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A neutron spectrometer for precise measurements of DT neutrons from 10 to 18 MeV at OMEGA and the National Ignition Facility

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A model independent method to determine fuel $\langle\rho R\rangle$ is to measure the energy spectrum and yield of elastically scattered primary neutrons in deuterium–tritium (DT) plasmas. As is the case for complementary methods to measure fuel $\langle\rho R\rangle$ (in particular from knock-on deuterons and tritons [S. Skupsky and S. Kacenjar, J. Appl. Phys. **52**, 2608 (1981); C. K. Li *et al.* (unpublished)]), minimizing the background is critical for successful implementation. To achieve this objective, a novel spectrometer for measurements of neutrons in the energy range 10–18 MeV is proposed. From scattered neutrons (10–13 MeV), the DT fuel $\langle\rho R\rangle$ will be measured; from primary neutrons (~14 MeV), the ion temperature and neutron yield will be determined; and from secondary neutrons, in the energy range 12–18 MeV, the fuel $\langle\rho R\rangle$ in deuterium plasmas will be inferred at the National Ignition Facility. The instrument is based on a magnetic spectrometer with a neutron-to-deuteron (*nd*) conversion foil for production of deuteron recoils at nearly forward scattered angles. In its initial phase of implementation, CR-39 track detectors will be used in the focal plane to detect the recoil deuterons with extremely high spatial resolution. Besides simplicity, CR-39 track detectors will facilitate a highly accurate energy calibration. However, in a later implementation of the spectrometer design, the recoils will also be detected by an array of fast scintillation counters functioning in current mode. In either detection scheme, the detection efficiency is about 10^{-9} for measuring 14 MeV neutrons with an energy resolution of about 3%. Due to its large dynamic range, its relatively high efficiency, and a compliant design that allows for significant background rejection, this spectrometer can be effectively used, with very high resolution, at both OMEGA and the National Ignition Facility. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1323243]

I. INTRODUCTION

The fuel-areal density ($\langle\rho R\rangle$) at burn time is a fundamental quantity since it, and the core temperature, largely determine the quality of the capsule implosion.[1] Herein we propose a novel high-resolution spectrometer to accurately determine fuel $\langle\rho R\rangle$ and the ion temperature. This will be accomplished by measuring scattered (10–13 MeV), primary (~14 MeV), and secondary neutrons (12–18 MeV). The instrument is based on a magnetic spectrometer with a neutron-to-deuteron (*nd*) conversion foil for production of deuteron recoils at nearly forward scattered angles. An analogous method[2,3] was developed for neutron studies on the Joint European Torus. The recoils will be detected, in the initial implementation of the spectrometer, by CR-39 track detectors. The advantage of CR-39 track detectors is its simplicity; complete energy coverage of the focal plane; extremely high spatial resolution that will enable a very accurate energy calibration; and the existence of highly accurate and detailed CR-39 calibrations[4] that will allow discrimination between the deuteron signal and the background (largely protons that result from *np* scattering in the CR-39 plastic). In its final implementation, the recoils will be detected by an array of fast scintillation counters functioning in current mode as well as by CR-39.

In the case of current-mode detection, the large stand-off distance between the *nd*-conversion foil and the detectors provides time separation between the signal and the primary neutron background (which arrives first). This allows for the

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recovery of the detectors from the background neutrons, and dramatically improves the signal-to-background ratio (S/B). Time gates adjustable to the specific energy of the signal deuterons will time discriminate most of the background. Due to its large dynamic range, the spectrometer will be useful for both OMEGA and the National Ignition Facility (NIF).

II. DESIGN PRINCIPLES

For a neutron spectrometer to be practical, it must satisfy a number of requirements specific to the application: it must have the highest possible detection efficiency for a given energy resolution; a large dynamic range; and insensitivity to different types of background. Finally, the design should be relatively simple to implement, and the mechanical interface should be reasonably straightforward. These features are inherent to this design.

In the deuteron recoil technique, neutrons impinge upon a thin deuterated foil (of order 100 μm), from which a small fraction (of the order of 10^{-3}) of neutrons scatter elastically from the target deuteron nuclei. For a specific neutron yield, Y_n, the total number of scattered deuteron recoils, N_d, emanating from the foil can be expressed as

$$N_d \approx n_d t_f Y_n \frac{\Omega_n}{2} \int_0^{\pi/2} \sin\theta \frac{d\sigma(\theta)}{d\Omega_{\mathrm{lab}}} d\theta. \tag{1}$$

Here n_d is the deuteron number density in the foil, t_f is the foil thickness, Ω_n is the solid angle subtended by the foil, and $d\sigma(\theta)/d\Omega_{\mathrm{lab}}$ is the differential cross section in the laboratory frame. The instrument design should be optimized to maximize the detection efficiency (N_d/Y_n) for a specified resolution.

The energy relationship between the neutrons and deuteron recoils is given by[5]

$$E_d = \tfrac{8}{9} E_n \cos^2\theta_{nd}, \tag{2}$$

where 8/9 is the maximum fractional energy transfer, E_n is the neutron energy, E_d is the deuteron recoil energy, and θ_{nd} is the scattering angle between the incoming neutron and the deuteron recoil. For optimal detection efficiency, forward scattered deuterons should be selected, since the *nd* cross section for elastic scattering has a maximum for $\theta_{nd} = 0°$. Selecting forward scattered recoils also ensures that the uncertainty in the kinematic energy shift is minimized, thereby enhancing the energy resolution. To the best of our knowledge, the only recoil spectrometer technique that can accept forward scattered deuterons, and at the same time keep the neutron background at relatively low levels, is the method described herein.

The energy resolution of the spectrometer is part of the response function, which is defined as the deuteron energy distribution at the detector plane when viewing a fluence of monoenergetic neutrons. The broadening of the deuteron energy distribution results from energy loss in the *nd* foil (ΔE_f), from the kinematic energy shift (ΔE_k) and from the effect of the ion-optical properties of the magnet (ΔE_s). These mechanisms, which will be discussed later, can be assumed to be uncorrelated and Gaussian in shape. The total instrument resolution (ΔE_I) can thus be expressed as

$$\Delta E_I \approx \sqrt{\Delta E_f^2 + \Delta E_k^2 + \Delta E_s^2}. \tag{3}$$

Depending on the location of the *nd* scattering in the foil, the deuteron recoils show an energy loss distribution from zero up to a maximum energy loss proportional to the foil thickness. The foil image size and aberrations constitute the ion-optical contribution (ΔE_s), which is, in a first order approximation, only dependent on the foil area and angular spread of the deuteron recoils. The kinematic term (ΔE_k) depends on several factors, namely Ω_n, the foil area (A_f) and the deuteron recoil aperture (Ω_d) of the spectrometer (see Fig. 2). By increasing Ω_d, one increases the neutron detection efficiency. However, this reduces the energy resolution due to, first, an increased kinematic energy spread; and second, due to an increased maximum recoil path length within the foil. In this context one has to consider Ω_n, as it is the angle θ_{nd} that determines the kinematic contribution (ΔE_k). Considering a foil with a finite thickness, Eq. (2) can be rewritten as

$$E_d \approx \frac{8}{9} E_n \cos^2\theta_{nd} - \frac{1}{\cos\varphi_d} \int_{x_0}^{t_f} \frac{dE(E_d)}{dx} dx. \tag{4}$$

Here, φ_d is the deuteron angle to the normal of the foil surface, x_0 is the *nd*-scattering position in the foil, and $dE(E_d)/dx$ is deuteron energy loss per unit length in the foil. It can be seen from Eq. (4) that the energy loss is minimized when selecting forward scattered recoils, which is another feature of the spectrometer that further improves its performance.

III. DESIGN AND CHARACTERIZATION

The magnet performance and the combination of the parameters Ω_n, Ω_d and foil thickness (t_f) determine the instrumental detection efficiency and the energy resolution. The code RAYTRACE[6] was used to find the optimal design of the spectrometer magnet, and Monte Carlo simulations were performed to determine the optimal combination of Ω_n, Ω_d, and t_f.

A. Optimal combination of Ω_n, Ω_d, and t_f

For 14 MeV neutrons, the results of Monte Carlo calculations for OMEGA suggest an optimized design that has a detection efficiency of about 10^{-9} at a resolution of 3%. The parameters of the optimized design are $A_f = 32\,\mathrm{cm}^2$ at a distance of 20–30 cm from the target [which corresponds to a solid angle (Ω_n) of the order of 80 ms], a foil-areal density of 4 mg/cm^2, and a deuteron recoil aperture of 48 cm^2 (at a distance of 235 cm from the target), which in part determines the deuteron recoil solid angle (Ω_d). An example of the results from the simulations is shown in Fig. 1, in which the detection efficiency and resolution $[(\Delta E_f^2 + \Delta E_k^2)^{0.5}/E_d]$ are shown as a function of foil distance to the target (for four different t_f and $A_f = 32\,\mathrm{cm}^2$). For the case of current mode detection, a short foil distance to the target is preferable in order to maximize the time separation between the primary neutron background and signal. The foil should, on the other hand, not be too close to the target, as it would result in a

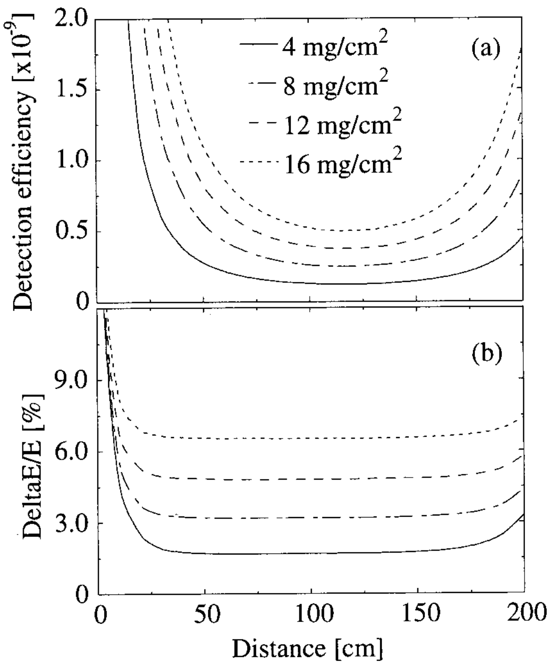

FIG. 1. For OMEGA, the detection efficiency (a), and resolution $[(\Delta E_f^2 + \Delta E_k^2)^{0.5}/E_d]$ (b), for 14 MeV neutrons, as a function of foil-to-target distance, for four different foil thicknesses and for a foil area of 32 cm^2. A deuteron recoil aperture of 48 cm^2 was used (see also Fig. 2).

reduced resolution caused by an increased ΔE_k. A foil-to-target distance of 20–30 cm is therefore a suitable distance for this application.

In the case of scattered and secondary neutrons, for which the yields will be about 2 to 3 orders of magnitude smaller than the primary 14 MeV yield, we anticipate degrading the resolution in order to substantially increase the detection efficiency. Future work will address this issue.

At the NIF, a deuteron recoil aperture distance of about 500 cm is more suitable, i.e., outside the target chamber. This will decrease the detection efficiency by about two orders of magnitude (due to a decreased Ω_n). However, this can be compensated for if the foil area (A_f) is increased. Another possibility might be to move the foil closer to the target allowing, in the case of current mode detection, better time separation between the signal and the primary neutron background. This will, on the other hand, slightly change the characteristics of the spectrometer. The detection efficiency, for the NIF, is likely to be one or more orders of magnitude lower than for the OMEGA, but this will be compensated for by much higher neutron yields that far exceed the required yield. In addition, the maximum tolerable neutron yield on the NIF will be higher than the nominal yield for an ignited target, since the parameters Ω_n, Ω_d, and t_f can be varied to match the expected neutron yield. Table I summarizes the required primary yields both on OMEGA and NIF for spectral measurements of scattered, primary and secondary neutrons.

B. Magnet design

The magnet will be based on a neodymium–iron–boron permanent (NdFeB) dipole with a pole gap of 5 cm producing a homogeneous field of 1.0 Tesla. The pole boundaries will be tapered for increased focusing properties in both the transverse and dispersive planes, where the latter provides for increased resolving power. A schematic drawing of the spectrometer, including foil, magnet and focal plane position, is shown in Fig. 2.

TABLE I. Required primary neutron yields on OMEGA and NIF for spectral measurements of scattered, primary and secondary neutrons. A spectrometer detection efficiency of about 10^{-9} at 3% resolution will be used on OMEGA for the primary neutron measurements, while a detection efficiency of about an order of magnitude higher will be used for the scattered and secondary neutron measurements. Future work will address this issue. At NIF, the neutron yields will far exceed the required levels and this will allow for extremely high-resolution measurements of the three types of neutrons. In addition, the maximum tolerable neutron yield for this spectrometer will be higher than the nominal yield for an ignited target on NIF since the parameters Ω_n, Ω_d, and t_f can be varied to match the expected neutron yield.

	OMEGA	NIF
Scattered neutrons	$\gtrsim 10^{13}$	$\gtrsim 10^{14}$
Primary neutrons	$\gtrsim 10^{11}$	$\gtrsim 10^{12}$
Secondary neutrons	$\gtrsim 3\times 10^{12}$	$\gtrsim 3\times 10^{13}$

To achieve optimal first-order focusing properties[7] $[(x/\theta)=0]$ of the magnet, an angle of incidence of +45°, a deflection angle of 107.6°, and an exit angle of −36.2° relative to the normal of the pole boundary were selected (see Fig. 2). In addition, a sector angle of 98.8° provides for good second-order focusing $[(x/\theta^2)=0]$ for a large range of deuteron energies. Also, the positive entrance angle[8] and the entrance fringing fields provide for transverse focusing, but not enough to make the instrument stigmatic.[9] Curved pole boundaries are normally used to correct for the (x/θ^2) term, which is the dominant aberration term. This feature, however, is precluded for our design since it would exceed allowable permanent magnet technology.

Table II shows, for OMEGA, calculated energy resolution and detection efficiencies for 14 MeV neutrons, and for three combinations of foil area and thickness. A foil-to-target

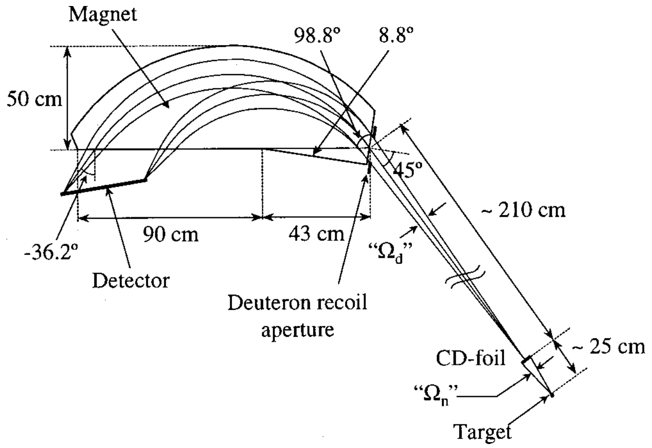

FIG. 2. For OMEGA, a schematic drawing of the spectrometer, including the CD foil, magnet, and the detector located at the focal plane. The trajectories shown are for deuteron energies of 9 and 16 MeV, corresponding to 10 and 18 MeV neutrons, respectively. A critical feature of this design is the space (~60 cm) between the OMEGA target chamber (175 cm) and the detector. This allows for substantial background shielding.

TABLE II. For OMEGA, calculated energy resolution and detection efficiencies (for 14 MeV neutrons) for three combinations of foil area and thickness. A foil-to-target distance of 25 cm, and a deuteron recoil aperture of 48 cm^2 were used in the calculations. (The foil-to-magnet aperture distance is 210 cm.) In the case of scattered and secondary neutrons, for which the yields will be quite small, we anticipate degrading the resolution in order to substantially increase the detection efficiency. Future work will quantitatively address this issue.

Combination	#1	#2	#3
Foil thickness, t_f ($\mathrm{mg/cm^2}$)	4	8	16
Foil area, A_f ($\mathrm{cm^2}$)	16	32	64
$(\Delta E_f^2+\Delta E_k^2)^{0.5}$ (keV)	219	427	904
ΔE_s (keV)	73.5	104	228
$\Delta E_I/E_d$ (%)	1.86	3.54	7.52
Detection efficiency ($\times 10^{-9}$)	0.41	1.66	6.62

distance of 25 cm (corresponding to a foil-to-magnet-aperture distance of 210 cm), and a deuteron recoil aperture of 48 cm^2 were used in the calculations. It is seen that the ion-optical broadening increases with larger foil area (A_f). This is a result of the larger acceptance angle of the recoils and the accentuated effects of aberrations.

The magnet dispersion, total resolution, and detection efficiency, as a function of neutron energy, in the range 10 to 18 MeV, are shown in Figs. 3(a) and 3(b). The spectrometer setting #2, in Table II, was used.

C. Signal-to-background S/B characterization

The background radiation that reaches the detector mainly consists of either primary or scattered neutrons, soft and hard x-rays from laser-plasma interactions, and γ-rays from (n,γ) interactions in the chamber walls, diagnostics and other structures. For the case of CR-39 track detector, it is extremely insensitive to photon interactions irrespective of energy. The neutron background, if unshielded, will, however, generate recoil protons in the CR-39 plastic through *np* interactions. Rejection of this background occurs because of the modestly low detection efficiency of CR-39 to neutrons ($\sim 10^{-4}$) (see Ref. 3). For example, in the case of primary neutrons measurements, the signal is about equal to the background. In event that greatly increased neutron background rejection is required—such as for the measurement of down-scattered neutrons (10–13 MeV) or for very high resolution ion temperature determinations—significant shielding can easily be placed around the detector plane since it is located well outside the OMEGA chamber wall (whose outer radius is 175 cm). By this method, and because of the space between the chamber wall and the detector, direct, unscattered neutrons can be substantially reduced from interacting with the CR-39. This is an important advantage of this design, i.e., an off-axis detection plane that is well outside the experimental chamber. In the event that even greater neutron background rejection is required, spatial coincidence techniques could be utilized with the CR-39.[10] (In such a situation, significant technological advances have occurred since the earlier work by Kacenjar *et al.* that used this method.[10])

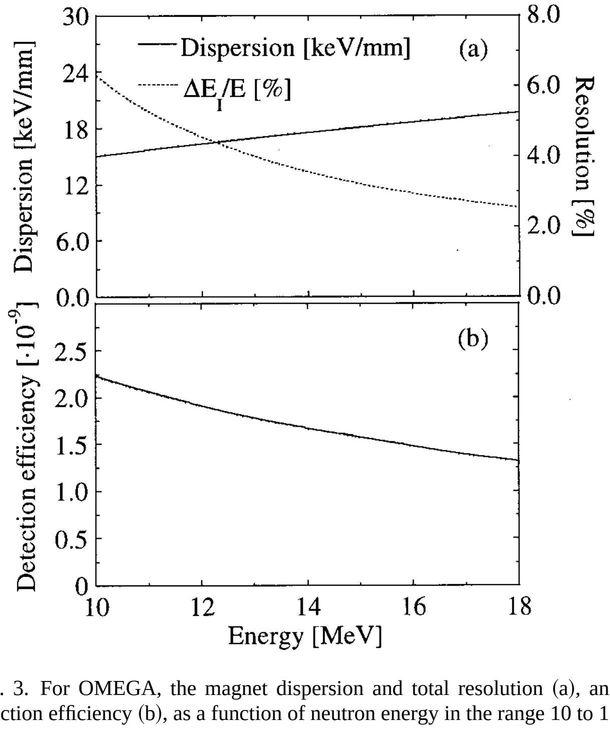

FIG. 3. For OMEGA, the magnet dispersion and total resolution (a), and detection efficiency (b), as a function of neutron energy in the range 10 to 18 MeV. Spectrometer setting #2, in Table I, was used.

For the case of current mode detection, a time gate of about 20–30 ns will reject the primary neutrons that have not been scattered. A fraction of the scattered neutrons will, on the other hand, be detected, although this too can be significantly reduced if shielded in a manner as described above. To further minimize this background, as well as that from γ-rays and x-rays, the volume of each individual scintillator (of which there are about 100), should be as small as possible. A scintillator thickness of about 1.5 mm will fully stop 16 MeV deuterons, and a width and length of 4 mm and 50 mm, respectively, will allow the best signal detection efficiency. Wider scintillators reduce the energy resolution and time response, resulting in increased background. In addition, wider scintillators will also decrease the dynamic range of the spectrometer. The fraction of scattered neutrons that will be detected can be characterized by moving the foil out of the spectrometer line of sight. In addition, codes like MCNP[11] and TART98[12] should also prove useful for characterizing the background.

IV. CONCLUSIONS

A novel neutron spectrometer, covering an energy range of 10–18 MeV, has been designed for high resolution measurements of scattered and primary neutrons in *dt* plasmas, and secondary neutrons in *dd* plasmas. The magnet design minimizes aberrations so that largest possible solid angle can be utilized. This provides for a detection efficiency of 10^{-9} at an energy resolution of about 3% when measuring 14 MeV neutrons. In the near future, the tradeoff between detection efficiency and resolution will be quantitatively investigated. This study will be essential for the practical implementation of low-yield measurements, in particular for the scattered and secondary neutrons.

Present plans would have the spectrometer initially operating with CR-39 in the focal plane. A later implementation would incorporate current-mode scintillation detection along with CR-39. As a consequence of the spectrometer's large dynamic range, because of its relatively high efficiency, and because of a compliant design that allows for significant background rejection, this spectrometer should effectively operate, with very high resolution, at both OMEGA and the National Ignition Facility.

ACKNOWLEDGMENTS

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