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

Johan Frenje
MIT - Plasma Science and Fusion Center

33rd Anomalous Absorption Conference
Lake Placid, NY
June 23-27, 2003
R. D. Petrasso*, C. K. Li, F. H. Séguin, J. DeCiantis,
S. Kurebayashi, J. R. Rygg and B.E. Schwartz
Plasma Science and Fusion Center
Massachusetts Institute of Technology

J. Delettrez, V. Yu. Glebov, D. D. Meyerhofer, T. C. Sangster,
C. Stoeckl and J. M. Soures
Laboratory for Laser Energetics
University of Rochester

S. Hatchett, S. Haan, G. Schmid, N. Landen and N. Izumi
Lawrence Livermore National Laboratory

D. Stelter
Dexter Magnetic Technologies Inc.

* Visiting senior scientist at LLE
A method to determine $\rho_{R_{\text{fuel}}}$ 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 $\rho_{R_{\text{fuel}}}$ 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 $\rho_{R_{\text{fuel}}}$ 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 $\rho_{R_{\text{fuel}}}$ measurements. The spectrometer has a large dynamic range ($>10^6$), and can operate at yields as low as $10^{12}$. This will allow $\rho_{R_{\text{fuel}}}$ 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

• $\rho R_{\text{fuel}}$ of warm, fizzle and ignited implosions can be measured at the NIF, and similarly for warm and cryo DT at OMEGA.

• $\rho R_{\text{fuel}}$ 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 ~ 100) ratio for most applications.

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

• High-resolution spectrometer ($\triangle E/E = 1.8\%$).

• Accurately measure $T_i$ ($\triangle T_i = \pm 30$ 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

- **Target chamber**
- **Target**
- **Neutrons**
- **Magnet**
- **Vacuum chamber**
- **Lead**

**Target**
- **CH-foil** or **CD-foil**
- **Protons** or **Deuterons**
- **Neutrons**

**6-24 MeV protons** or **3-12 MeV deuterons**

**Detectors**
- **Coincidence CR-39**
- **CVD-strip detectors**
- **Current-mode scintillators**

**Scintillators**
- **Current-mode scintillators**
MRS principle - Detection efficiency \((\varepsilon_n)\)

- The detection efficiency can be expressed as

\[ \varepsilon_n \propto \Omega_n \int \frac{d\sigma}{d\Omega_{\text{lab}}} \ d\Omega \]

- Maximum differential cross section at forward scattering angles, focusing aspects and large aperture significantly enhances \(\varepsilon_n\).
MRS principle - Resolution ($\Delta E_i$)

- Resolution ($\Delta E_i$) 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

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

- $\Delta E_f = \text{Energy loss in foil} \propto \text{foil thickness}$
- $\Delta E_k = \text{Kinematic energy broadening} \propto \text{foil and aperture size}$
- $\Delta E_s = \text{Ion optical energy broadening} \propto \text{magnet performance}$
MRS design
Design philosophy

Initial and potentially the final implementation
\((\rho R_{\text{fuel}} \text{ and } T_i)\)

- Neutrons
- Protons
- CH-foil

Target
- \(~ 230 \text{ cm on OMEGA}\)

Aperture
- \(~ 570 \text{ cm on NIF}\)

Magnet

6 MeV

24 MeV

Coincidence
CR-39
Potential upgrade \((\rho R_{\text{fuel}})\)

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

Design philosophy

Target

CD-foil

\(~ 570 \text{ cm on NIF} \)
\(~ 230 \text{ cm on OMEGA} \)

Magnet

Aperture

\(~ 3 \text{ MeV} \)
\(~ 12 \text{ MeV} \)
Design of the MRS at OMEGA and the NIF

Target CH-foil

~ 15 cm (Ω)
~ 20 cm (NIF)

~ 215 cm (Ω)
~ 550 cm (NIF)

Magnet

~ 11 cm wide aperture
~ 35 cm

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

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
- Thin BC422
- Fast PMT
- Bkgd monitor
We will develop coincidence CR-39 and one of two electronic detector systems

<table>
<thead>
<tr>
<th>Detector</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coincidence CR-39**</td>
<td>Totally insensitive to EMP, X-rays &amp; $\gamma$-rays Shielding not required Robust technology</td>
<td>9-12 hour turn around</td>
</tr>
<tr>
<td>CVD-strip detector</td>
<td>Large dynamic range Fast Insensitive to $\gamma$’s Radiation hardened</td>
<td>Sensitive to EMP</td>
</tr>
<tr>
<td>Current-mode scintillator</td>
<td>Fast Well-known technology Sensitive to $\gamma'$ Sensitive to EMP</td>
<td></td>
</tr>
</tbody>
</table>

** At Vulcan, only CR-39, radiochromic film, and film can be reliably used.
MRS performance
## Performance of MRS at OMEGA and the NIF

<table>
<thead>
<tr>
<th>Facility</th>
<th>Type of measurement</th>
<th>Foil</th>
<th>$\varepsilon_n$</th>
<th>$\Delta E_i$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMEGA “”</td>
<td>$\rho R_{fuel}$ &amp; $T_i$</td>
<td>CH</td>
<td>$5 \times 10^{-10}$</td>
<td>250</td>
</tr>
<tr>
<td>“”</td>
<td>$\rho R_{fuel}$ &amp; $T_i$</td>
<td>“”</td>
<td>$6 \times 10^{-9}$</td>
<td>3000</td>
</tr>
<tr>
<td>“”</td>
<td>$\rho R_{fuel}$</td>
<td>CD</td>
<td>$8 \times 10^{-10}$</td>
<td>250</td>
</tr>
<tr>
<td>“”</td>
<td>$\rho R_{fuel}$</td>
<td>“”</td>
<td>$1 \times 10^{-8}$</td>
<td>3000</td>
</tr>
</tbody>
</table>

At the NIF, $\varepsilon_n$ is about one order of magnitude smaller for the same $\Delta E_i$. 
Predicted signal ($S$) for $\rho R_{\text{fuel}}$ measurements of a cryo DT target at OMEGA

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

$$S \sim \frac{1000 \times 2 \text{ MeV}_{\text{ee}}}{100 \text{ eV/photon}} \sim 2 \times 10^7 \text{ photons}$$
Predicted Noise (N) for $\rho R_{\text{fuel}}$ 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 $5 \times 10^5$ 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 $\rho R_{\text{fuel}}$ 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.

\[
N \sim \frac{1200 \times 0.1 \text{ MeV}_{ee}}{100 \text{ eV/photon}} \sim 1 \times 10^6 \text{ photons}
\]

\[
\Rightarrow \quad \text{S/N} \sim \frac{2 \times 10^7}{1 \times 10^6} \sim 20
\]

\[
\frac{S}{N} \propto \frac{\rho R_{\text{fuel}} \times Y_{1n}}{Y_{1n}} = \rho R_{\text{fuel}} \quad \Rightarrow \quad \text{At NIF, S/N} \sim 200
\]
# Predicted signal-to-noise (S/N) ratio for the different measurements at OMEGA and the NIF

<table>
<thead>
<tr>
<th>Implosion</th>
<th>$\rho R_{\text{fuel}}$ [mg/cm$^2$]</th>
<th>Facility</th>
<th>S/N (CR-39)</th>
<th>S/N (BC422)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm DT</td>
<td>~ 10</td>
<td>OMEGA</td>
<td>~ 40</td>
<td>~ 2</td>
</tr>
<tr>
<td>Cryo DT</td>
<td>~ 100</td>
<td>OMEGA</td>
<td>~ 400</td>
<td>~ 20</td>
</tr>
<tr>
<td>Cryo DT fizzle (9x10$^{14}$)</td>
<td>~ 1000</td>
<td>NIF</td>
<td>~ 160</td>
<td>~ 200</td>
</tr>
<tr>
<td>Cryo D$_2$</td>
<td>~ 1000</td>
<td>NIF</td>
<td>~ 1600</td>
<td>~ 200</td>
</tr>
</tbody>
</table>
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.
$\rho R_{\text{fuel}}$ measurements
Accuracy analysis of $\rho R_{\text{fuel}}$ measurements using the MRS at OMEGA

The number of measured signal events ($S$), which are generated by down-scattered neutrons, is linearly proportional to $\rho R_{\text{fuel}}$, and the relative statistical uncertainty in $S$ can be expressed as

$$\frac{\Delta S}{S} = \sqrt{\frac{\rho R_{\text{fuel}} + 6}{10^{-12} \rho R_{\text{fuel}}^2 Y_{\text{ln}}}}$$

(2)**

when operating the MRS at $\Delta E = 3000$ keV. $\rho R_{\text{fuel}}$ is given in mg/cm$^2$. Eq. (2) can be rewritten as

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

(3)

** Eq. (2) assumes that S/B scales linearly with $\rho R_{\text{fuel}}$, which is the case for electronic detection.
$\rho R_{\text{fuel}}$ vs Yield at OMEGA for different $\Delta S/S$ when operating the MRS at $\Delta E_l = 3000$ keV
\( \rho R_{\text{fuel}} \) vs Yield at NIF for different \( \Delta S/S \) when operating the MRS at \( \Delta E_I = 3000 \text{ keV} \) (a), and \( \Delta E_I = 250 \text{ keV} \) (b)
Haan and Hatchett calculations
$\rho R_{\text{fuel}}$ asymmetries, at OMEGA and the NIF, could be inferred from yield of down-scattered neutrons in energy range 7-10 MeV

$\Delta E_l = 500 \text{ keV} \Leftrightarrow \Delta \Theta = 5^\circ$
Using down-scattered neutrons, $\rho R$ asymmetries of a pancaked $P_2$ Haan fizzle can be measured with MRS.

Yield = $9 \times 10^{14}$ or 2.6 kJ

Most primary neutrons are generated in central hot-spot.
With the MRS, $\rho R$ asymmetries can be measured on NIF for this Haan P2 fizzle of $9 \times 10^{14}$

$9 \times 10^{14}$ is about a factor 10 larger than is required to measure this $\rho R$ asymmetry.
Orthogonal MRS would be desirable at the NIF

Hohlraum

MRS view of pole (through laser-entrance)

MRS view of equator (through hohlraum wall)

Not to scale
$T_i$ measurements
$T_i$ can be accurately measured with the MRS: 
$\Delta T_i = \pm 30 \text{ eV (perfect statistics)}$

30 keV / mm at 14.1 MeV (p)

Dominant error

Error in detector position relative to magnet:

$\Delta x = \pm 1 \text{ mm}$

$\Delta E = \pm 30 \text{ keV}$

$\Delta E = 177 \sqrt{T_i}$

$\Delta T_i = \pm 30 \text{ eV}$
Using the CH-foil, the MRS can measure deviations from Maxwellian distributions when operated at $\Delta E_i = 250$ 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.)
The relative statistical uncertainty in the $T_i$ measurement can be expressed as

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

$\Delta E_i$ is the instrumental response function, $\Delta E_D$ 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 $\Delta E_i$.

\[ \frac{\Delta T_i}{T_i} = \left[ 1 + \left( \frac{\Delta E_i}{\Delta E_D} \right)^2 \right] \sqrt{\frac{2}{3.3 \times 10^{-10} \text{ Yield} \frac{\Delta E_D}{100 \text{ keV}}} = N} \]
$\Delta T_i / T_i$ vs Yield at the NIF for different instrumental point response functions $\Delta E_i$

\[
\frac{\Delta T_i}{T_i} = \left[ 1 + \left( \frac{\Delta E_i}{\Delta E_D} \right)^2 \right] \sqrt{\frac{2}{3.3 \times 10^{-11} \text{Yield} \frac{\Delta E_D}{100 \text{keV}}}} = N
\]