Section 1
PROGRESS IN LASER FUSION

1.A Diagnosing High Density with "Knock-Ons"

The DT fuel density in recent high-compression experiments[1,2] at LLE was measured using the "knock-on" diagnostic.[3] Previously this diagnostic had been used only in low-density experiments in which there was a negligible amount of slowing down of the knock-on particles within the target.[4,5] In the present experiments, the target density-radius product (ρR) was sufficiently large to significantly moderate the knock-on particles, so that a new technique had to be developed to accommodate the distorted spectrum.

The principle behind the knock-on diagnostic is as follows (see Fig. 36.1). DT fusion reactions in the fuel produce energetic (14-MeV) neutrons. As the neutrons traverse the fuel region, there is a small probability that they will elastically scatter off of deuterium (D) and tritium (T) ions in the fuel. The number of such scattering events is directly proportional to the fuel ρR times the neutron yield Y. Thus, by counting the number of elastically scattered D and T ions (knock-ons) and by measuring the neutron yield, it is possible to infer the fuel ρR. The knock-ons were detected in the solid-state track detector CR-39. The technique used to discriminate between D or T knock-on tracks and tracks produced by other charged particles restricted the counted tracks to only a fraction F ($\lesssim 10\%$) of the total number of knock-ons. Only those tracks that crossed the entire CR-39 thickness with entrance diameters larger than a specified number were counted, corresponding to knock-ons in a well-defined energy window. (See Ref. 1 for a discussion of this selection technique.) As a result, the relation between fuel ρR and measured quantities depends on the fraction F:

$$\rho E_{\text{fuel}} = \frac{Q}{YF} \times 5.4 \times 10^3 \text{ mg/cm}^2 , \qquad (1)$$

where Q is the number of tracks that meet the selection criterion. The constant factor is $(M_D + M_T)/(\sigma_D + \sigma_T)$, where σ_D and σ_T are the elastic scattering cross sections for 14-MeV neutrons on deuterons and tritons (0.62b and 0.92b, respectively), M_D and M_T are the respective masses, and equimolar DT is assumed.

Proper implementation of the diagnostic requires determining the fraction F of those knock-ons that are in the selection energy window. Unfortunately, F is a function of target conditions. If the knock-ons are slowed down within the target, a different part of the spectrum will move into the track-detector energy window, resulting in a different value for F. In general, F is a function of both fuel and shell ρR, as well as temperature, so that the ratio Q/Y will not uniquely determine the fuel ρR.

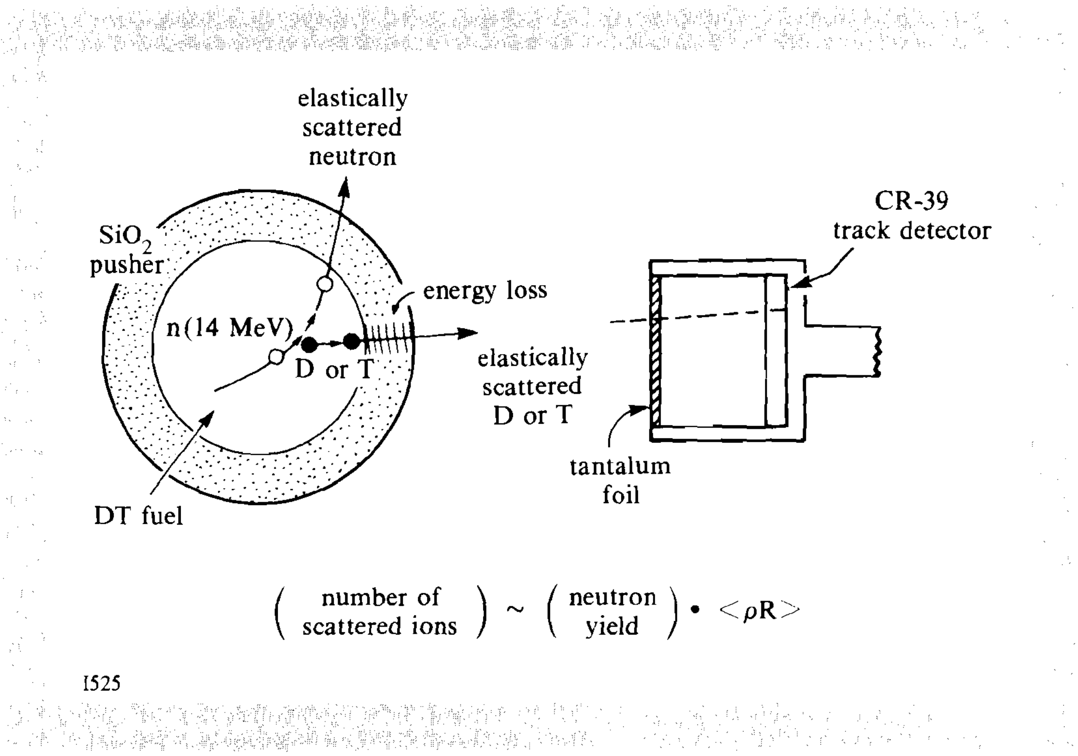
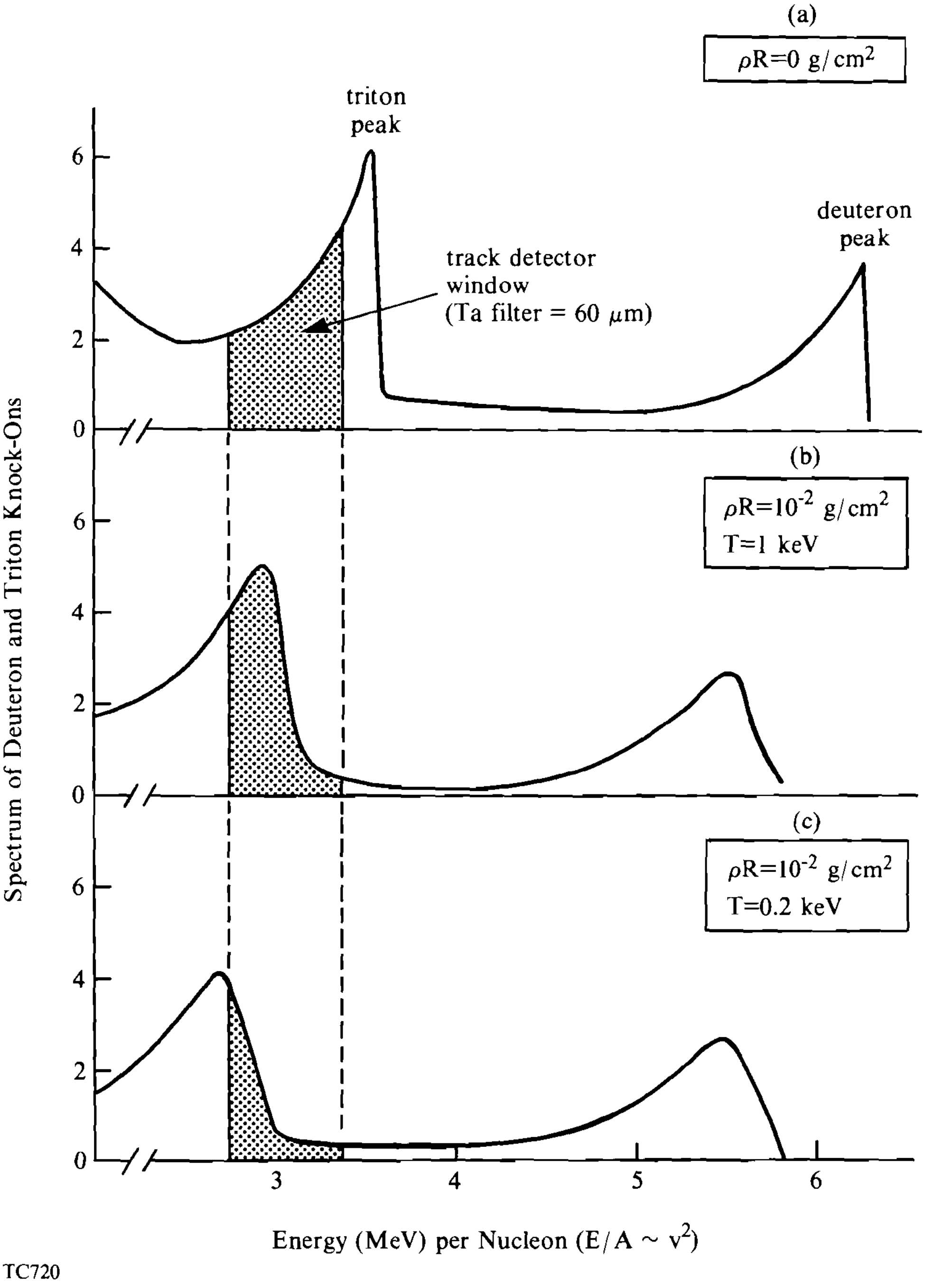


Fig. 36.1
Schematic of the knock-on diagnostic.

An example of how F can change with target conditions is illustrated in Fig. 36.2, showing the superposition of the deuteron and triton knock-on spectra. (It is not necessary to discriminate between these particles.) The shape of the spectrum, with peaks at high and low energy, results from the asymmetric cross section for 14-MeV neutron elastic scattering, which is peaked for forward and backward scattering in the center of mass system. In this example, a 40-μm tantalum filter was used to bring the triton peak into the energy window of the track detector when there is no significant slowing down of the knock-ons in the target [Fig. 36.2(a)]. For conditions where there is increased slowing down due to, for instance, increased *ρR* or decreased temperature, the triton peak will shift out of the energy window to lower energies; also, the fraction of the total spectrum that is detected will be reduced, as in Figs. 36.2(b) and 36.2(c).

Fig. 36.2
Example showing how target conditions affect the fraction *F* of knock-ons in the track-detector energy window.



To resolve this difficulty, we have replaced the single-foil track detector with multiple, stacked foils in two configurations, allowing us to measure a larger fraction of the knock-on spectrum and to remove the sensitivity of F to target conditions for the range of ρR attained in the OMEGA experiments. With this technique, F becomes a single number ($0.85 \pm 5\%$) over the range of total target ρR varying from 0 to ~ 50 mg/cm^2, with the track count Q in Eq. (1) now replaced by the sum of tracks meeting the selection criterion in each of four track-detector foils. For total target ρR greater than ~ 50 mg/cm^2, F again becomes dependent on target conditions, but it will always remain less than ~ 0.085 so that, at worst, use of $F = 0.085$ in Eq. (1) will yield a lower bound for the fuel ρR. This result is model independent and does not depend on the source of knock-on spectral distortion within the target, whether it is from the fuel ρR, the shell $\rho \Delta R$, temperature, or temporal or spatial variation of conditions in the target.

The five-foil, two-stack configuration of CR-39 used in the experiments is shown in Fig. 36.3. The first tantalum filter is required to block target debris and charged particles produced in the DD and DT nuclear reactions. The stacked CR-39 foils serve a dual purpose. Each detector is used (1) to detect knock-on tracks and (2) to slow down knock-on particles so that a different part of the spectrum is in the selection energy window of subsequent track detectors. The tantalum foils also help shift the knock-on spectrum. The most energetic of the knock-on particles leave tracks in the farthest foil. The first CR-39 foil in each of the two stacks detects the same part of the spectrum and is used for consistency checks. Although no attempt was made to separate deuterons from tritons, the first foil predominantly detected the tritons while the deuterons were distributed among the remaining four detectors.

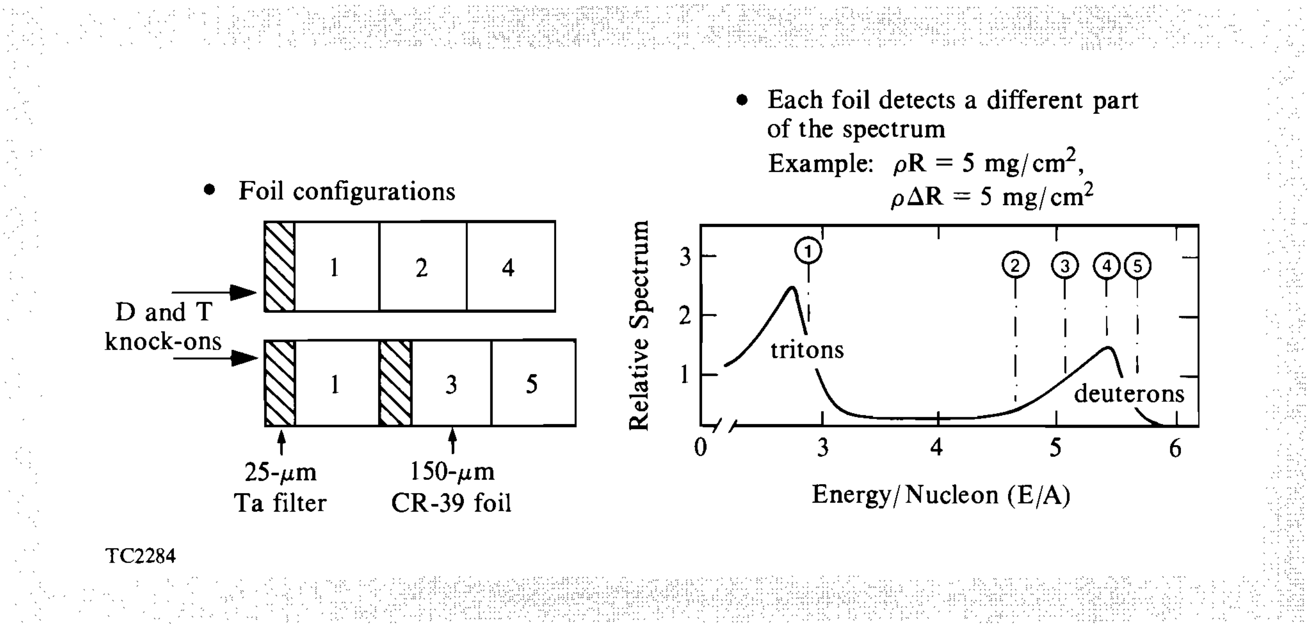


Fig. 36.3
The five-foil set used in the high-density experiments and the approximate region of the knock-on spectrum that meets the selection criterion for each foil.

The effect of knock-on moderation within the target is shown in Fig. 36.4 for the five-foil system, based on computer simulations of two targets with total ρR = 20 mg/cm^2 and 40 mg/cm^2. The slow-down of the knock-ons is clearly discernible with the increased ρR, as the deuteron peak moves from foil 5 to foil 3, and the triton peak moves partially out of the window of foil 1. Clearly, the fraction of the knock-on spectrum in the window of any single detector has changed substantially due to the spectrum moderation. However, note that the sum of tracks in foils 2–5 remains relatively constant, ~8.5%, as it represents the total fraction of knock-ons in the high-energy deuteron peak and does not depend on the exact position of the peak. Furthermore, it does not depend on what conditions in the target produced the moderation of the spectrum. Only after the total ρR exceeds about 50 mg/cm^2 will the moderation be large enough to start shifting the peak out of these foils, in which case, the sum of tracks will be less than 8.5%. Thus, F = 8.5% represents an upper bound for this parameter in Eq. (1). It provides for an accurate determination of fuel ρR for total target ρR less than ~50 mg/cm^2; otherwise, it provides a lower bound on the fuel ρR.

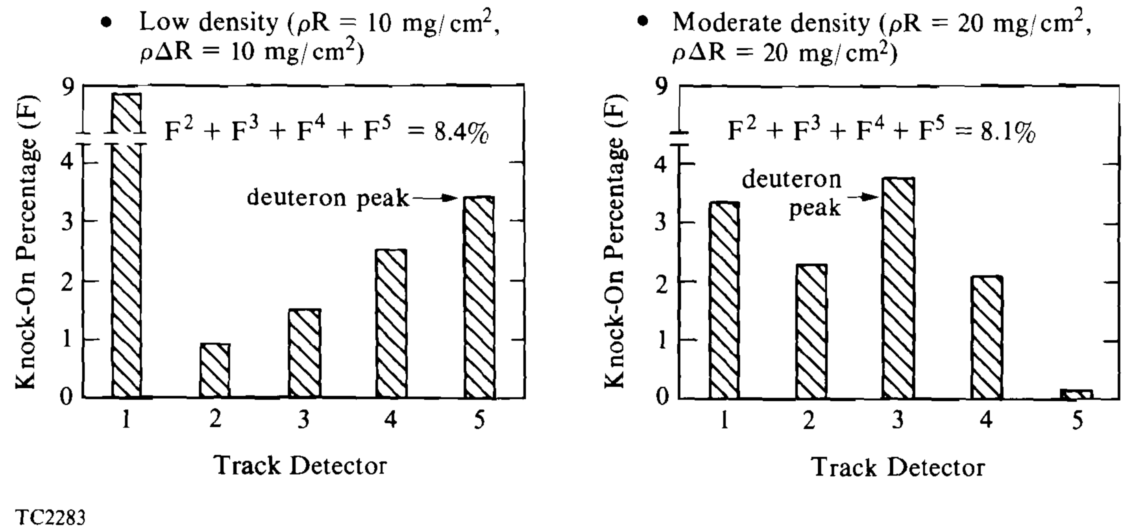


Fig. 36.4
Relative number of knock-ons in each of the five CR-39 foils for the two cases of total target ρR equals 20 mg/cm^2 and 40 mg/cm^2.

Figures 36.5 and 36.6 illustrate application of this diagnostic to experimental data. Whereas the diagnostic itself is model independent, it is useful to deploy a particular model to demonstrate at what point the diagnostic becomes sensitive to target conditions. The model assumes a sphere of constant-density DT fuel surrounded by a constant-density glass shell. For the following examples, the results are relatively insensitive to the temperatures or densities of the fuel and shell, or to the distribution of neutron production in the fuel. The values of fuel ρR and shell $\rho\Delta R$ were varied and the resulting moderated knock-on spectrum and track-detector response were calculated.

Figure 36.5 shows an example of a moderate-density gaseous DT experiment. The curve marked "deuterons" shows the region of fuel $\rho\Delta R$ that would be consistent with the number of knock-on tracks observed in foils 2–5 for that particular shot. The width of the curve is determined by the statistical error, given by the square root of the number of counts. Note that the curve rises nearly vertically, uniquely determining the fuel ρR, and is relatively independent of $\rho\Delta R$. The curve marked "tritons" is determined by the number of tracks in foil 1, which is dominated by the triton high-energy peak. This curve initially rises vertically, but then shifts to the right as the increasing target ρR slows the tritons out of the energy window of this detector, i.e., with a decrease in the fraction of knock-ons Q, the observed number of tracks can only be produced by a larger value of fuel ρR. Thus, the triton curve alone cannot uniquely determine the fuel ρR. However, the intersection of the triton and deuteron curves shows a point of ρR and $\rho\Delta R$ that is consistent with both track observations. Whereas this diagnostic was designed to determine only fuel ρR, we now also find that $\rho\Delta R$ can be determined (though the latter is somewhat model dependent) by demanding consistency among all the track-detector foils.

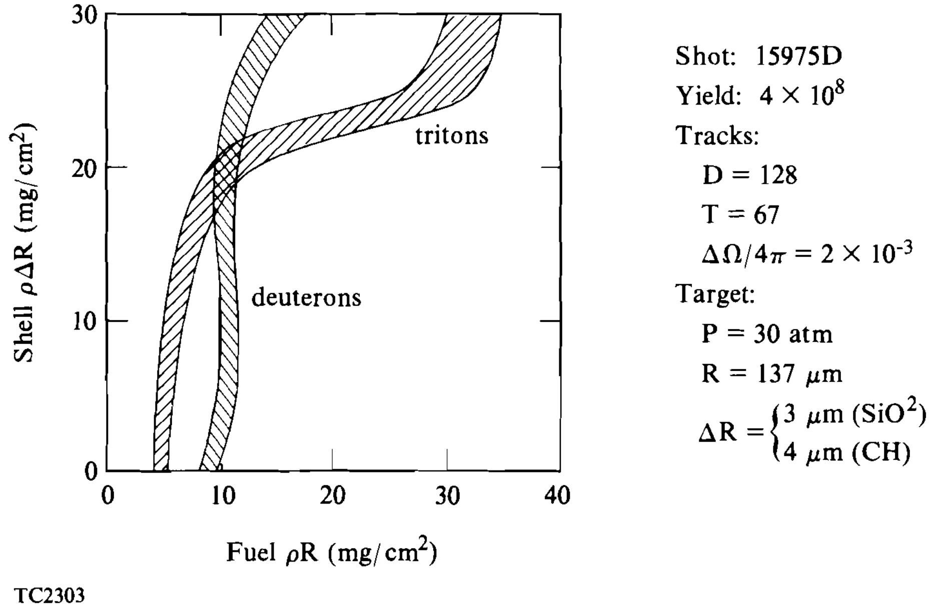
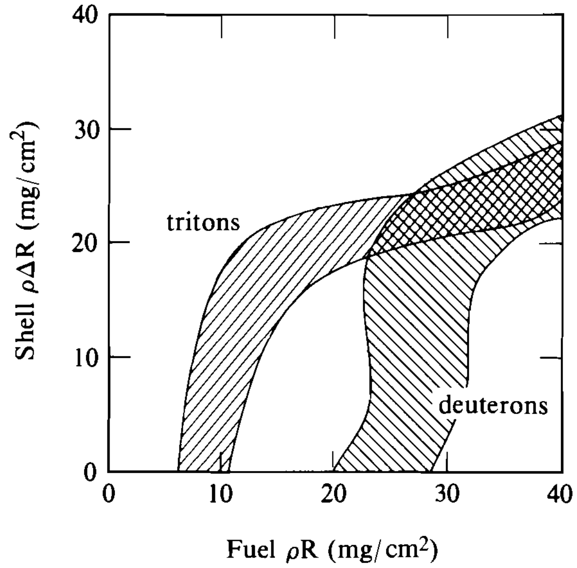


Fig. 36.5
Region of fuel ρR and shell $\rho\Delta R$ consistent with the number of tracks observed in a moderate density implosion with gaseous DT. The "deuteron" curve represents the sum of tracks in foils 2–5 meeting the selection criterion. The "triton" curve represents the tracks in foil 1.

The second example (Fig. 36.6) is for a shot aimed at higher density, this time using cryogenic DT fuel. For this shot, the higher fuel ρR was not enough to compensate for the low neutron yield, which resulted in a small number of knock-ons. This is reflected in the much wider curves in Fig. 36.6. The deuteron curve now rises nearly vertically only until $\rho\Delta R + \rho R \approx 50$ mg/cm^2; then it moves to the right as the deuteron peak begins to move out of the combined windows of track detectors 2-5. A lower limit on the fuel ρR is well determined at ~25 mg. The kink in the curve for $\rho\Delta R < 5$ mg/cm^2 is due to the presence of some high-energy tritons in foil 2, but these are quickly moved out at higher $\rho\Delta R$ values. The intersection of the deuteron and triton curves suggests a shell $\rho\Delta R$ value of ~20 mg/cm^2, which is consistent with "rad chem" measurements on similar targets.



Shot: 16054D
Yield: 9.6×10^6
Tracks:
D = 41
T = 16
$\Delta\Omega/4\pi = 1\%$
Target:
P = 100 atm
R = 120 μm
ΔR = 5 μm

TC2304

Fig. 36.6
Same as Fig. 36.5, but for a higher-density implosion using cryogenic DT fuel.

In summary, a technique has been developed to measure fuel ρR with knock-on particles in a model-independent way for experiments where the total target ρR is less than ~50 mg/cm^2. The technique takes into consideration moderation of the knock-ons within the target and is independent of the moderation source whether it be in the fuel or shell. Even if there is mixing between the fuel and shell, the diagnostic measures the ρR of the fuel portion. In addition, $\rho\Delta R$ of the shell can be estimated by demanding consistency among the number of tracks in different foils.

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