Performance of and Initial Results from the OMEGA EP Laser System

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Abstract. The OMEGA EP Laser System was completed in April 2008. It consists of four NIF-like beamlines that will each produce 6.5 kJ per beam at a 351-nm wavelength in a 10-ns pulse. Two of the beamlines can be configured as high-energy petawatt (HEPW) beamlines that will each produce 2.6 kJ in a 10-ps laser pulse. This paper describes the current status of the OMEGA EP Laser System and some initial experimental results.

1. Introduction
The Laboratory for Laser Energetics completed its new long-pulse ultraviolet and high-energy petawatt (HEPW) laser system, OMEGA EP, in April 2008 [1–3]. It consists of four NIF-like beamlines [4] that will each produce 6.5 kJ per beam at a 351-nm wavelength in a 10-ns pulse. Two of them can be configured as high-energy petawatt (HEPW) beamlines that will each produce 2.6 kJ in a 10-ps laser pulse at a wavelength of 1.053 μm. The current UV laser performance is limited by the installed optics. Higher-damage-threshold UV optics have been ordered to achieve full UV capability in FY11.

The HEPW energy has been ramped to 2.1 kJ in a 12-ps pulse. The energy is limited by the intensity modulations in the beam near field and lower optics vacuum damage thresholds than expected. Significant progress has been made in developing OMEGA EP as a fully equipped user facility. Many diagnostics have been installed and a number of exciting physics results have been obtained.

Section 2 describes the current performance of the OMEGA EP HEPW Laser System. Section 3 describes some of the initial experimental results. Section 4 concludes this article.
2. Performance of the OMEGA EP Laser System

A significant effort has been devoted to increasing the on-target HEPW laser energy. In August–September 2009, the IR energy was ramped to 2.1 kJ in a 12-ps laser pulse. Damage was observed on the final grating and a few downstream optics. The damage appears to be related to near-field modulations on the amplified beam and lower than expected optics damage thresholds in vacuum. The damaged optics have been replaced and routine operation with 1.5-kJ, 10-ps laser pulses is anticipated by mid-FY10. Work will continue in FY10 to improve the beam performance and understanding vacuum optics damage thresholds leading to the generation of full-system energy (2.6 kJ in 10 ps) in FY11.

Laser-diagnostic capabilities on OMEGA EP are improving in parallel with system performance. The focal spot is determined from the measured beam-wavefront and phase errors in the optical path to the target chamber [5,6]. This technique has been experimentally validated with direct focal-spot measurements of low-energy laser pulses. Figure 1 shows the encircled energy calculated for a 1-kJ, 10-ps laser pulse, showing a 22.7-μm radius encloses 80% of the beam’s energy. The inset shows the calculated intensity distribution in the target plane. Ongoing improvements to the wavefront quality of the OMEGA EP beamlines will reduce the focal-spot size.

![Figure 1. Encircled energy of an OMEGA EP beam at best focus. The inset shows the focal-spot image on a logarithmic scale. The IR pulse energy was 1 kJ in a 10-ps laser pulse.](E18355J1)

The optical contrast of high-intensity laser pulses can affect the laser–target interaction physics. LLE is developing two diagnostics to measure the on-shot contrast. Both have been shown to measure the pulse contrast to 80 dB or higher. The optical contrast within 0.5 ns of the peak of the pulse will be measured with a single-shot cross-correlator based on pulse replication [7]. The optical contrast up to 0.5 ns before the peak of the pulse will be measured with a fast photodiode and oscilloscope. This device was installed for a series of 1.5-kJ, 10-ps laser pulse target experiments. Figure 2 shows the optical contrast in this time window for three shots. The pedestal is reproducible at the –60-dB level. This pedestal contains approximately 0.01% of the pulse energy (~150 mJ). Note that if the pulse were compressed to 1-ps duration, the energy in the pedestal would be unchanged and the intensity contrast would be ~70 dB.
Figure 2. Measurements of the optical contrast of the OMEGA EP HEPW beamline up to 0.5 ns before the main pulse. The laser pulse energy was 1.5 kJ in a 10-ps laser pulse for all shots.

3. Initial results from the OMEGA EP Laser System

When an intense laser pulse interacts with a solid target, a significant fraction of the laser beam’s energy is converted into energetic electrons [8,9]. As the electrons reach the rear surface of the target some escape, setting up a sheath field that confines the remaining electrons to the target [10–12]. The electrons collide with the target atoms heating the target and producing K-shell radiation. The amount of K-shell radiation is proportional to the total energy in the energetic electrons [13]. As the target is heated, the atoms are ionized, reducing the population in the levels that produce the K\(_{\beta}\) radiation so that the ratio of the K\(_{\beta}\)-to-K\(_{\alpha}\) signals decreases [12,14]. As a result, K-shell spectroscopy provides two ways of determining the laser-to-energetic-electron conversion efficiency. The amount of target heating should be consistent with the conversion efficiency determined from the K\(_{\alpha}\) yield.

A series of experiments were carried out on the MTW Laser System [15] (1 ps, 1 to 10 J) at the Laboratory for Laser Energetics, where the absolute K\(_{\alpha}\) yield and the K\(_{\beta}\)-to-K\(_{\alpha}\) ratio was measured [16,17]. The K\(_{\beta}\)-to-K\(_{\alpha}\) ratio data is shown in Fig. 3 (black dots) as a function of laser energy divided by target volume (target energy density). Both the yield and the ratio are consistent with a laser-to-energetic-electron conversion efficiency of 20±10% (20% shown in the solid black line). The right-hand axis shows the temperature of the target determined from this ratio that is consistent with the predicted energetic-electron conversion efficiency. Solid density conditions with temperatures in excess of 200 eV are inferred.

Figure 3: The ratio of the K\(_{\beta}\)-to-K\(_{\alpha}\) signals from high-intensity laser interactions with small mass targets as a function of the energy density (laser energy/target volume). The black points have a laser energy of 1 J in 1 ps, while the blue points are from OMEGA EP with energies up to 1.3 kJ in 10 ps. The black line is a prediction of line ratio as a function of energy density of a laser-to-electron conversion efficiency of 20%. The right-hand axis shows the solid density target temperature inferred in these experiments.
These experiments were extended to the OMEGA EP Laser System with energies up to 1.3 kJ in a 10-ps pulse [18]. The $K_{\beta}$-to-$K_{\alpha}$ ratios are shown as the blue points in Fig. 3, again as a function of target energy density. The OMEGA EP data are consistent with the MTW data, suggesting that the conversion efficiency is unchanged from 1 J, 1 ps to 1300 J, 10 ps.

4. Summary
The OMEGA EP Laser System was completed in FY08 and began operation for users in FY09. The laser-system performance and its diagnosis continues to improve. In its first year OMEGA EP conducted 350 target shots for 30 principal investigators. In one series of experiments, the conversion efficiency from high-intensity laser energy to electrons was found to be ~20%, independent of laser energy between 1 and 1300 J and pulse duration between 1 and 10 ps.

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References
[1] Maywar D N et al. 2008 J. Phys., Conf. Ser. 112 032007
[2] Waxer L J et al. The OMEGA EP High-Energy, Short-Pulse Laser System presented at CLEO/QELS 2008 (San Jose, CA, 4–9 May 2008) paper JThB1
[3] Waxer L J et al. 2005 Opt. Photonics News 16 30–6
[4] Moses E I 2008 Fusion Sci. Technol. 54 361–6
[5] Bromage J, Bahk S-W, Irwin D, Kwiatkowski J, Pruyne A, Millecchia M, Moore M and Zuegel J D 2008 Opt. Express 21 16,561–72
[6] Zuegel J D et al. 2009 Rev. Laser Eng. 37 437–42
[7] Dorrer C, Bromage J and Zuegel J D 2008 Opt. Express 16 13,534–44
[8] Chaker M, Kieffer J C, Matte J P, Pépin H, Audebert P, Maine P, Strickland D, Bado P and Mourou G 1991 Phys. Fluids B 3 167–75
[9] Kieffer J C et al. 1989 Phys. Rev. Lett. 62 760–3
[10] Hatchett S P et al. 2000 Phys. Plasmas 7 2076–82
[11] Snively R A et al. 2000 Phys. Rev. Lett. 85 2945–48
[12] Myatt J, Theobald W, Delettrez J A, Stoeckl C, Storm M, Sangster T C, Maximov A V and Short R W 2007 Phys. Plasmas 14 056301
[13] Theobald W et al. 2006 Phys. Plasmas 13 043102
[14] Gregori G et al. 2005 Contrib. Plasma Phys. 45 284–92
[15] Bagnoud V, Begishev I A, Guardalben M J, Puth J and Zuegel J D 2005 Opt. Lett. 30 1843–45
[16] Nilson P M, Theobald W, Myatt J, Stoeckl C, Storm M, Gotchev O V, Zuegel J D, Betti R, Meyerhofer D D and Sangster T C 2008 Phys. Plasmas 15 056308
[17] Nilson P M, Theobald W, Myatt J F, Stoeckl C, Storm M, Zuegel J D, Betti R, Meyerhofer D D and Sangster T C 2009 Phys. Rev. E. 79 016406
[18] Nilson P M, Theobald W, Myatt J, Stoeckl C, Storm M, Gotchev O V, Zuegel J D, Betti R, Meyerhofer D D and Sangster T C 2009 Effect of Laser Energy and Pulse Duration on Energetic-Electron Production in Intense Laser–Solid Interactions submitted to Phys. Rev. Lett.