Novel Laser and Diagnostic Technologies for the OMEGA EP High-Energy Petawatt Laser

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(Received March 23, 2009)

OMEGA EP (extended performance) is a petawatt-class laser facility that includes two NIF-like beamlines designed to operate in a chirped-pulse-amplification mode to produce up to 2.6 kJ in a pulse-width range of <1 to 100 ps at 1,053 nm. The OMEGA EP performance and the laser engineering of enabling technologies required to meet these goals are discussed.

Key Words: Petawatt laser, Chirped pulse amplification

1. Introduction

OMEGA EP (extended performance)¹⁾ is an addition to OMEGA²⁾ that was completed in April 2008. It includes four National Ignition Facility (NIF)³⁾ scale beamlines, two of which can be operated in a chirped-pulse-amplification (CPA) mode⁴⁾ that can be compressed to short pulses (<1 ps to 100 ps). These CPA beamlines deliver multikilojoule energies in picosecond pulses yielding petawatt powers. The Omega EP Laser System benefits significantly from advances pioneered for the NIF, as well as new laser technology developed specifically for this high-energy petawatt (HEPW) laser, which are reviewed below.

The principal mission for this new laser system is performing high-energy-density physics experiments enabled by the HEPW laser capabilities. These new capabilities include integrated fast-ignition studies in joint operation with the 60-beam, 30-kJ (ultraviolet) Omega Laser Facility, short-pulse, high-intensity, high-energy x-ray backlighting for direct-drive implosions, advanced backlighting concepts like proton beam imaging, and high-intensity physics and extreme-states-of-matter research. Initial experimental campaigns that access new regimes of laser-matter interactions in all these areas have been completed.

2. OMEGA EP Laser Technologies

Numerous enabling technologies were required to achieve the high-energy, high-power performance goals of OMEGA EP, including a high-performance, OPCPA front-end⁵⁾ with high-fluence beam shaping⁶⁾ and chromatic aberration correction.⁷⁾ The design also leverages NIF technologies, like 40 × 40-cm² disk amplifiers,⁸⁾ plasma-electrode Pockels cell⁹⁾ switches, and adaptive optics with large-aperture deformable mirrors¹⁰⁾ that required technological improvements to meet HEPW-laser-specific requirements.

The OMEGA EP HEPW laser architecture, shown in Fig. 1, is based on the multipass NIF architecture “folded” into two levels. The upper level includes a 7-disk booster amplifier that receives a seed laser pulse injected into the transport spatial filter from a hybrid OPCPA glass-amplifier front end.⁵⁾ Each beamline can be independently timed with a pulse width set by an adjustable stretch ratio set in the front end. The beamline lower level is a multipass cavity that includes a plasma-electrode Pockels cell (PEPC), a cavity spatial filter, an 11-disk main amplifier, and a deformable mirror.

After amplification, the chirped pulse is directed by switchyard mirrors (not shown) to either of two independent compressors using four matched multilayer-dielectric (MLD)^{11,12)} tiled-grating^{13–16)} assemblies and are then temporally compressed. Another vacuum-compatible deformable mirror located after the fourth tiled grating assembly provides static wavefront correction, primarily for grating phase errors. The instruments in the short-pulse diagnostic package (SPDP) receive a sample beam from a leaky mirror to diagnose the short-pulse properties of the beams,^{17–21)} as well as to provide alignment sources for the short-pulse transport paths to the target, and Fizeau interferometers in the grating compressor chamber to set the grating tiling.

After passing through their individual compressors, the two short-pulse OMEGA EP beams can be co-aligned through a polarizing beam combiner (not shown) and delivered to either the OMEGA or OMEGA EP target chamber, or delivered along separate beam paths to the OMEGA EP target chamber for separate “backlighter” and “sidelighter” applications. The beams are focused using off-axis parabolic mirrors. The B-integral of the OMEGA EP HEPW laser system is limited to approximately 1 radian to minimize degradation of focusing, so the pulse width of the compressed pulse transmitted through the polarizer must be longer than 80 ps at full system energy when the two beams are polarization

Fig. 1 Schematic of an OMEGA EP short-pulse beamline configuration. The short-pulse beams in the OMEGA EP target chamber can be focused from orthogonal directions with off-axis parabolas OAP1 and OAP2. (PEPC: plasma-electrode Pockels cell; POL: polarizer).

combined.

2.1 High-Energy, High-Repetition-Rate Broadband Front End

The OMEGA EP front end uses optical parametric chirped-pulse amplification (OPCPA)^{22,23)} to support the required bandwidth. The OPCPA system delivers high-energy (>250 mJ), high-repetition-rate (5 Hz), broadband (>8 nm) pulses⁴⁾ to the beamlines for pre-shot alignment operations and laser-glass amplification for target shots. Seed pulses are generated by a mode-locked Nd:phosphate oscillator (Time Bandwidth Products GLX-200) operating at 76 MHz that is synchronized to the OMEGA master clock. Using critically phase-matched lithium triborate (LBO) crystals the two-stage OPCPA system has a net gain of $> 5 \times 10^8$. The preamplifier delivers ~60-mJ pulses to a power amplifier stage that produces output energies exceeding 0.5 J. In normal operation, the output is derated to 30 mJ from the preamplifier and 200 mJ from the power amplifier to increase reliability. The OPCPA system is pumped by a frequency-doubled Nd:YLF-based laser with uniform intensity in both space and time.²⁴⁾

2.2 High-Fluence Beam Shaping

HEPW laser systems like OMEGA EP require spatial beam shaping to maximize the amplifier fill factor and to precompensate for the spatially varying gain of the large disk amplifiers. OMEGA EP requires a beam-shaping capability at a fluence of 0.5 J/cm² for a 2.4-ns pulse duration to shape the OPCPA output beam before amplification in Nd:glass amplifiers. These high-fluence beam shapers employ a binary pattern of metal pixels produced on a glass substrate using lithographic techniques with features on the 10-μm scale.⁶⁾ The binary transmission pattern (0 % or 100 %) imposed on the beam by the apodizer is transformed into a continuous distribution after the beam is propagated through a spatial filter. The distribution of binary pixels on the apodizer is calculated using error-diffusion algorithms to set the local pixel density. Error diffusion is a deterministic procedure that generates a pixellated binary distribution approximating a continuous transmission after filtering. The inherent local error induced by the choice of the transmission value of one pixel is used to bias the design transmission of adjacent pixels

in order to locally cancel the transmission error. The algorithm produces low-noise, high-resolution beam shaping for both high-order super-Gaussian beam profiles and precompensation of the spatial gain for OMEGA EP. After beam apodization produces the required square beam profile, the pulse energy injected into the glass amplifiers is approximately 100 mJ, which constitutes approximately a 50 % energy throughput for the OPCPA system output. Beam profile shaping to compensate for glass amplifier spatial gain variations introduces additional losses of approximately 50 %.

2.3 Chromatic Aberration Correction

Axial chromatic aberration accumulating from the refractive lenses used to image-relay laser light²⁵⁾ through OMEGA EP would severely limit the focal irradiance caused by both spatial and temporal spreading. Pulse-front curvature, also resulting from axial chromatic aberration, further broadens the Fourier-transform-limited pulse shape in the focal plane. Uncorrected, the combination of spatial and temporal spreading, illustrated in Fig. 2 (a), reduces the focal-plane irradiance by more than a factor of 8 compared to the ideal case in Fig. 2 (b). Optical modeling shows that simultaneous correction of spectral spreading in both space and time can be realized using a single diffractive color corrector (DCC) located at the input to the transport spatial filter, as shown in Fig. 2 (c).⁷⁾ This diffractive surface combined with a refractive lens is installed in OMEGA EP and compensates all the chromatic aberrations of the large-aperture lenses in OMEGA EP. The kinoform surface is generated by single-point diamond turning an acrylic polymeric film deposited on a glass substrate. The polymer significantly has a damage-threshold close to 20 J/cm².

2.4 High-Contrast, Double-Pulse Plasma-Electrode Pockels Cell (PEPC)

The plasma-electrode Pockels cell (PEPC) is an electro-optic device developed at LLNL⁷⁾ for use on the NIF to switch the beam into and out of the amplifier cavity. The LLNL design has been adapted for use on OMEGA EP,²⁷⁾ where the PEPC is also used to provide isolation from light retroreflected from the target using a double-pulsed high-voltage driver. The LLNL PEPC design, constrained by a close-packing-density requirement and requiring only a switching contrast ratio

exceeding 50:1 at each point of the beam, was unsuitable for this purpose. A new PEPC cell with circular windows was developed with a measured switching contrast ratio exceeding 500:1 at all points over the entire clear aperture. The local contrast ratio is plotted in Fig. 3 (a) with the minimum value over 1000:1. Reliability was demonstrated by operating the PEPC for a full day at a 0.1-Hz pulse rate and measuring the contrast. After a 20-min warm-up period, every measured PEPC shot exceeded the 500:1 requirement, with a typical minimum contrast ratio of approximately 1000:1.

2.5 Multilayer Dielectric (MLD) Gratings

One of the major technological challenges to achieving HEPW laser performance is the grating compressor at the output of the Omega EP Laser System. Large-aperture, high-efficiency gratings with high damage thresholds and high wavefront quality are required. The energy-limiting component in Omega EP is the last grating in the four-grating compressor that experiences the shortest pulse and is the most susceptible to damage. Holographically formed reflection gratings fabricated on a multilayer-dielectric (MLD) high-reflector coating provide the required performance. LLE collaborated closely with LLNL to develop the MLD gratings used in Omega EP. This collaborative effort included a range of efforts to improve thin-film coating fabrication (LLE), etching and cleaning (LLNL), as well as laser damage testing (LLE).

An MLD reflection grating is composed of a binary surface relief formed in the top layer of a high-damage-threshold MLD stack.²⁸⁾ The grating is made by coating a uniform layer of photoresist – a photosensitive material – onto the top (SiO_2) layer of a multilayer dielectric coating. The photoresist is exposed to the interference pattern formed at the intersection of two coherent ultraviolet laser beams and etched to form the surface relief pattern. After etching through this relief pattern

Fig. 2 Calculated OMEGA EP focal irradiance (a) with chromatic aberration and (b) corrected using a diffractive color corrector. (c) Schematic showing the use of a diffractive color corrector as part of the transport-spatial-filter injection system. The DCC consists of an air-spaced doublet with a diffractive lens on the flat surface of the second element.

and removal of the photoresist, the grating is formed in the top layer of SiO_2 . Process witness samples of the MLD gratings used on OMEGA EP have been damage tested with both submillimeter- and centimeter-scale laser-spot sizes. Laser damage testing is performed single-shot with the test fluence ramped after each shot to identify the value at which damage is first observed. Fig. 4 shows pulse-length scaling for one 100-mm-diam MLD grating sample consistent with the $\tau^{1/2}$ scaling previously reported for pulses in the 20-ps to 1-ns pulse-length range for bulk fused silica.²⁹⁾

2.6 Tiled-Grating Compressor

OMEGA EP has two independent grating compressors supporting two short-pulse beams with output pulse lengths in the range <1 ps to 100 ps. Each pulse compressor consists of four sets of tiled-grating assemblies (TGA1 to TGA4), shown in Fig. 5, composed of three $47 \times 43\text{-cm}^2$ MLD gratings.¹⁶⁾ The width of the assembly is required to accommodate the OMEGA beam footprint at the 72.5° input incidence angle, which offers a large pulse-compression ratio and relaxes the damage-threshold requirements for the gratings. The vertical grooves of the gratings have a pitch of 1,740 grooves/mm. The three tiles are mounted on a precision six-axis stage for

Fig. 3 (a) Contrast-ratio map measured in a scanning polarimeter with the PEPC actively switching. (b) Measured minimum local contrast ratio for individual shots during extended testing over more than 6 h. The dashed line indicates the minimum required contrast ratio.

Fig. 4 Pulse-length (τ) dependence of threshold damage fluence for a 100-mm-diam, 1,740 lines/mm, multilayer dielectric grating tested at a 61° angle of incidence. The solid lines are fits to the data below and above $\tau = 20$ ps.

Fig. 5 A tiled-grating assembly, comprising three tiled gratings on a tile support beam placed on a six-axis base used for compressor alignment. Each of the outer grating tiles has a precision control system used to align the beam wavefront to that of the center tile.

compressor alignment.

The outer tiles of a TGA are precisely aligned, using an interferometer incorporated into the vacuum compressor chamber, to the center tile to control tip, tilt, rotation, piston, and shift to minimize errors in the combined wavefront. Fourier fringe analysis³⁰⁾ is used to retrieve the phase of each tile and calculate the differential tilt, tip, and piston between the central tile and each outboard tile. The differential values are used as feedback to control the tiling actuators to minimize the overall wavefront of the full TGA. This near-field tiling process has been automated.¹⁵⁾ Tiled positions are maintained by closing the actuator control loop with the feedback of position displacement sensors. Submicroradian angular-tiling stability has been achieved for all eight tiled-grating assemblies.

After tiled-grating and compressor alignment, temporal pulse compression and focusing were compared for single-central-tile and triple-tile configurations for both OMEGA EP

Fig. 6 Auto-correlation scanning results for single-tile and triple-tile configurations for the (a) lower compressor and (b) upper compressor.

compressors. Fig. 6 shows that the measured second-order autocorrelation traces for both compressors are nearly transform limited with no significant pulse-duration change due to tiling. Similarly, focal-spot measurements show that grating tiling does not degrade the spatial performance, other than improving the diffraction-limited spot size, as expected because of the larger beam size.¹⁶⁾

2.7 Short-Pulse Diagnostics

Characterizing the Omega EP Laser System output is crucial for successful target experiments. Accurate laser diagnostics are also required to safely operate the laser system since it operates close to its damage threshold. A short-pulse diagnostic package (SPDP) includes instruments to diagnose the properties of the beams measuring the beam quality, energy, alignment, spectrum, optical-component damage, output wavefront, pulse width, and pulse contrast. The SPDP also includes a dual-wavelength IR alignment laser (1,053 nm and 1,047 nm) that can illuminate the short-pulse transport paths to the target and to the Fizeau interferometers in the grating compressor chamber.

OMEGA EP produces high-energy pulses over the 0.5- to 100-ps range, presenting significant challenges for a single pulse-measurement device. Electronic devices are typically limited to pulses longer than a few picoseconds, whereas photon-based devices are typically limited to pulses shorter than a few picoseconds. As a result, the ultrafast temporal diagnostics (UTD's) consist of a suite of complementary diagnostics with overlapping ranges.¹⁷⁾ For pulse widths in the 8- to 300-ps range, an ultrafast streak camera based on the ROSS (Rochester Optical Streak System) platform¹⁸⁾ measures both short-pulse beams with a resolution of a few picoseconds. For shorter pulses, a time-expanded single-shot autocorrelator

(TESSA) measures the autocorrelation of pulses with widths from 0.4 ps to 12 ps, and therefore overlaps with the ultrafast streak camera range. A second-generation temporal diagnostic based on electro-optic shearing interferometry (EOSI) providing full temporal electric-field characterization of a pulse in a single shot²⁰⁾ has also been demonstrated and is being engineered for implementation on OMEGA EP.

Direct measurement of the high-energy OMEGA EP focus during target shots is impractical, so the on-shot focal-spot diagnostic (FSD)¹⁹⁾ uses pre- and on-shot wavefront and near-field spatial-profile measurements to characterize the spatial irradiance pattern on target. High-resolution Shack-Hartmann wavefront sensors³¹⁾ measure the wavefront and fluence of the sample beam, from which the far-field irradiance is calculated numerically using standard scalar diffraction theory. Additional measurements using diffraction-limited probe beams are required before the shot to account for aberrations from the sample-beam down-collimation optics and from the main beam-transport and focusing system. Good agreement is obtained with direct measurements of the focal spot over four decades of dynamic range.

2.8 Off-Axis Parabolic Mirror Focusing

After the laser pulses are compressed and polarization combined³²⁾ for copropagating pulses, they are transported in vacuum to target in any of the three available beam paths by steering mirrors and focused by an $f/1.8$ off-axis parabola with

a 1-m focal length. The off-axis parabola (OAP) requires precise alignment to the optical axis of the system to avoid aberrations, which is accomplished using a parabola alignment diagnostic (PAD). The PAD produces a diffraction-limited alignment beam from the intended focal point that can be counter-propagated through any of the transport paths to set the OAP mirror alignment. A five-axis OAP inserter/manipulator, shown in Fig. 7, positions the focusing mirror with measured three-axis translational and two-axis rotation accuracies of 0.1 μm and 0.1 μrad , respectively.

3. Conclusion

The four-beam OMEGA EP laser facility (including nanosecond ultraviolet beams) was completed in April 2008. Short-pulse system performance has been ramped to 1-kJ at 10 ps to support initial target experiments, including the first cone-in-shell fast-ignition target interactions, isochoric heating, and laser-to-fast-electron-coupling experiments. Efforts are underway to ramp up to the OMEGA EP design performance of 2.6-kJ at 10 ps and 1-kJ at 1 ps to support its missions of high-energy and high-brightness backlighting, integrated fast-ignition experiments, development of advanced backlighting techniques for HED physics, and, finally, ultrahigh-intensity laser-matter interaction experiments.

Acknowledgments

This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC52-08NA28302, the University of Rochester, and the New York State Energy Research and Development Authority. The support of DOE does not constitute an endorsement by DOE of the views expressed in this article.

References

- 1) 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, *et al.*: J. Phys. IV France **133** (2006) 75.
- 2) T. R. Boehly, D. L. Brown, R. S. Craxton, R. L. Keck, J. P. Knauer, J. H. Kelly, T. J. Kessler, S. A. Kumpan, S. J. Loucks, S. A. Letzring, F. J. Marshall *et al.*: Opt. Commun. **133** (1997) 495.
- 3) C. A. Haynam, P. J. Wegner, J. M. Auerbach, M. W. Bowers, S. N. Dixit, G. V. Erbert, G. M. Heestand, M. A. Hennesian, M. R. Hermann, K. S. Jancaitis, K. R. Manes, *et al.*: Appl. Opt. **46** (2007) 3276.
- 4) D. Strickland and G. Mourou, Opt. Commun. **56** (1985) 219.
- 5) V. Bagnoud, I. A. Begishev, M. J. Guardalben, J. Puth, and J. D. Zuegel: Opt. Lett. **30** (2005) 1843.
- 6) C. Dorrer and J. D. Zuegel: J. Opt. Soc. Am. B **24** (2007) 1268.
- 7) T. J. Kessler, H. Huang, and D. Weiner: presented at the *International Conference on Ultrahigh Intensity Laser Development*, Science and Emerging Applications 2006 ICUIL, Cassis, France, 25-29 September 2006.
- 8) T. Alger, A. Erlandson, S. Fulkerson, J. Horvath, and K. Jancaitis: Lawrence Livermore National Laboratory, Livermore, CA, Report UCRL-ID-132680, NTIS Order No. DE2002-791837 (1999).
- 9) M. A. Rhodes, B. Woods, J. J. DeYoreo, D. A. Roberts, and L. J. Atherton: Appl. Opt. **34** (1995) 5312.
- 10) R. A. Zacharias, N. R. Beer, E. S. Bliss, S. C. Burkhart, S. J. Cohen, S. B. Sutton, R. L. Van Atta, S. E. Winters, J. T. Salmon, M. R. Latta, C. J. Stolz *et al.*: Opt. Eng. **43** (2004) 2873.
- 11) L. Li and J. Hirsh: Opt. Lett. **20** (1995) 1349.
- 12) B. W. Shore, M. D. Perry, J. A. Britten, R. D. Boyd, M. D. Feit, H. T. Nguyen, R. Chow, G. E. Loomis, and L. Li: J. Opt. Soc. Am. A

Fig. 7 (a) The off-axis parabola inserter/manipulator provides highly stable and precise positioning of the OAP focusing mirror. (b) The OAP mirror is inserted into either the OMEGA or OMEGA EP target chamber through a vacuum interlock.

- 14** (1997) 1124.
- 13) T. J. Kessler, J. Bunkenburg, H. Huang, A. Kozlov, and D. D. Meyerhofer: *Opt. Lett.* **29** (2004) 635.
- 14) J. Bunkenburg, T. J. Kessler, W. Skulski, and H. Huang: *Opt. Lett.* **31** (2006) 1561.
- 15) J. Qiao, A. Kalb, M. J. Guardalben, G. King, D. Canning, and J. H. Kelly: *Opt. Express* **15** (2007) 9562.
- 16) J. Qiao, A. Kalb, T. Nguyen, J. Bunkenburg, D. Canning, and J. H. Kelly: *Opt. Lett.* **33** (2008) 1684.
- 17) J. Bromage, J. D. Zuegel, S.-W. Bahk, D. S. Vickery, L. J. Waxer, D. Irwin, V. Bagnoud, R. Boni, M. D. Moore, R. Jungquist, and C. Stoeckl: *J. Phys. IV France* **133** (2006) 705.
- 18) R. A. Lerche, J. W. McDonald, R. L. Griffith, G. Vergel de Dios, D. S. Andrews, A. W. Huey, P. M. Bell, O. L. Landen, P. A. Jaanimagi, and R. Boni: *Rev. Sci. Instrum.* **75** (2004) 4042.
- 19) J. Bromage, S.-W. Bahk, D. Irwin, J. Kwiatkowski, A. Pruyne, M. Millecchia, M. Moore, and J. D. Zuegel: *Opt. Express* **21** (2008) 16, 561.
- 20) J. Bromage, C. Dorrer, I. A. Begishev, N. G. Usechak, and J. D. Zuegel: *Opt. Lett.* **31** (2006) 3523.
- 21) C. Dorrer, J. Bromage, and J. D. Zuegel: *Opt. Express* **16** (2008) 13, 534.
- 22) A. Dubietis, G. Jonusauskas, and A. Piskarskas: *Opt. Commun.* **88** (1992) 437.
- 23) I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier: *Opt. Commun.* **144** (1997) 125.
- 24) V. Bagnoud, M. J. Guardalben, J. Puth, J. D. Zuegel, T. Mooney, and P. Dumas: *Appl. Opt.* **44** (2005) 282.
- 26) H. M. Heuck, P. Neumayer, T. Kuhl, and U. Wittrock: *Appl. Phys. B* **84** (2006) 421.
- 27) B. E. Kruschwitz, J. H. Kelly, M. J. Shoup III, L. J. Waxer, E. C. Cost, E. T. Green, Z. M. Hoyt, J. Taniguchi, and T. W. Walker: *Appl. Opt.* **46** (2006) 1326.
- 28) J. B. Oliver, T. J. Kessler, H. Huang, J. Keck, A. L. Rigatti, A. W. Schmid, A. Kozlov, and T. Z. Kosc: *Laser-Induced Damage in Optical Materials: 2005* ed. G. J. Exarhos, A. H. Guenther, K. L. Lewis, D. Ristau, M. J. Soileau, and C. J. Stolz (SPIE, Bellingham, WA, 2005), Vol. 5991, p. 402.
- 29) B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry: *Phys. Rev. B* **53** (1996) 1749.
- 30) M. Takeda, H. Ina, and S. Kobayashi: *J. Opt. Soc. Am.* **72** (1982) 156.
- 31) S.-W. Bahk: *Opt. Lett.* **33** (2008) 1321.
- 32) J. B. Oliver, A. L. Rigatti, J. D. Howe, J. Keck, J. Szczepanski, A. W. Schmid, S. Papernov, A. Kozlov, and T. Z. Kosc: *Laser-Induced Damage in Optical Materials: 2005* ed. G. J. Exarhos, A. H. Guenther, K. L. Lewis, D. Ristau, M. J. Soileau, and C. J. Stolz (SPIE, Bellingham, WA, 2005), Vol. 5991, p. 394.