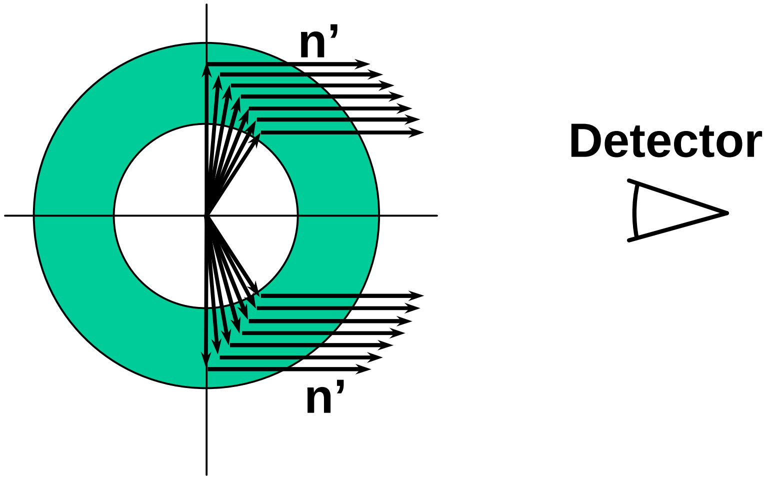


Haan and Hatchett calculations

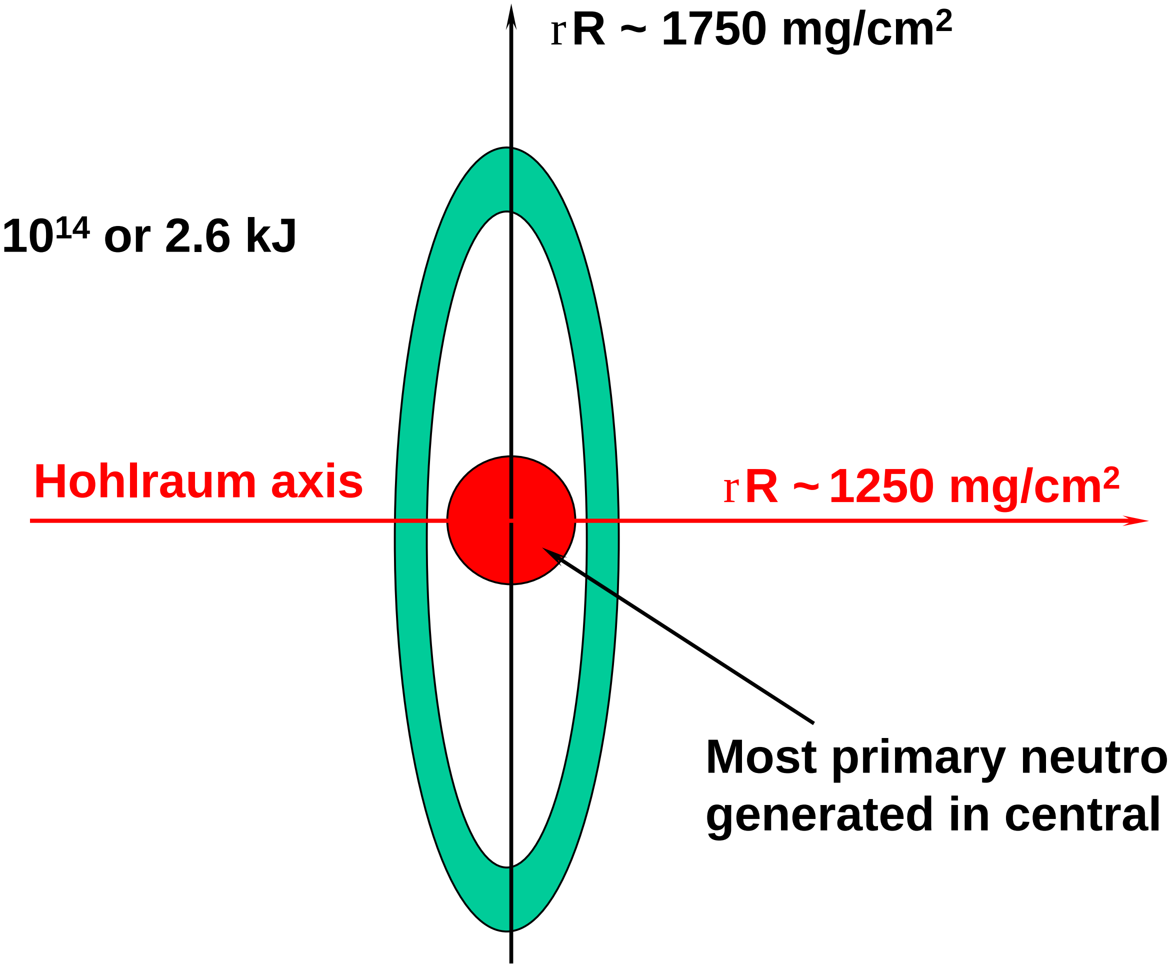
rR_{fuel} asymmetries, at OMEGA and the NIF, could be inferred from yield of down-scattered neutrons in energy range 7-10 MeV

$DE_l = 500$ keV ⇔ $DQ = 5°$





Using down-scattered neutrons, rR asymmetries of a pancaked P_2 Haan fizzle can be measured with MRS



rR ~ 1750 mg/cm^2

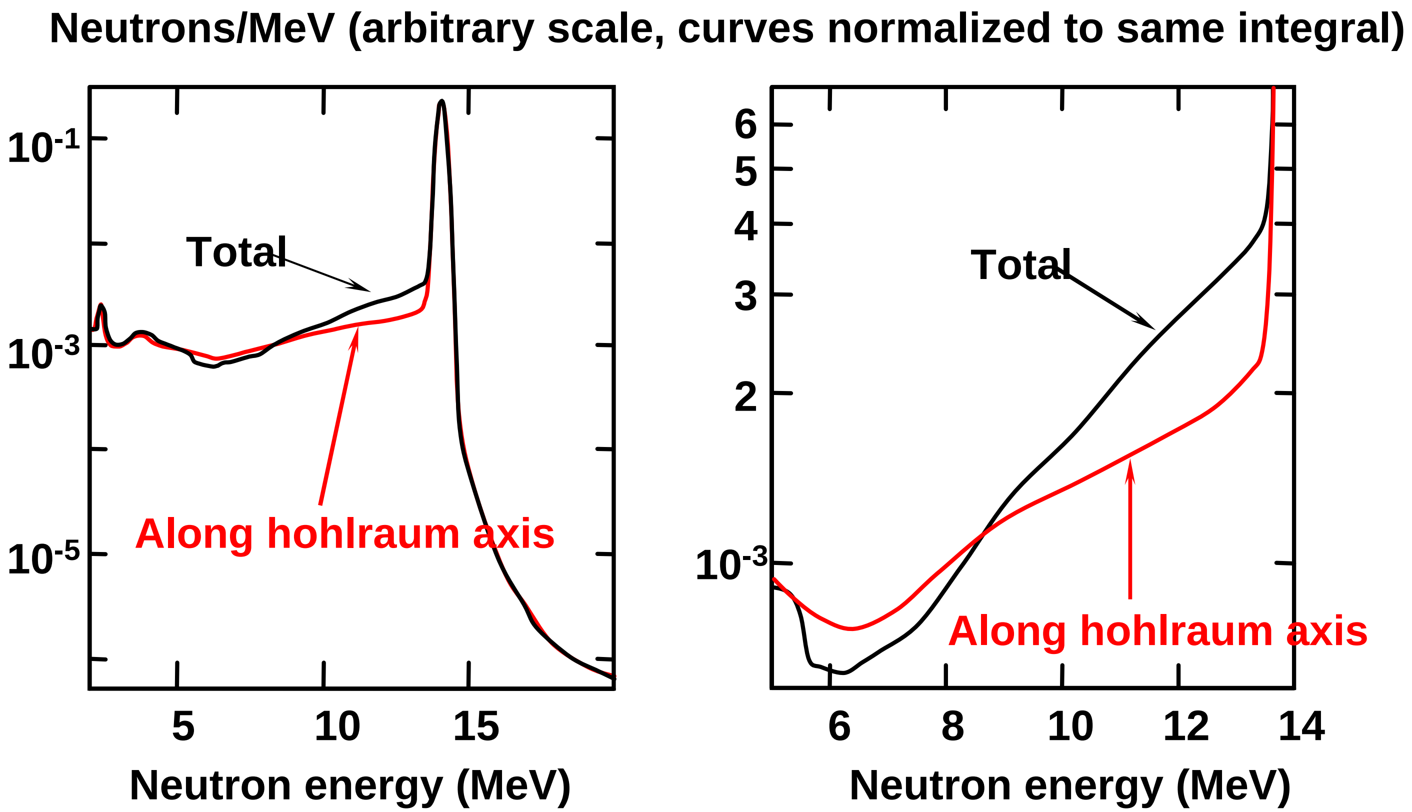
Yield = 9×10^{14} or 2.6 kJ

Hohlraum axis

rR ~ 1250 mg/cm^2

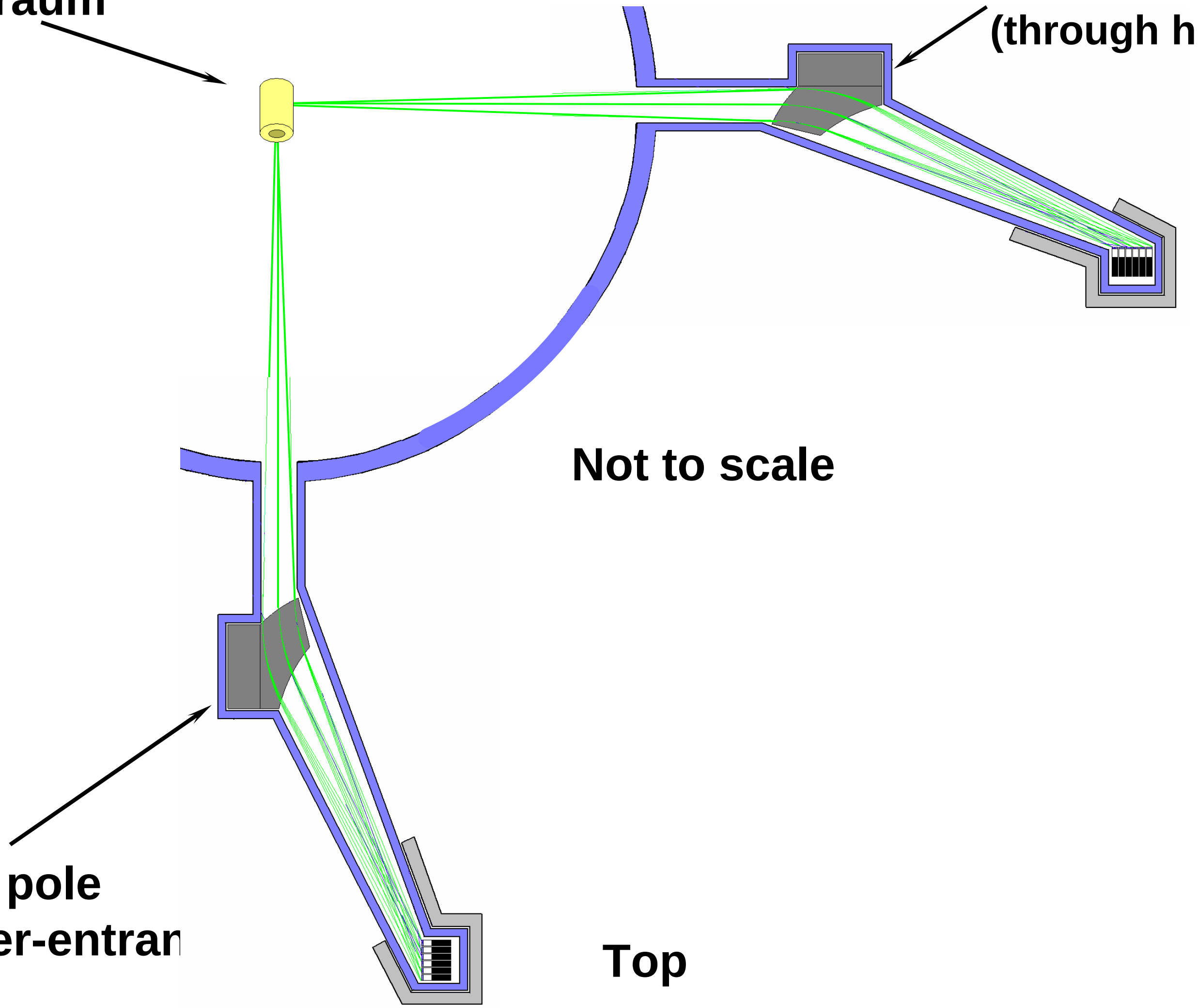
Most primary neutrons are generated in central hot-spot

With the MRS, rR asymmetries can be measured on NIF for this Haan P2 fizzle of 9×10^{14}



9×10^{14} is about a factor 10 larger than is required to measure this rR asymmetry.

Orthogonal MRS would be desirable at the NIF



Hohlraum

MRS view of equator
(through hohlraum wall)

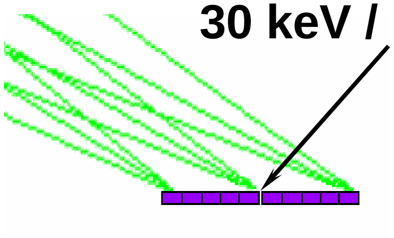
Not to scale

MRS view of pole
(through laser-entran

Top

T_i measurements

T_i can be accurately measured with the MRS: $DT_i = \pm 30$ eV (perfect statistics)



30 keV / mm at 14.1 MeV (p)

Dominant error

<u>Error in detector position relative to magnet:</u>

$Dx = \pm 1$ mm

⇓

$DE = \pm 30$ keV

⇓

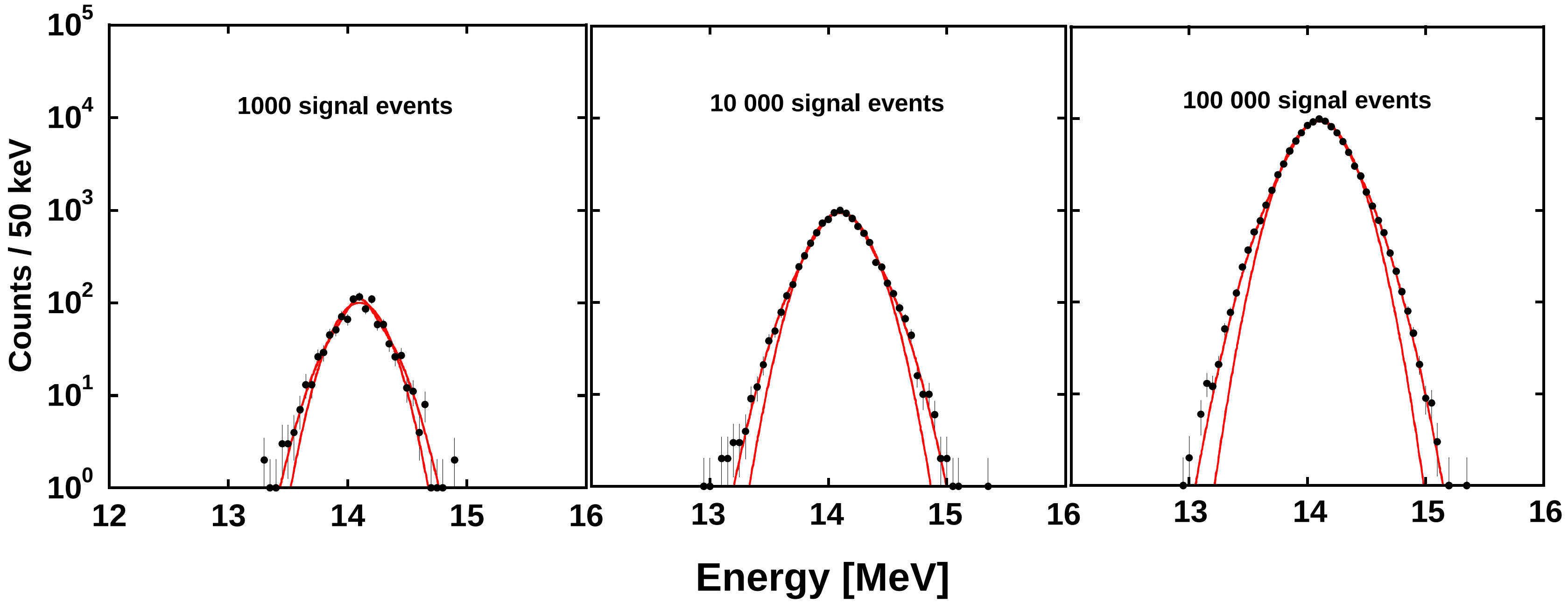
$DE = 177\sqrt{T_i}$

⇓

$DT_i = \pm 30$ eV

Using the CH-foil, the MRS can measure deviations from Maxwellian distributions when operated at DE$_l$ = 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

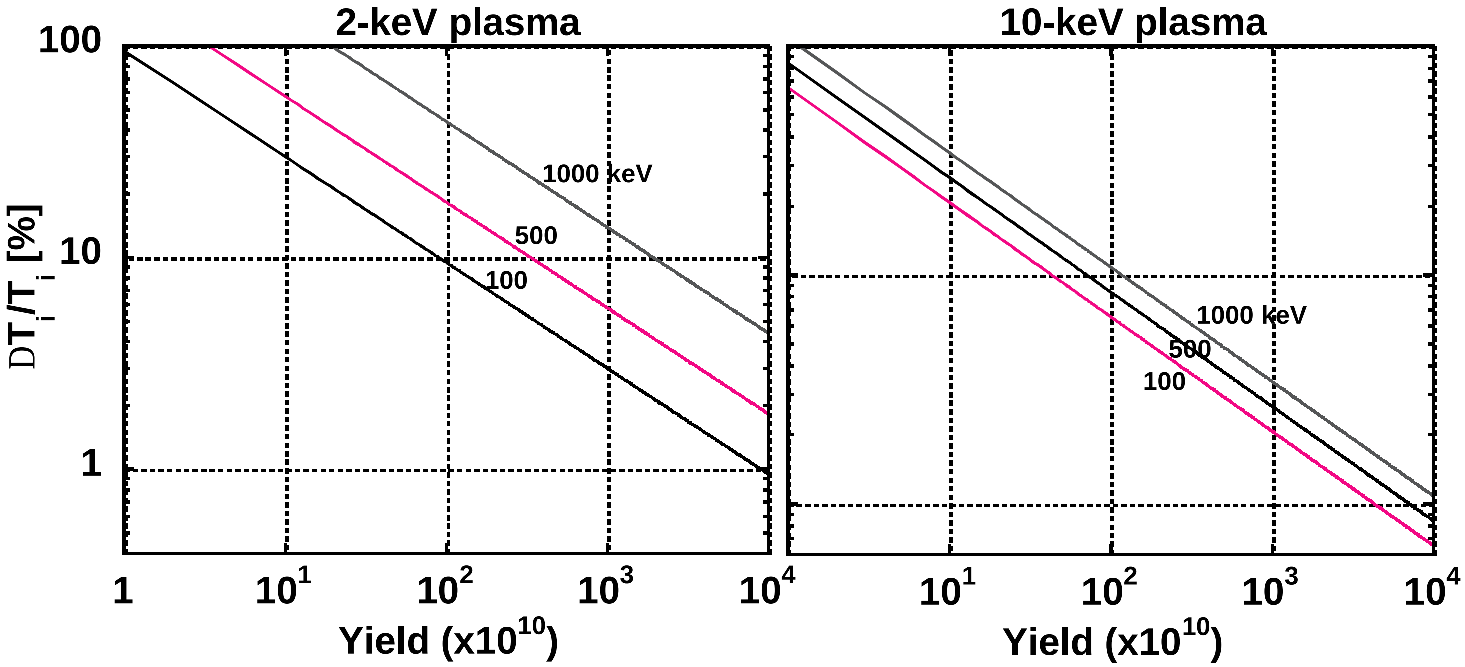
The <u>relative statistical uncertainty in the T_i measurement</u> can be expressed as

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

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

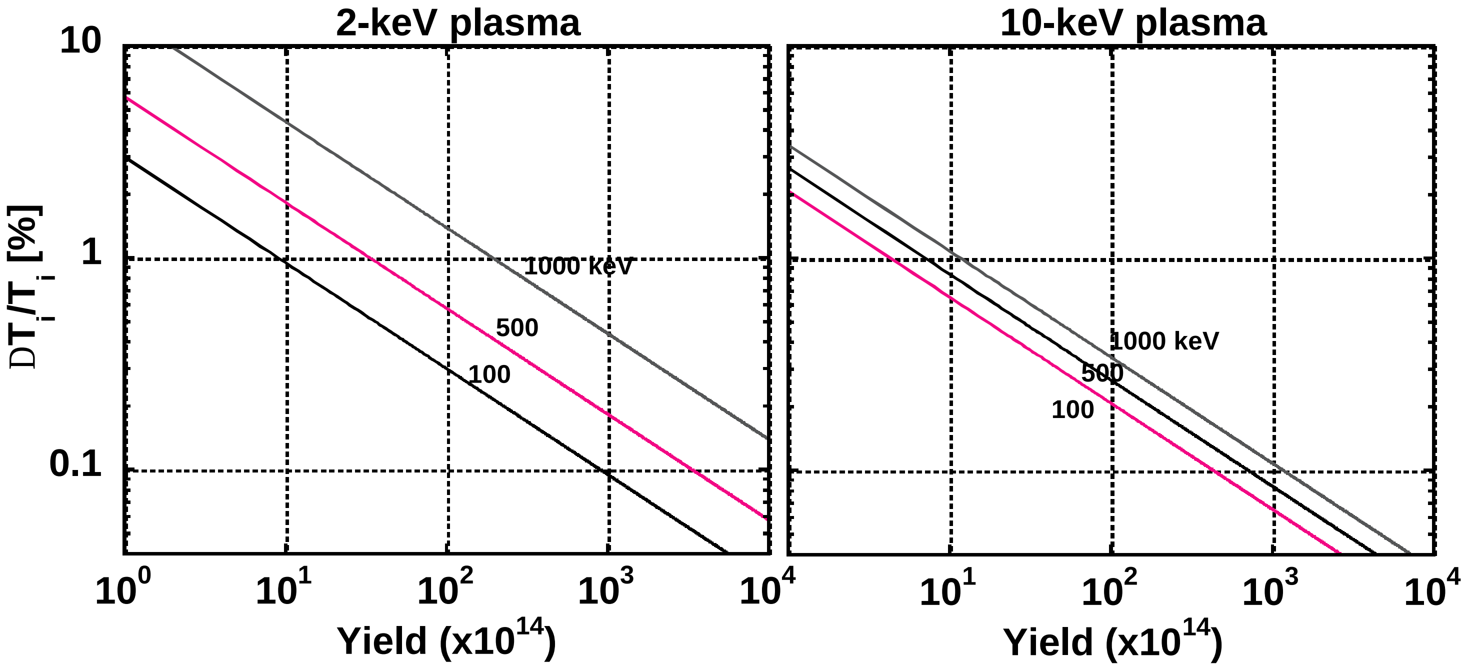
**** Eq. (1) assumes that the point response function is characterized very well, ie, $\Delta(\Delta E_I) = 0$. The equation also assumes that background is negligibly small.**

$\Delta T_i/T_i$ vs Yield at OMEGA for different instrumental point response functions ΔE_I



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

$\Delta T_i/T_i$ vs Yield at the NIF for different instrumental point response functions ΔE_I



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