A Reflective Optical Transport System for Ultraviolet Thomson Scattering on OMEGA

Introduction

Thomson scattering has become a routine diagnostic in high-energy-density laser–plasma experiments[1–4] for characterizing the electron and ion temperatures by scattering 2ω ($\lambda_{2\omega}$ = 0.527 μm) or 4ω ($\lambda_{4\omega}$ = 0.263 μm) light from ion-acoustic waves.[3,5] Recently the electron density was measured[6] on OMEGA[7] by scattering 2ω light from electron plasma waves, but scattering with a 2ω probe limits these measurements to relatively low densities ($n_e \approx 5 \times 10^{20}$ cm^{-3}).

A reflective optical transport system recently implemented on the OMEGA Thomson-scattering system enables one to diagnose light from 190 nm to 850 nm. Improved spectral sensitivity at lower wavelengths allows for the observation of electron plasma wave scattering using a 4ω probe beam. The spectral range is limited by air attenuation in the UV and photocathode sensitivity in the IR. This extends the peak density from which electron plasma waves can be measured by an order of magnitude ($n_e \approx 2.0 \times 10^{21}$ cm^{-3}) (Fig. 131.34). A high-quality imaging system provides localized measurement of the plasma conditions and reduces the unwanted emission (typically bremsstrahlung and scattering from laser beams other than the probe beam). A localized measurement is obtained by overlapping the image of light scattered from the probe beam (~60-μm diameter) with a 100-μm-diam pinhole located at the entrance of the spectrometer (Fig. 131.35). When accounting for the magnification of the optical transport system (m = 1.4), light is collected from a 60-μm × 70-μm × 70-μm volume (Thomson-scattering volume).

The system consists of a reflective telescope mounted in a ten-inch manipulator (TIM) that collects scattered light and directs it along the TIM-6 line of sight to an instrument cart located approximately 8 m away from the target. A set of Pfund telescopes focus the scattered light into three independently configurable target diagnostics. To measure the ion-acoustic features, a 1-m Czerny–Turner spectrometer (3600 ll/mm grating) is coupled to a Rochester Optical Streak System (ROSS), resulting in a measured spectral resolution of 0.02 nm over a 4-nm spectral range and a pulse-front–limited time resolution of ~200 ps (Ref. 8). A 0.3-m spectrometer (600 ll/mm grating) coupled to a second ROSS is used to measure the electron plasma features. This system has a measured resolution of 0.5 nm over a 90-nm spectral range and a pulse-front–limited

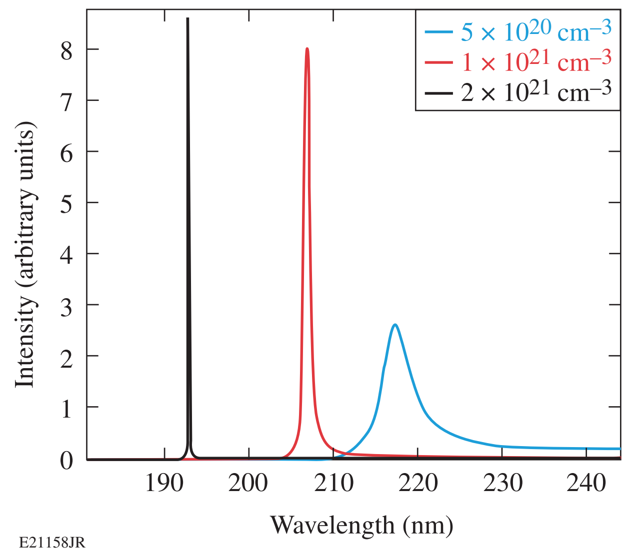

Figure 131.34
A series of calculated Thomson-scattering spectra obtained by assuming a 0.263-μm probe beam is scattered from three densities: 5×10^{20} cm^{-3}, 1×10^{21} cm^{-3}, and 2×10^{21} cm^{-3}. The scattering angle is 60° with an electron temperature of 1.8 keV.

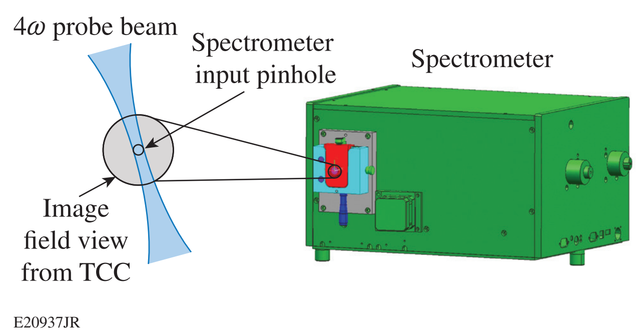

Figure 131.35
The spectrometer entrance slit is replaced with a pinhole assembly. TCC: target chamber center.

time resolution of ~50 ps. An intensified gated charge-coupled–device (CCD) camera captures two-dimensional (2-D) images with a 1.5-mm field of view and a 10-μm spatial resolution in the plasma plane. The minimum gate duration for the camera is 3 ns.

Optical Transport

1. Collection System

The TIM-mounted telescope is based on a Schwarzschild objective that uses two concentric spherical mirrors to provide diffraction-limited imaging across all reflected wavelengths.[9] The telescope was built using an *f*/10 off-axis segment of a traditional *f*/1.25 Schwarzschild objective [Fig. 131.36(a)]. The unobstructed configuration allows one to collect light at a higher *f* number while maintaining the geometry inherent to a Schwarzschild that eliminates third-order aberrations. This allows one to mount the primary and secondary mirrors without a diffraction-inducing support structure common to many reflective objectives. The telescope produces a 19-mm-diam collimated beam.

2. Collimated Transport System

Flat aluminum mirrors are used to direct collected light over an approximately 8-m distance from the OMEGA target chamber to the instrumentation cart. Beamlines for the three separate instruments are produced using uncoated wedge pickoffs or semi-aluminumized beam splitters. Each optical path has provisions to include filtering in the collimated beam to control signal level and spectral throughput.

3. Focusing System

Images are formed for each diagnostic using reflective Pfund telescopes [Fig. 131.36(b)]. Collimated light strikes a flat primary mirror with a central through-hole and is directed toward a concave, spherical secondary mirror. Light reflected off the secondary mirror is focused back through the hole of the primary mirror, allowing one to align the system on its optical axis. The primary mirror through-hole is counter sunk at a 45° angle to prevent clipping of the focusing beam on the rear surface of the mirror.

The minimum through-hole diameter is determined by the required field angle needed to image the entire Thomson-scattered volume at the desired working *f* number. The 1-m and 0.3-m systems use a 5-mm through-hole that provides a 350-μm field of view at target chamber center (TCC) with a magnification of 1.4×. Full coupling of the probe beam's waist can be accomplished with a spectrometer input image of 100 μm. Approximately 7% of the overall signal is lost through the hole in the primary mirror.

Optical Performance

Historically, efforts to observe the electron plasma wave features on OMEGA with a 4ω probe beam have been limited by the performance of the existing optical transport.[10] Previously, scattered light was collected using a fused-silica and calcium-fluoride doublet and focused with a Pfund telescope. The rapidly changing index of refraction of the doublet glasses across the deep UV spectrum introduced an 8-mm focal plane shift between focus at 265 nm and 200 nm [Fig. 131.37(a)]. As a result, the detection efficiency of the system drops significantly at wavelengths below 240 nm [Fig. 131.37(b)]. This is a result of a reduction in the signal intensity as the defocused spot size increases and the reappearance of the central through-hole in the Pfund telescope as a far-field image is presented to the spectrometer.

The reflective system has a 100-μm focal shift from 265 nm to 200 nm. The slight chromatic shift is caused by a 3-mm-thick fused-silica blast window located in front of the Schwarzschild

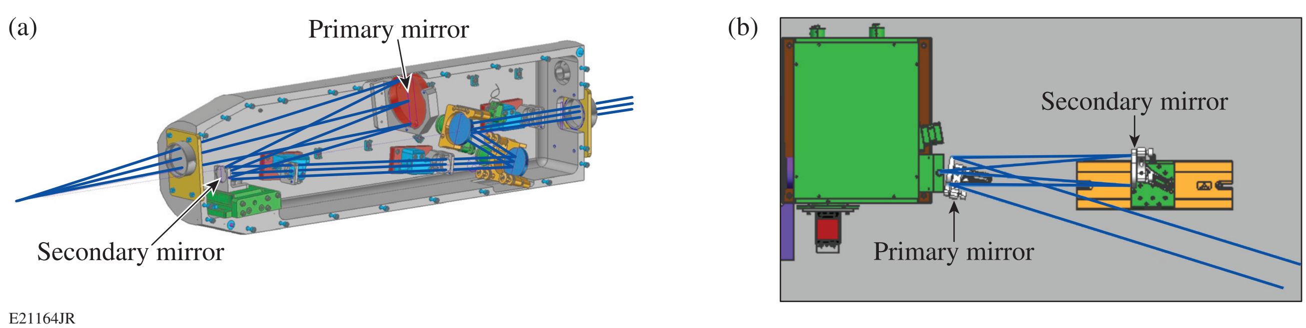

Figure 131.36
(a) An *f*/10 off-axis section of a Schwarzschild objective is used to collect scattered light. (b) A Pfund telescope focuses the scattered light to the diagnostic.

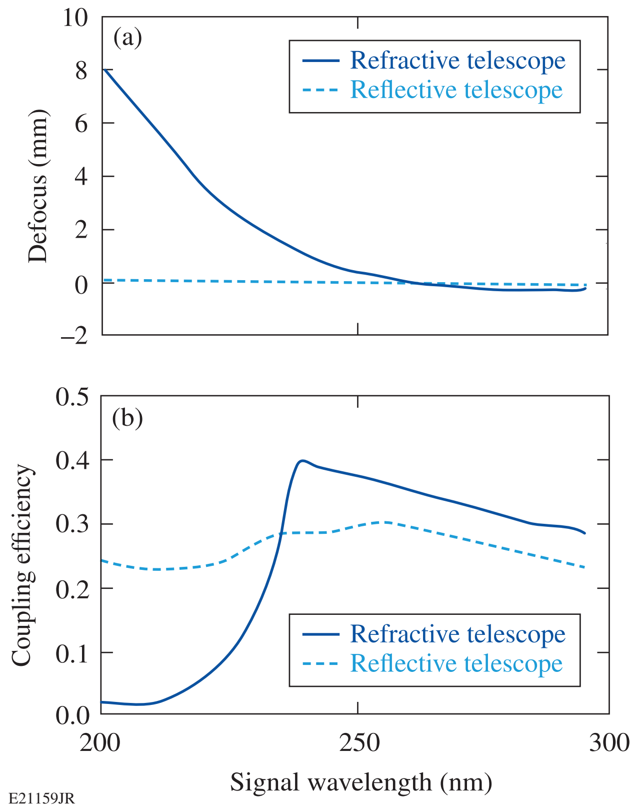

Figure 131.37
(a) Focal shift of the image plane at the spectrometer input for the refractive Thomson-scattering system. (b) Calculated transmission of an on-axis point source through the 100-μm spectrometer pinhole for the refractive system (solid curve) and the reflective system (dashed curve).

objective used to protect the primary mirror from target debris. The maximum transmission of the reflective system is slightly reduced compared to the refractive system because of the addition of four aluminum mirror elements required to collect and steer scattered light from TCC to the instrument cart. Air attenuation of deep UV signals limits the reflective systems transmission to 190 nm.

Summary

A reflective optical transport system has been designed for the Thomson-scattering system on OMEGA to provide suitable performance from 190 nm to 850 nm. This will enable the operator to perform Thomson-scattering measurements of UV light scattered from electron plasma waves.

ACKNOWLEDGMENT

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REFERENCES

1. D. H. Froula, S. H. Glenzer, N. C. Luhmann, and J. Sheffield, *Plasma Scattering of Electromagnetic Radiation: Theory and Measurement Techniques*, 2nd ed. (Academic Press, Burlington, MA, 2011).
2. S. H. Glenzer *et al*., Phys. Rev. Lett. **79**, 1277 (1997).
3. A. J. Mackinnon, S. Shiromizu, G. Antonini, J. Auerbach, K. Haney, D. H. Froula, J. Moody, G. Gregori, C. Constantin, C. Sorce, L. Divol, R. L. Griffith, S. Glenzer, J. Satariano, P. K. Whitman, S. N. Locke, E. L. Miller, R. Huff, K. Thorp, W. Armstrong, W. Bahr, W. Seka, G. Pien, J. Mathers, S. Morse, S. Loucks, and S. Stagnitto, Rev. Sci. Instrum. **75**, 3906 (2004).
4. D. H. Froula, J. S. Ross, L. Divol, N. Meezan, A. J. MacKinnon, R. Wallace, and S. H. Glenzer, Phys. Plasmas **13**, 052704 (2006).
5. D. H. Froula, J. S. Ross, L. Divol, and S. H. Glenzer, Rev. Sci. Instrum. **77**, 10E522 (2006).
6. J. L. Ross, S. H. Glenzer, P. Amendt, R. Berger, L. Divol, N. L. Kugland, O. L. Landen, C. Plechaty, B. Remington, D. Ryutov, W. Rozmus, D. H. Froula, G. Fiksel, C. Sorce, Y. Kuramitsu, T. Morita, Y. Sakawa, H. Takabe, R. P. Drake, M. Grosskopf, C. Kuranz, G. Gregori, J. Meinecke, C. D. Murphy, M. Koenig, A. Pelka, A. Ravasio, T. Vinci, E. Liang, R. Presura, A. Spitkovsky, F. Miniati, and H.-S. Park, Phys. Plasmas **19**, 056501 (2012).
7. J. H. Kelly, L. J. Waxer, V. Bagnoud, I. A. Begishev, J. Bromage, B. E. Kruschwitz, T. J. Kessler, S. J. Loucks, D. N. Maywar, R. L. McCrory, D. D. Meyerhofer, S. F. B. Morse, J. B. Oliver, A. L. Rigatti, A. W. Schmid, C. Stoeckl, S. Dalton, L. Folnsbee, M. J. Guardalben, R. Jungquist, J. Puth, M. J. Shoup III, D. Weiner, and J. D. Zuegel, J. Phys. IV France **133**, 75 (2006).
8. A. Visco, R. P. Drake, D. H. Froula, S. H. Glenzer, and B. B. Pollock, Rev. Sci. Instrum. **79**, 10F545 (2008).
9. M. J. Riedl, *Optical Design Fundamentals for Infrared Systems*, 2nd ed., Tutorial Texts in Optical Engineering, Vol. TT48 (SPIE Press, Bellingham, WA, 2001).
10. J. S. Ross, L. Divol, C. Sorce, D. H. Froula, and S. H. Glenzer, J. Inst. **6**, P08004 (2011).