The dependence of backscatter of high-irradiance (10^{15}–10^{16} W/cm^2) Nd-laser pulses from prepulse-formed plasma has been shown to be proportional to irradiance and prepulse–to–main-pulse time delay, logarithmically dependent upon prepulse amplitude, and insensitive to target material and geometry. Although projections of these results suggest that some laser-fusion designs may encounter servere backscatter, the applicability of these results to continuous temporally structured pulses or their laser wavelength scaling remains to be tested.

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[1] B.H. Ripin, J.M. McMahon, E.A. McLean, W.M. Manheimer, and J.A. Stamper, Phys. Rev. Lett. **33**, 634 (1974).
[2] "Direct backscatter" or "backscatter" is defined here as the laser energy scattered back through the focusing lens only.
[3] B.H. Ripin, F.C. Young, J.A. Stamper, C.M. Armstrong, R. Decoste, E.A. McLean, and S.E. Bodner, Phys. Rev. Lett. **39**, 611 (1977).
[4] B.H. Ripin, NRL Memo Report No. 3684, 1977 (unpublished).
[5] D.W. Phillion, W.L. Kruer, and V.C. Rupert, Phys. Rev. Lett. **39**, 1529 (1977).
[6] J.L. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, Nature (London) **239**, 139 (1972).
[7] B.H. Ripin, J.A. Stamper, and E.A. McLean, *Proc. of* 1978 *IEEE Int'l Conf. on Plasma Science*, Monterey, Calif. (IEEE, New York, 1978).
[8] K. Eidmann and R. Sigel, *Laser Interaction and Related Plasma Phenomena*, edited by H. Schwarz and H. Hora (Plenum, New York, 1973), Vol. 3, p. 667.
[9] R.H. Lehmberg, Phys. Rev. Lett. **41**, 863 (1978).
[10] D.G. Colombant and W.M. Manheimer Proc. of 1979 Int'l Conf. on Plasma Science, Montreal, 1979 (unpublished). The work utilizes the saturation mechanism used in W.M. Manheimer and R.W. Flynn, Phys. Fluids **17**, 409 (1974).
[11] When the heat source (incident laser energy) is still on during the relevant expansion, as in a continuous pulse, an isothermal expansion model is appropriate and the density scale length at a given density is $L_n = c_s t$ [F. Felber and R. Decoste, Phys. Fluids **21**, 520 (1978)]. The plasma expansion following a prepulse, however, is slower (adiabatic) due to the lack of a heat source to maintain the plasma temperature.
[12] F. Amiranoff, R. Benattar, R. Fabbro, E. Fabre, C. Garban, C. Popovics, A. Poquerusse, R. Sigel, C. Stenz, J. Virmont, and M. Weinfield, 7th Int'l Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978, paper IAEA-CN-37-D4 (unpublished).

Technique for profiling ^{1}H with 2.5-MeV Van de Graaff accelerators[a]

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We describe an elastic recoil detection (ERD) analysis technique for profiling ^{1}H in the near-surface regions of solids using a 2.5-MeV Van de Graaff accelerator commonly used for ion-backscattering analysis. Energy analysis of ^{1}H forward scattered by 2.4-MeV ^{4}He incident on the target tilted at an angle of $\sim 75°$ yields a depth resolution of $\lesssim 700$ Å and a sensitivity of better than 0.1 at.% for ^{1}H to depths of $\lesssim 0.6$ μm in solids.

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Ion-beam analysis [1] has been demonstrated to be a powerful technique for sensitive measurements of the atomic composition and impurity concentrations in the near-surface ($\lesssim 1$–2 μm) regions of solids. The most commonly used techniques are ion-backscattering [2] and nuclear-reaction analysis. [3] In ion-backscattering analysis, light ions such as H or He with energies of ~ 1–3 MeV are incident on the sample under investigation and ions backscattered at some well-defined angle are detected. Analysis of the energy distribution of these backscattered ions yields the near-surface depth distribution of atomic species with masses greater than that of the projectile beam. In nuclear-reaction analysis, incident ions undergo inelastic nuclear reactions with a particular isotope of interest in the target. The isotope of interest is then profiled by analysis of one of the reaction products—typically a particle or a γ ray.

Hydrogen (^{1}H) is the most difficult atomic species to profile. Because of its light mass, ion backscattering cannot be used; nuclear reactions which give good depth resolution and sensitivity, [4] e.g., ^{1}H(^{15}N,$\alpha\gamma$) ^{12}C at 6.4 MeV ^{15}N energy or $_1$H(^{19}F,$\alpha\gamma$) ^{16}O at either 6.4 or 16.5 MeV ^{19}F energy, require higher energies than can be readily obtained from the 2.5-MeV Van de Graaff accelerators commonly in use for backscattering analysis. A reaction [5] which has been used to profile ^{1}H with 2.5-MeV Van de Graaff accelerators is ^{1}H(^{11}B,α) ^{8}Be, where the ^{8}Be decays to 2α, which occurs at a ^{11}B energy of ~ 2 MeV; however, the resonance in this reaction is relatively weak and there is a large nonresonant contribution to the ^{4}He yield so that satisfactory measurements of the ^{1}H concentration are difficult to achieve. As a result, most of the ^{1}H profiling measurements to data have been made using tandem Van de Graaff accelerators which can readily provide moderate currents of either ^{15}N or ^{19}F at high energy.

We have developed a forward-scattering elastic recoil

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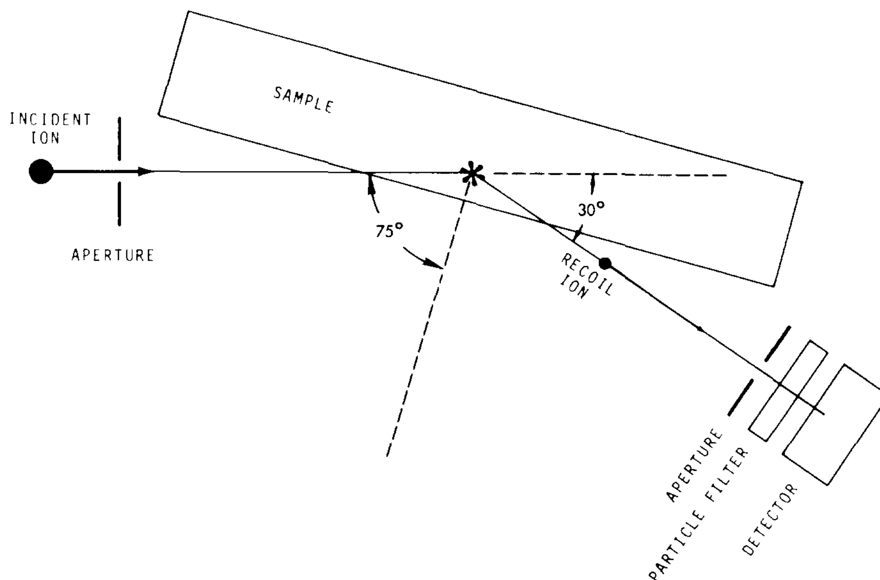

FIG. 1. Schematic illustration of the experimental arrangement for profiling H in solids using ERD.

detection (ERD) analysis technique which provides accurate measurements of ^{1}H concentration in the near-surface region of solids using 2.5-MeV Van de Graaff accelerators. The purpose of this letter is to describe this low-energy ERD technique and compare it with high-energy ERD and with nuclear-reaction analysis measurements of ^{1}H using the $^{1}H(^{19}F,\alpha\gamma)$ ^{16}O resonant nuclear reaction at 6.4 MeV ^{19}F energy.

Detection of forward-scattered ions has previously been used to profile light atomic species (masses up to 20 amu) in thin films [6] and in the near-surface region of solids. [7] These measurements used heavy projectile ions at high energy—e.g., ^{35}Cl at 30 MeV—and yield a depth resolution of $\lesssim 300$ Å and a sensitivity of $\lesssim 10^{15}$ $^{1}H/cm^2$. The experimental arrangement we use for ERD is illustrated schematically in Fig. 1. Since we are detecting the elastically recoiled particles, the angle between the detector and the incident beam must be small; angles between 20° and 30° are typically used with the sample tilted so that the angles between the sample surface and the incident and recoiled beams are identical. Because these angles are small, the surface of the sample must be smooth to achieve good depth resolution. A 10-μm Al foil is used as a particle filter to shield the detector from the forward-scattered analysis beam.

For smooth surfaces the depth resolution is determined by the stopping power of the incident and recoiled ions in the target and particle filter, straggling of recoiled ions in the detector foil, by the scattering angle and by the solid angles defined by the incident and recoiled beams. The depth resolution and the depth which can be probed also depend on the scattering angle and the angle of incidence. Depths of up to 1.5 μm can be profiled with a depth resolution of ~ 300 Å, using 12-MeV ^{12}C and a scattering angle of 30°. This is illustrated by the data in Fig. 2, where ^{1}H profiles in silicon nitride measured by nuclear-reaction analysis and ERD using 12-MeV ^{12}C, as well as 2.4-MeV ^{4}He, are compared.

The nuclear-reaction analysis data [8] in Fig. 2 were taken using the 6.4-MeV resonance in the $^{1}H(^{19}F,\alpha\gamma)$ ^{16}O reaction. This resonance yields a depth resolution of ~ 140 Å in silicon nitride and a sensitivity of ~ 200 ppm. The nuclear reaction data in Fig. 2 were taken using 2 μC/point for a total integrated charge of 66 μC, whereas the ERD data were taken using a total integrated charge of 5 and 10 μC for the ^{12}C and ^{4}He beams, respectively. As can be seen from comparison of these data, the sensitivity of ERD is quite comparable to that of nuclear-reaction analysis while the ERD resolution is only down by a factor of ~ 2 for 12-MeV ^{12}C. The sensitivity of ERD was limited for this particular experiment by the background produced from secondary collisions—i.e., by multiple scattering of both the analysis and ^{1}H recoil beams—and by projectile ions which penetrated the (perhaps nonuniform) detector foil.

A major advantage of the ERD technique is that low-energy ions can be used to profile ^{1}H; this is illustrated by the data in Fig. 2. The depth-resolution capabilities for low-en-

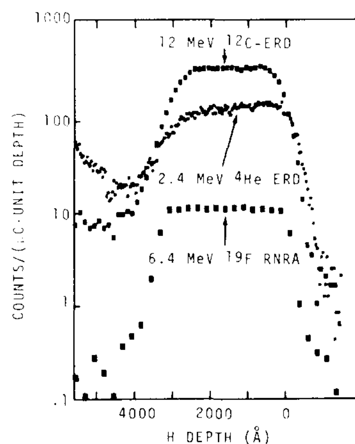

FIG. 2. Comparison between ^{1}H profiles in Si_3N_4 measured by nuclear-reaction analysis using the $^{1}H(^{19}F,\alpha\gamma)$ ^{16}O resonance at 6.4- and 12-Mev ^{12}C ERD and 2.4-Mev ^{4}He ERD. The measured yields are plotted on a log scale in units such that the yield differences are inversely proportional to the time required to collect the spectra.

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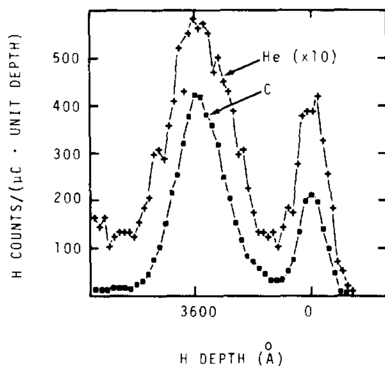

FIG. 3. Comparison of the measured profile of implanted ^{1}H in silicon measured by ERD using 12-MeV ^{12}C and 2.4-MeV ^{4}He.

ergy ERD is illustrated by the data in Fig. 3, where the ERD profiles for ^{1}H implanted into Si are compared for 2.4-MeV ^{4}He and 12-MeV ^{12}C analysis beams. The depth resolution is ~ 700 Å and the sensitivity is ~ 0.1 at.% for the 2.4-MeV ^{4}He data. Although the depth resolution and sensitivity for 2.4-MeV ^{4}He beams are degraded from those for higher-energy heavier analysis beams, much less energy is deposited into the target. Hence, the target undergoes less heating for low-energy ^{4}He analysis beams than for higher-Z analysis beams and much less beam-induced sample damage is anticipated. Indeed, it may be that low-energy beams of higher mass, e.g., ^{12}C at 2.5 MeV, will yield advantages compared to ^{4}He.

Another significant benefit of ERD compared to nuclear-reaction analysis is that multiple light elements can be profiled simultaneously with the same analysis beam. In particular, with 2.4-MeV ^{4}He, one can profile all of the hydrogen isotopes— ^{1}H, ^{2}D, and ^{3}T—in one run. At a 30° scattering angle, ^{1}H, ^{2}D, and ^{3}T can be recoiled with sufficient energy to penetrate the 10-μm Al particle filter with surface ^{2}D and ^{3}T both having a detected energy about two times that of surface ^{1}H. This capability is valuable for measurements of hydrogen retention and isotopic exchange in first-wall or coating materials subject to fusion reaction environments.

In conclusion, ERD using a 2.4-MeV ^{4}He analysis beam is a viable alternative to nuclear-reaction analysis for obtaining ^{1}H (and its isotopes) profiles in solids. Although there is some loss in sensitivity (~ 0.1 at.%) and depth resolution (~ 700 Å) compared to high-energy ERD or nuclear-reaction analysis, low-energy ^{4}He ERD offers such benefits as: (1) less energy is deposited in the target to obtain a profile, so that less beam-induced damage is expected; (2) the measurement is sensitive to all hydrogen isotopes, and only hydrogen isotopes, simultaneously; and, perhaps, most important, (3) hydrogen profiling measurements can be performed in a low-energy accelerator laboratory using the same instrumentation currently used for ion-backscattering analysis.

[1]See, for example, Nucl. Instrum. Methods **149** (1978).
[2]G. Foti, J.W. Mayer, and E. Rimini, *Ion Beam Handbook for Material Analysis*, edited by J.W. Mayer and E. Rimini (Academic, New York, 1977), pp. 21–65.
[3]L.C. Feldman and S.T. Picraux, Ref. 2, pp. 109–309.
[4]C.A. Barnes, J.C. Overley, Z.E. Switkowski, and T.A. Tombrello, Appl. Phys. Lett. **31**, 239 (1977).
[5]E. Ligeon and A. Guivarc'h, Radiat. Eff. **27**, 129 (1976).
[6]J.L'Ecuyer, C. Brassard, C. Cardinal, J. Chabbal, L. Dêschenes, J.P. Labrie, B. Terreault, J.G. Martel, and R. St.-Jacques, J. Appl. Phys. **47**, 881 (1976).
[7]B. Terrault, J.G. Martel, R.G. St.-Jacques, and J.L'Ecuyer, J. Vac. Sci. Technol. **14**, 492 (1977).
[8]For experimental details, see P.S. Peercy, H.J. Stein, B.L. Doyle, and S.T. Picraux, J. Electron. Mater. **8**, 11 (1979).

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