3.B The Upgrade to the OMEGA Laser System

The upgrade to the OMEGA laser system will provide a unique capability to validate high-performance, direct-drive laser-fusion targets. The ultimate goal of the experimental program on the OMEGA Upgrade is to study the physics of hot-spot formation under near-ignition conditions (ignition scaling), using cryogenic targets whose hydrodynamic behavior scales to that of high-gain targets. Specific performance goals of these experiments are the achievement of a convergence ratio (C_R) $\gtrsim$ 20, an ion temperature (T_i) of 2 to 3 keV, and a total fuel areal density (ρR) in excess of 0.2 g/cm^2 for targets whose Rayleigh-Taylor growth factors are in excess of 500. In this article, the top-level specifications required for these experiments will be presented along with the constraints they place on the laser system. The configuration of the laser system and the target-irradiation facility will be reviewed, as will the control system.

System Specifications

The conceptual design for the OMEGA Upgrade was completed in 1989 and resulted in a preliminary design document (Title I).[1] Since completion of that document, a number of changes have been made to the laser system to optimize the configuration and performance. This article will describe the most recent configuration of the laser system and explain its design.

The total energy, uniformity, and pulse-shaping requirements for the proposed ignition-scaling experiments call for a 60-beam system, which will produce 30 kJ on target in temporally shaped pulses with peak powers in excess of 40 TW. The upgraded system will fit into the existing building, will allow for maximum use of existing hardware, and will satisfy budgetary constraints. The top-level performance requirements for this system are given in Table 55.VIII.

A key parameter of this system is the number of beams on target. The 60-beam configuration has been adopted as it provides a significant improvement of uniformity over the existing 24-beam system with minimal additional complexity. The 60 beams are sufficient to meet theoretical uniformity requirements, and compared to systems with fewer beams, the 60-beam system provides a lower sensitivity to individual beam characteristics. In addition, the beam aperture required to supply 30 kJ in 60 beam lines is sufficiently small that beam segmentation can be avoided, allowing the use of optical components with reasonable cost per unit area.

Co-Propagation and Pulse Shaping

The shaped pulse required for an efficient ablative target implosion presents a significant problem because of the limited dynamic range of practical frequency-tripling schemes. The solution incorporated into the upgrade design is the co-propagation, through the laser system, of two spatially separated pulses. In this design, a small-diameter foot pulse, of circular cross section, co-axially propagates inside an annular main pulse (Fig. 55.33). The two pulses are separated by a null zone that has no laser light propagating in it. By concentrating the low-power portion of the pulse in the foot, the intensity of both the main and foot pulses can be matched for efficient frequency conversion. While this benefit in conversion efficiency is about equal to the losses inherent in the null zone, co-propagation will be used in the upgrade because it offers attractive opportunities for pulse shaping and laser-uniformity schemes.

Table 55.VIII: OMEGA Upgrade design goals.

Energy on target	Up to 30 kJ (pulse shaped)
Wavelength	351 nm (third harmonic of Nd:glass)
Lasing medium	Nd-doped phosphate glass
Number of beams	60
On-target irradiation uniformity	1%–2% rms
Diagnostic solid angle	π sr
Repetition rate	1 shot/h

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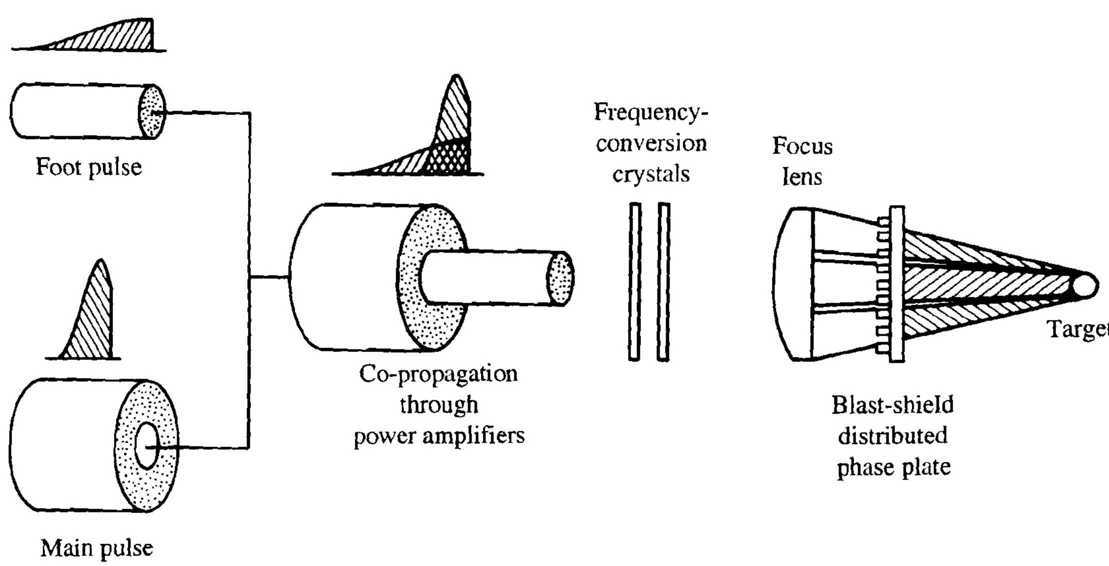

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Fig. 55.33
Schematic of the co-propagated main- and foot-pulse beams for the OMEGA Upgrade.

Figure 55.34 is a scale drawing of the beam's cross section at the frequency-conversion crystals; the dark areas represent the nominal beam areas (where the beam is approximately flat topped), and the lighter shading indicates the transition regions where the intensity of each beam falls to zero, roughly as an order-eight super-Gaussian. The null zone, which contains no laser energy, is maintained between the pulses to allow for their separate diagnosis, to prevent constructive interference that could result if the beams were to overlap, and to minimize the risk of inadvertent damage to the system. It is important to note that this co-propagation configuration can be used to irradiate fusion targets only because distributed phase plates (DPP's) are used at the focus lenses: since each DPP element irradiates the whole target, the locations of the foot and main beams in the near field are immaterial.

Co-propagation begins at the front end of the laser system, where two oscillator pulses are first amplified in separate laser drivers and then appropriately apodized and combined into a single beam. This coaxial combination of separate pulses is maintained through the remainder of the laser system. The size of the UV beam and its aspect ratio are chosen so that the UV energy loading, multiplied by a safety factor to accommodate intensity modulations, does not exceed the damage threshold of the high-reflectance and anti-reflection coatings in the UV beam transport system.

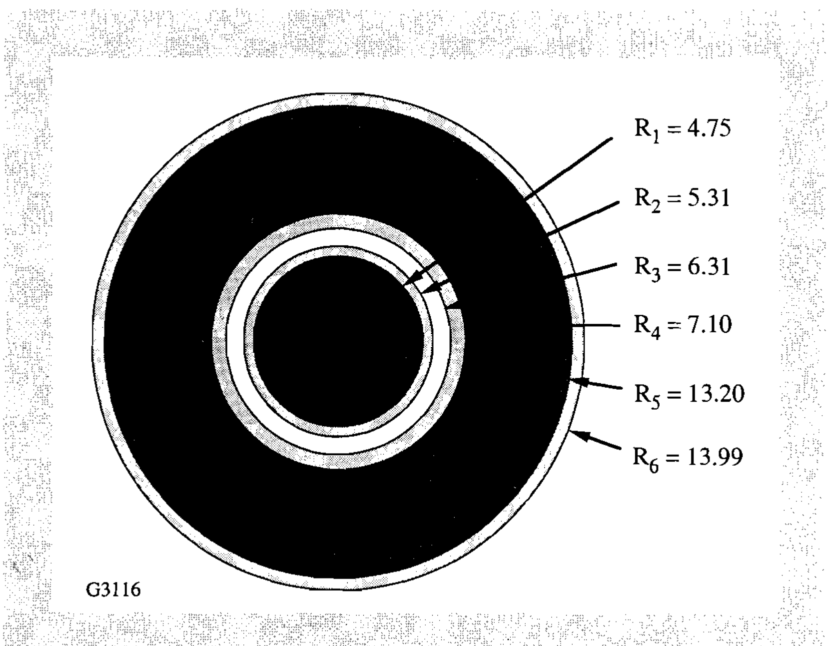

Fig. 55.34
Cross section of beams at frequency-conversion crystals. All radii are given in centimeters; the null-zone thickness is 1 cm.

Each of the laser drivers will produce the applicable portion of the total pulse so that the desired shape results when the two are combined at the target. The base-line pulses needed for experiments are the picket-fence [Fig. 55.35(a)] and continuous [Fig. 55.35(b)] pulses. For picket-fence pulses it is natural to assign the final picket to the main beam and the other pickets to the foot. For the continuous pulse, there is flexibility in the definition of the split; Fig. 55.35(b) shows one possible division. The choice is made by balancing the need for higher foot-pulse intensity for frequency conversion with limits on the foot-pulse

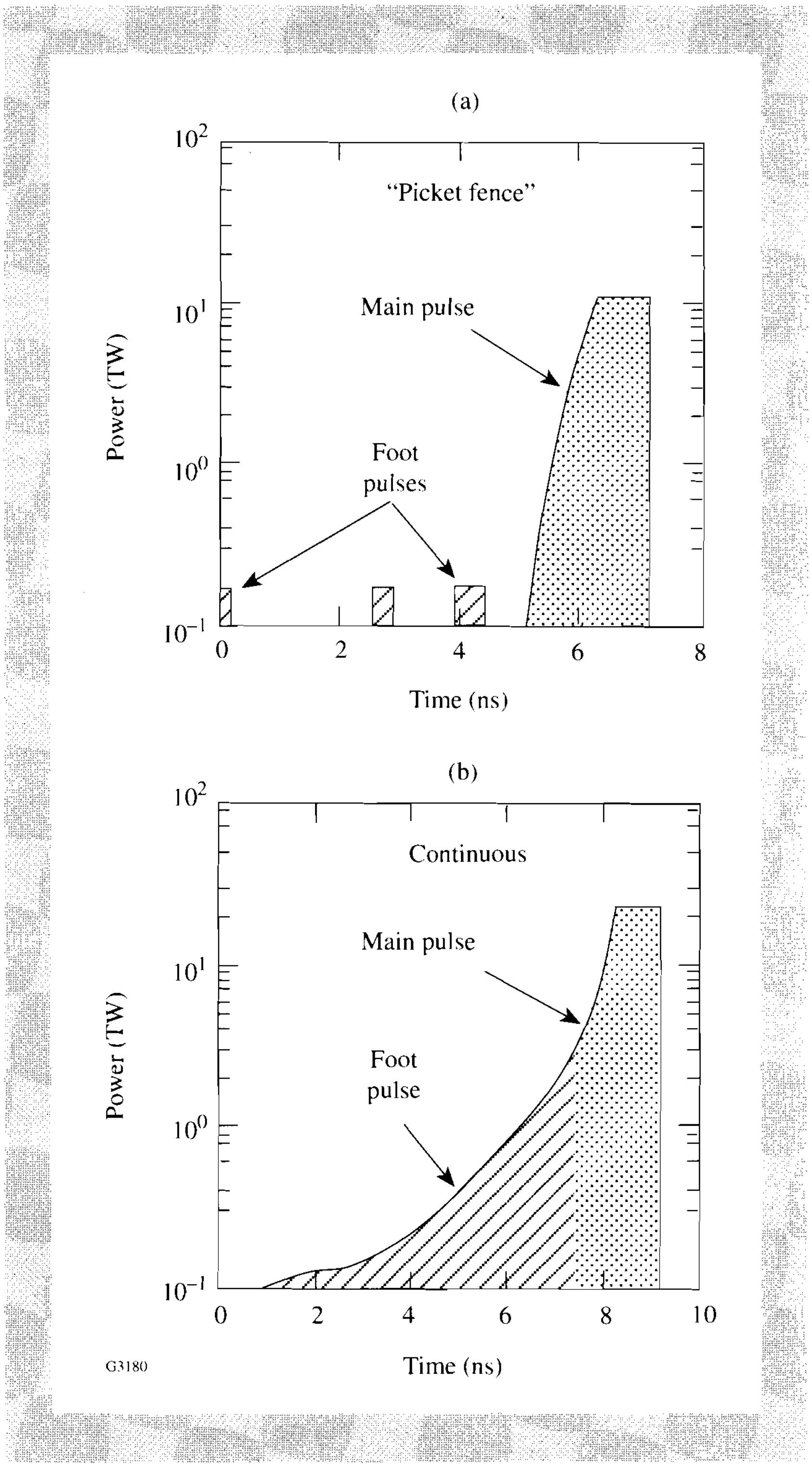

Fig. 55.35
The pulse shapes required for ignition-scaling experiments on the OMEGA Upgrade; (a) picket-fence pulse and (b) continuous pulse.

energy due to the UV damage threshold of the optical coatings. In the example of Fig. 55.35(b), the ratio of powers in the main and foot pulses of nearly 10:1 results in a ratio of intensities at the crystals of only ~1.4:1. This allows the use of a single-thickness KDP crystal for frequency conversion, the thickness of which is optimized primarily for the main pulse.

The overall energy performance predicted for the OMEGA Upgrade is shown in Table 55.IX. This table assumes a continuous pulse shape of the form shown in Fig. 55.35(b) and gives predictions for two peak powers, 23 TW and 39 TW. [The 39-TW pulse is a shortened version of the 23-TW pulse of Fig. 55.35(b) obtained by scaling the abscissa by a factor of 0.59 and keeping the energy constant.] That pulse shape is produced using a foot pulse with an approximately *N*th-order rise (with N ~2–4) and a flat-topped main pulse with duration of 1.1 ns (23 TW) or 0.7 ns (39 TW). The laser performance for both the 23-TW and 39-TW cases was calculated by fixing the on-target UV energy, then working backwards through the system to obtain the IR performances for each case. The energies quoted are summed over the 60 beams and indicate that the IR system must produce ~1 kJ per beam line. The UV numbers account for losses due to DPP's and the transport system. Since we expect that new technologies such as continuous phase plates[2] will have marked improvements in efficiencies, these values are quite conservative.

Table 55.IX: Energy performance of the OMEGA Upgrade.

		Main Pulse		Foot Pulse	
Peak Power		23 TW	39 TW	23 TW	39 TW
Beam area (cm²)		385		70	
UV:	Energy on target (kJ)	26.5		3.5	
	Energy on DPP (kJ)	33.5		4.4	
	Energy after FCC (kJ)	36.9		4.9	
	Average fluence after FCC	1.6 J/cm²		1.2 J/cm²	
	Peak fluence after FCC	2.9 J/cm²		2.2 J/cm²	
Conversion efficiency (1.2-cm-thick crystals)		76.5%	84.6%	42%	52%
IR:	Energy before FCC (kJ)	48.2	43.6	11.8	9.4
	Avg. fluence before FCC	2.0 J/cm²	1.8 J/cm²	2.6 J/cm²	2.1 J/cm²
	Peak fluence before FCC	3.6 J/cm²	3.2 J/cm²	4.7 J/cm²	3.8 J/cm²

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The peak fluence in the UV portion of the system is limited by the damage fluence of the transport mirrors, which is 2.9 J/cm^2 at 0.7 ns. This value is assumed to scale only weakly with temporal pulse width and is therefore applicable to both main pulses (23 TW and 39 TW). The average fluence is taken as 0.56 times the peak fluence based on experience at LLE and elsewhere.[3] Since the maximum fluence in the UV system occurs immediately after the FCC, the UV component most susceptible to damage is the first transport mirror immediately after the FCC.

System Configuration

The overall layout of the upgrade is illustrated in Fig. 55.36. The need to fit all the hardware (including the extra amplifiers, the extra beamlines, and a larger target chamber) into existing building space has led to a substantial rearrangement of the OMEGA laser. The oscillators and preamplifiers, including the SSD and pulse-shaping hardware, are located in a room below the laser bay. The driver amplifiers will be located on the laser-bay level; there will be two sets of amplifiers, one each for the main and foot pulses. The apodizers and the mirror, which will combine the two beams into one, will also be located on the laser-bay level.

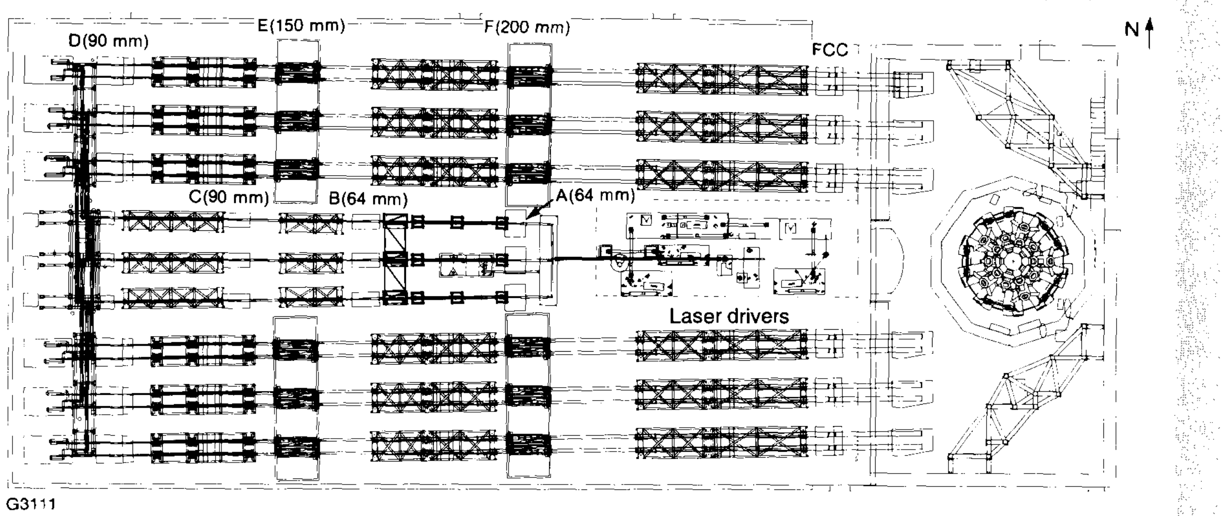

Fig. 55.36
Layout of the OMEGA Upgrade. The location of four stages of rod amplifiers (A–D), two stages of disk amplifiers (E, F), and the frequency-conversion crystals (FCC's) are indicated.

Once combined and amplified in the laser driver, the co-propagated beam is spatially filtered and then split three ways. Each beam is then amplified and split five ways, resulting in 15 beams. The amplifiers for both these stages (amplifier stages A and B of Fig. 55.36) are 64-mm rod amplifiers. All beam splitters are combined with an automated polarization-control wave plate that provides accurate energy balance between beams. The 15 beams are propagated through 90-mm OMEGA amplifiers (stage C) and spatial filters in the center of the bay in three stacks of five beams each. Each beam is split four ways at the end of the bay, at which point the 60 resulting beams pass through assemblies that permit ±1.5 m of gross path-length adjustment needed to compensate for the inequality in transport paths to the target chamber and to provide precision beam-timing capability.

The 60 beams then propagate back along the outside of the laser bay in six clusters of ten beams (two wide, five high); each beam passes through another 90-mm rod amplifier (stage D) before being amplified by the stages E and F disk amplifiers (of diameters 150 mm and 200 mm, respectively). Both types of rod amplifiers (64 mm and 90 mm) are modified versions of the OMEGA amplifiers, which incorporate major portions of the parent assemblies. New glass laser rods will be installed on all amplifiers. The disk amplifiers have been designed and prototyped at LLE; their performance will be reviewed in the next issue of the LLE Review.

The outputs of the last amplifiers are spatially filtered, magnified, and passed through thin-film polarizers before reaching the frequency-conversion crystals. (The polarizers ensure that the correct linear polarization is incident upon the crystals in order to maximize conversion efficiency.) Back-reflected UV light is prevented from propagating backward through the laser system by a UV-absorbing window on the input of the frequency-conversion cells. After frequency conversion, the beams pass through the concrete shield wall and enter the target bay.

Next, the beam encounters the stage-F ASP, which is the alignment fiducial for the entire system. The ASP's are housed in six structures constructed of a cast epoxy/granite composite. These massive structures (10,000 kg each) are used to ensure the stability that facilitates alignment to 1-μrad accuracy, which is required of the system. Also in these structures are the optical pick-offs, which distribute a fraction of the beam energy to the alignment and energy diagnostics. The harmonic-energy detectors (HED) are double-integrating spheres that measure the energies at the fundamental (1054-nm), second (527-nm), and third (351-nm) harmonics and provide individual measurements for the foot and main pulses. The alignment sensor package (ASP) provides the alignment reference to which IR and UV alignment beams are aligned; both beams are referenced to a position determined by the pulsed IR beam.

Beyond the stage-F ASP the beam is transported to the target chamber via two mirrors, the end mirror (on the beam axis) and the target mirror. The target mirror structure (TMS) supports the target mirrors plus the target chamber and its ancillary systems. These will be described in detail in a later section.

The 30 beams propagating toward the target bay on each side of the laser bay are all mutually parallel but angled at 0.75° toward the center of the laser bay. This angle is required to accommodate the nearly random mapping of the 60 beams onto the target chamber while limiting the incident angle on the end and target mirrors to 60° or less. Additional advantages of this wedged configuration are that it reduces the in-air path length of the UV transport system by 1.4 m (to 18 m), and it provides an additional 0.6 m between the outer beams and the shield wall in the target bay. The two-mirror UV-transport system was chosen to minimize the number of mirrors required and to reduce the path length of the UV beam. The former reduces cost; the latter reduces the chance that stimulated rotational Raman scattering (SRRS) will occur.

At each stage of the laser, spatial filtering is used to remove high-spatial-frequency noise in the beam and to ensure correct image relaying.[4] Image relaying is critical to the performance of laser beams with SSD because it prevents excessive excursions of different frequencies across the beam aperture. These deflections result from the frequency-dependent, grating-induced differences in propagation directions. It also prevents the formation of intensity modulations caused by interference effects. To further reduce interference effects, the size of the null zone between the foot and main pulses is chosen to be sufficient to prevent spatial overlap of the two pulses but is otherwise minimized to limit the aperture of disks and other optical components.

Oscillators and Laser Drivers

The driver for the Upgraded OMEGA laser will be comprised of several subsystems that supply co-propagated main and foot pulses for injection into the main beam lines, which contain the power amplifiers. Additional capability is provided to inject a third, backlighter pulse into 20 of the beam lines. The laser-driver subsystems, outlined in Fig. 55.37, are located in several areas: the oscillator room (OR), the pulse-generation room (PGR), and the *laser bay*.

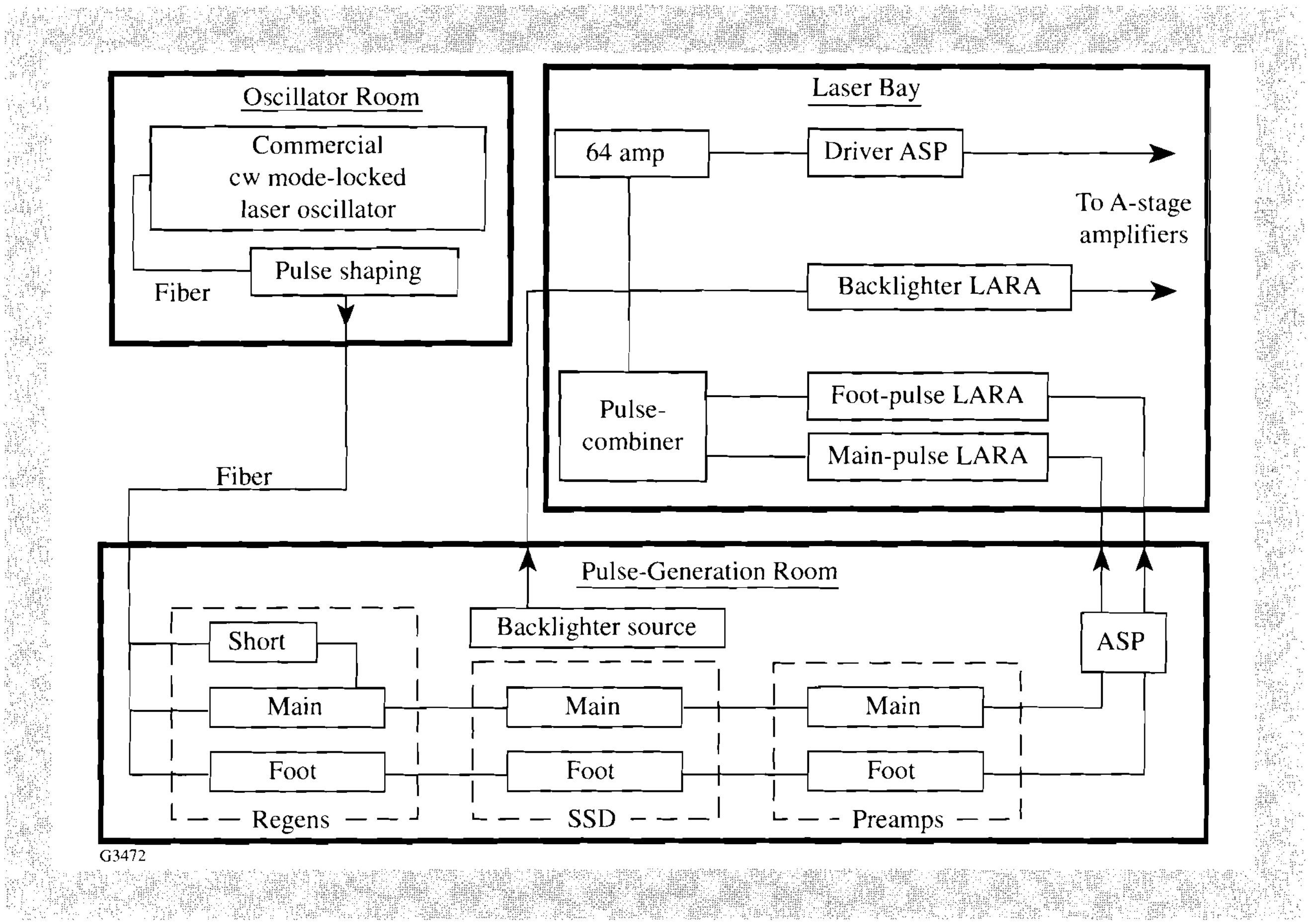

Fig. 55.37
The laser-driver subsystem for the OMEGA Upgrade is located in three separate areas: the oscillator room, pulse-generation room, and central laser bay.

Pulses for the OMEGA system originate in the OR, where 80-ps-wide pulses, produced at a rate of ~76 MHz, originate from a commercially available mode-locked laser. At the outset of OMEGA operations these pulses will directly seed the regenerative amplifiers in the PGR. In addition to amplifying the pulses, those amplifiers will stretch the pulses to their desired lengths. Ultimately, the Upgrade will require complex pulse shapes that will be generated in the OR using either of two pulse-shaping methods: electro-optic or spectral filtering. Once implemented, these systems will generate the desired shape and length of the pulses (main and foot), and the regenerative amplifiers in the PGR will be used for amplification and timing only. The OR is physically remote (~20 m) from the PGR and is fiber optically coupled to the PGR. Fiber optics are used throughout the OR for flexibility and alignment insensitivity.

The PGR is a 36-ft × 19-ft room located below the laser bay and home of several major elements of the laser driver, including pulse switchout, regenerative amplification, pulse truncation, driver diagnostics, amplification, smoothing, and alignment. As shown in Fig. 55.37, the main-, foot-, and short-pulse regenerative amplifiers are seeded by pulses from the OR. The main and foot regenerative amplifiers increase the ~1.0-nJ energy of the input pulses to 0.1 mJ, using 40 round trips. The short-pulse regen creates a pulse of similar energy that can be used to fire electro-optic switches used to truncate the trailing edge of the main pulse. Various diagnostics measure the energy, timing, alignment, and stability of the regens. A master timing system, which is synchronously timed to the mode-locked seed laser, is used throughout the laser driver and laser system as a temporal reference.

Beyond the regenerative amplifiers the pulses encounter the electro-optic modulators and gratings required for the smoothing by spectral dispersion (SSD). These systems impress the bandwidth and angular dispersion required for high irradiation uniformity on target. To accommodate for any losses in these systems the pulses are further amplified (by as much as 10) in a preamplifier stage that is a single-pass, 7-mm amplifier in each of the main and foot pulse lines. The output of these amplifiers brings the pulses back up to the 0.1-mJ level.

To de-couple the sensitive PGR optical configuration from heat sources, much of the driver electronics are housed in a driver electronics room that has a separate HVAC system. Located in this room are the various timing circuits, high-speed Pockels cell drivers, and microwave generators needed by the PGR.

The PGR output (0.1 mJ) is directed, via a periscope, up to the next set of amplifiers, located on the laser-bay level. These amplifiers are 40-mm, large-aperture ring amplifiers (LARA's); one each is provided for the main, foot, and backlighter pulses. Each amplifier provides a gain of 5,000–10,000 in a total of four round trips, thereby producing a 0.6-J output pulse in each beamline. The foot and main pulses are coaxially combined co-propagation using a mirror that is reflective for the annular main pulse and transmissive for the circular foot pulse. Once combined, both beams are amplified to ~4 J each by a single 64-mm, single-pass amplifier (the last driver amplifier). Alignment of the pulses relative to the system and to each other is monitored at two separate locations. The first alignment sensor package (ASP) is located in the driver area after the last amplifier. The laser-driver output is spatially filtered and propagated to the first beam splitter (stage A), where the laser-driver pulses are injected into the OMEGA power amplifiers. The stage-A ASP, located in this splitter, has a collimation monitor that is used to measure the collimation of the foot and main beams as well as that of the cw-IR alignment laser.

Laser Amplifiers

A total of 93 rod amplifiers will be required for stages A–D. The 54 existing amplifier assemblies will be refitted with new glass rods and modified for use in the new system. The remaining 39 units will be fabricated from an updated design that will incorporate improvements to the existing amplifier. The disk amplifiers are of conventional box geometry[5,6] utilizing a 15-cm-diam stage E followed by a 20-cm-diam stage F, with each amplifier containing four disks. The clear aperture of the final amplifier is set by damage constraints, specifically the sol-gel anti-reflection coating on the input lens of the final spatial filter, which damages when the main pulse reaches 9.8 J/cm^2. The 15-cm stage provides a main-pulse saturated gain of 3.1, and the 20-cm stage a gain of 2.3. Saturated gains for the foot pulse are slightly lower because the longer pulse operates at a higher fluence. The performance of prototypes of the 15-cm and 20-cm disk amplifiers has recently been measured.[7] These prototypes have been used in the old OMEGA system and the recently completed GDL prototype beamline to verify that 1 kJ IR can be produced by these amplifiers.[8] These tests demonstrate that the upgraded OMEGA system will meet the IR energy specification.

For reasons of economy, the disk-amplifier design makes use of water-cooled flash lamps, which facilitate operation at a high storage efficiency. Both amplifier stages utilize the same power-conditioning and pulse-forming network. The cooling times for the disk amplifiers are sufficiently short to permit a 1-h shot cycle. The modular nature of the design allows for the rapid change of flash-lamp pump modules within this shot cycle.

Target Area

The structure holding the target mirrors (see Fig. 55.38) is highly modular, with five-fold rotational symmetry about the vertical axis reflecting the soccer-ball symmetry, i.e., 20 hexagons and 12 pentagons. The 60 laser beams are located at the vertices of those polygons. The laser beams are directed through hexagonal tubes that are part of the structure. The design provides for segmented personnel platforms and integrates the optical mounts with structurally rigid, hexagonal beam tubes. The target mirrors are mounted on the ends of these beam tubes. The structure has a 6-m diameter, with the target mirrors centered on a 7.2-m diameter. The beam-transport geometry is such that no angle of incidence at either an end mirror or a target mirror exceeds 60°. The end mirrors are held on two, separate, space-frame structures (top and bottom of Fig. 55.36).

The target chamber, constructed of 5083-0 aluminum alloy, has an outer radius of 1.65 m and a 9-cm wall thickness. It has 60 beam ports (of 45-cm diameter) in the geometry mentioned; located at the centers of the soccer-ball polygons are 32 additional ports for diagnostics—20 of large diameter (60 cm)

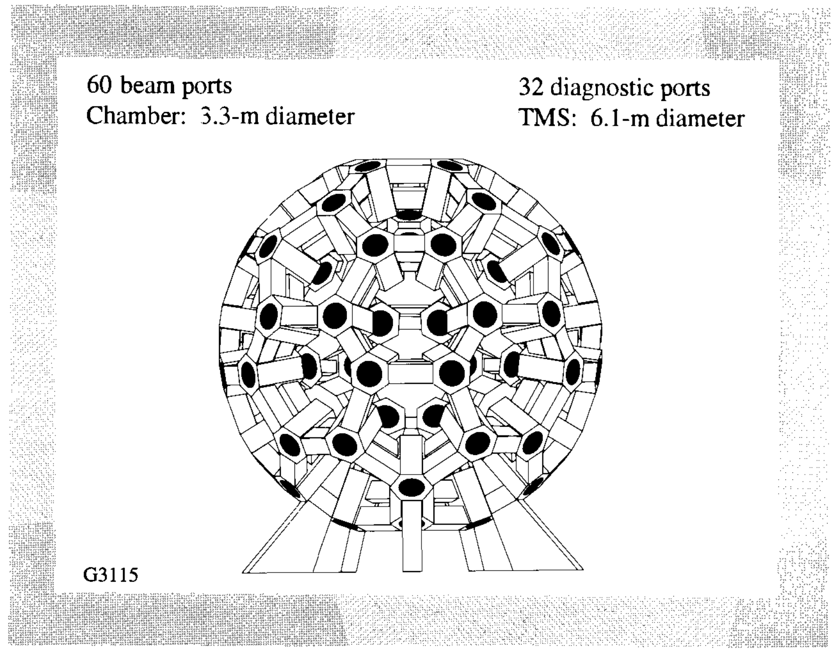

Fig. 55.38
The target-mirror support structure has a soccer-ball configuration and provides for diagnostic mounting and personnel access. The outer diameter is 6 m; the target mirrors will be mounted on a 7.2-m diameter.

on the hexagonal faces and 12 of smaller diameter (45 cm) on the pentagonal faces. The large diagnostic ports are particularly useful for instruments requiring a large, solid angle, such as a high-resolution, neutron time-of-flight spectrometer. Alternatively, these ports may be fitted with a reducing flange to allow use of existing OMEGA instruments or multiple, small diagnostics. The present complement of OMEGA diagnostics (with modifications where appropriate) will be available for the Upgrade. The Upgrade's target-area design actually allows a greater free volume for the placement of diagnostic instruments than is presently the case on OMEGA because in the Upgrade the beams are transported to the target-mirror structure from the outside rather than between the target mirrors and the target chamber.

Alignment

The Upgrade alignment system uses two wavelengths, unlike the former system that was aligned in the IR from the oscillator to the target. While two wavelengths increase complexity, they eliminate the two disadvantages of single-wavelength alignment: the transport mirrors no longer need dual IR/UV coatings, and the focus lenses will not have to be translated ~109 mm after IR alignment to compensate for chromatic shift. The former improves the damage threshold of the UV coating; the latter improves the operational accuracy of alignment. The IR portion of the laser is aligned using a 1054-nm Nd:YLF laser, together with alignment sensor packages located at stages A, C, and F within each beam line. For alignment of the UV portion of the system, a full-aperture, 351-nm cw laser is injected into the beam just after the FCC's, using movable mirrors located in the target bay.

At the heart of the alignment system are 60, stage-F, alignment sensor packages, which utilize achromatic optics. Located in the target bay just prior to the beam-line end mirrors, these sensors view small fractions of the IR and UV beam energies reflected off the diagnostic pickoffs. These beams can be aligned to each other and to a spatial fiducial. The injection of the UV beam is carried out sequentially by mobile injection mirrors located on the target-bay shield wall, each mirror servicing a column of five beam lines. After co-alignment with the IR beam, target alignment is performed by monitoring the UV reflections from a surrogate target transmitted back to a UV alignment table. This periscope mirror assembly (PMA) provides two beams (north and south) simultaneously, allowing the system to be aligned sequentially two beams at a time.

Laser Diagnostics and Control Systems

The laser-alignment, diagnostic, and power-conditioning subsystems rely heavily on computer-control and data-acquisition systems. On the current OMEGA laser these systems have largely been independent; for the Upgrade, developments in network technology are used to facilitate high-speed communication between the different systems.

Central intelligence is distributed among three levels of computers: (1) a host computer (workstation), which is the core of the intelligence; (2) an intermediate computer (a PC), which performs network and translation functions; and (3) microprocessor-based controllers at the individual devices. The basis for this system is the use of a local operating network (LON), which places a Neuron® microprocessor from Echelon Corporation at each device. The configuration provides widespread parallel-processing capabilities, which facilitate rapid system alignment and operation. Global commands from the central computer are relayed by PC to the LON and out to the hardware devices. These devices act independently and are fully capable of carrying out relatively simple tasks without host intervention. The alignment system also uses an intermediate computer to operate clusters of frame grabbers. This computer processes the beam-alignment images obtained by the alignment sensor packages to determine alignment-error measurements. This information is sent back to the host computer where algorithms will command beamline realignment to remove the error. The power-conditioning system utilizes a similar hierarchy for subsystem control. Power conditioning has a separate LON, and each of the 213 laser amplifiers has its own microprocessor capable of managing the charging, firing, and diagnostics of the amplifier pulse-forming networks (PFN's). The laser-energy-measurement system will utilize a vendor data bus, such as VME or Fastbus, to acquire and reduce calorimetry and diode data acquisitions.

Beam-energy measurements are required at various points in the laser chain. The most important measurement is made just after the frequency-conversion crystals, where a Fresnel reflection from an uncoated surface of a pickoff transports 4% of the beam energy into a diagnostic package. The HED is similar to the multiwavelength, energy-sensing system currently used on OMEGA, except two integrating spheres are used, one for the main pulse and one for the foot pulse. The optical layout ensures that the co-propagated aperture is relayed to a hole in the rear surface of the first (main-pulse) integrating sphere, so that the foot pulse passes through to the second integrating sphere. Separate measurements are therefore possible for the main and foot pulses at all three wavelengths (1054 nm, 527 nm, and 351 nm).

To ascertain the UV energies actually incident on target, accurate measurements of the transport losses from the pickoff to the target are required for each beamline. The baseline is to measure the losses using a small, adjustable integrating sphere, which is inserted into the center of the target chamber and successively pointed in each of the 60 beam directions. A reference beam and ratiometer are used to characterize relative transmission of each beam line—the same method used in the old OMEGA system.

Status of Project

Detailed design of the OMEGA Upgrade will be completed by October 1993. Contracts are in place for all of the major optical, laser, and structural components; shipments arrive daily. The building project is proceeding on schedule, toward completion in August. At the conclusion of the building project, integration will begin with the installation of the first structures. A detailed status report on the Upgrade will be presented in the next issue of the LLE Review.

ACKNOWLEDGMENT

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