MASTER

PREPRINT UCRL-77243.

Conf-751125--5

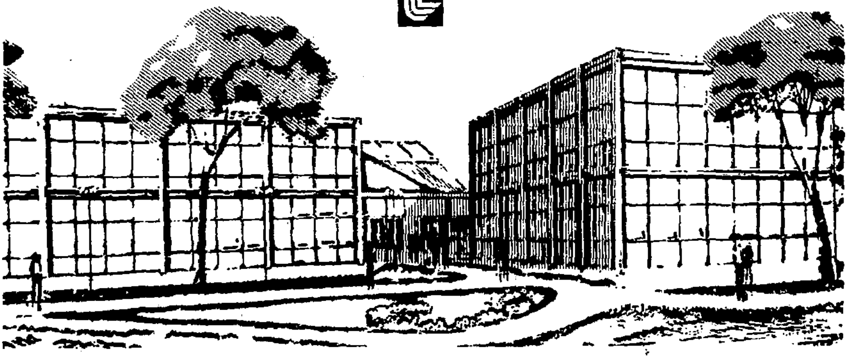
Lawrence Livermore Laboratory

LASER STARTUP OPTICS FOR BASEBALL II AND FUTURE MIRROR MACHINES

Alan M. Frank
Anthony K. Chargin
Norman J. Brown

October 31, 1975

This paper was prepared for submittal to the Proceedings of the Sixth Symposium on Engineering Problems of Fusion Research, San Diego, California, November 18-21, 1975.



LASER STARTUP OPTICS FOR BASEBALL II AND FUTURE MIRROR MACHINES*

Alan M. Frank, Anthony K. Chargin, Norman J. Brown
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

Summary

The laser startup system for Baseball II-T uses a 300-J CO_2 laser to hit a 100-μ diameter pellet with a laser power density on the order of 10^{13} W/cm^2. The laser is a 20-cm diameter unstable resonator transversely excited (TEA) oscillator. The beam is split and then focused using off-axis parabolas. The symmetric configuration and central obscuration of the CO_2 beam allow coaxial alignment and pellet detection optics. This experiment primarily uses commercially available systems and components. Optical elements were fabricated both by direct machining and standard polishing techniques. The laser and optical systems are directly scalable to reactor requirements using demonstrated technologies.

Introduction

Using a laser to create a hot plasma appears to be a viable technique for starting up a magnetic mirror machine. Hitting a solid pellet with a focused, high-power laser produces a plasma rapidly enough to overcome the buildup instabilities of other techniques. In the Baseball II-T experiment, the laser-produced plasma becomes the target for neutral beam build-up experiments (Fig. 1).

The start-up of Baseball II-T requires a plasma with a temperature of about 1 keV and which will fill *a two-liter volume with a density of* 10^{14}/cc. This requirement can be fulfilled by hitting a 100-μ-diameter pellet with a laser-power density on the order of 10^{13} W/cm^2. At this power density, the

*Work performed under the auspices of the U.S. Energy Research & Development Administration, under contract No. W-7405-Eng-48.

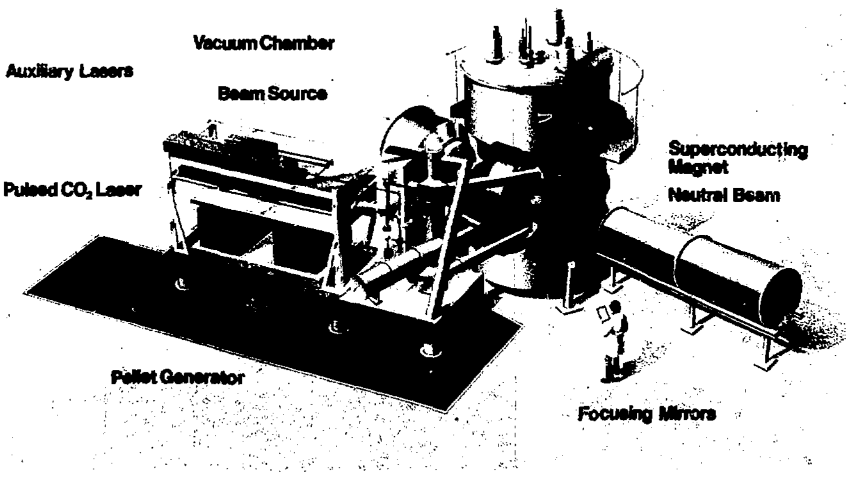


Fig. 1. Baseball II-T, a target plasma build-up experiment.

pellet burns through in about 50 ns and absorbs about 50 J of the laser energy.

The ability to produce the required plasma in this way has been demonstrated in a test bed experiment at LLL by Osher and Potter.[1] This test bed used a small CO_2 laser to demonstrate the physics of laser plasma production and to work out engineering problems.

System Description

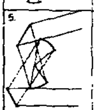
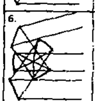
A commercially available CO_2 laser meets the above requirements with sufficient margin to allow a broad range of experiments. The laser is designed to provide 300 J in a 50-ns pulse. The CO_2 laser was chosen over Nd/glass because of its high efficiency and longer pulse lengths. Pulses of about 50 ns are required for complete burn-through of the pellet. Variation of the laser gas mixture allows some adjustment of the pulse lengths so that optimum conditions can be investigated. A TEA laser was chosen over an electron be. ı pumped device to minimize the interference fro. che strong magnetic fields.

Focusing a laser beam(s) on a pellet at the center of the Baseball II magnet is severely constrained by the mechanical configuration and operating environment of the magnet. The shape and size of the magnet, the location of mirror points, and the locations of other components limit the size and number of input beams. Rigid mechanical specifications of the optics and pellet systems preclude mounting any component to the magnet or main chamber, thereby requiring a separate optical structure. Cryogenic and vacuum requirements also constrain the system.

The horizontal axes of the magnet was not available for laser injection as one was preempted by the neutral-beam line and the other has insufficient clearance for the 20-cm diameter beam. The vertical axis was available; however, straight-in approaches were eliminated by equipment above and below the magnet.

A trade-off study was carried out for various optical approaches. Recent experimental results' show that pellet rocketing in a single arm system is unacceptable, although this result was anticipated at the time of the study. Figure 2 compares eight different approaches, including single beam and both symmetric and asymmetric multiple beams. Only one lens approach is included; however, lens analogies of various other mirror cases are possible, but not practical. Lens systems were essentially discarded on practical grounds of availability, reliability, and cost of 20-cm aperture elements for 10.6 μ.

Focusing is accomplished by on-axis parabolas (Fig. 2) in scheme numbers 1, 5, and 6; off-axis

Scheme	Number of paths	Major optics count	Alignment complexity factor	Symmetric?	Alignment	System compatibility	Optics fabrication	Variable cost considerations	Variable cost totals
1. 	1	2	4	No	Require set up target		Diamond turn	Mirrors ~$15k Mounts ~$10k 1 window ~$5k 2 arms Alignment $4k	$34k
2. 	1	1	1	No	Require set up target		Conventional "state of art"	Mirror $58k Mounts ~$5k 1 window ~$5k 1 arm Alignment $1k	$69k
3. 	2	2	8	Yes	Interferometric self consistant no target	Double energy density on optics	Conventional "state of art"	Mirrors $80k Mounts $10k 2 windows ~$10k 2 arms Alignment ~$8k	$108k
4. 	2	3	18	Yes	Split field interferometric	Double energy density on optics	Upper mirror beyond state of art!	Upper mirrors $70k if possible? Lower ~$10k Uppermount ~$30k Remotely Lower ~$8k adjustable 1 window ~$5k 2 arms Alignment ~$18k	$141k
5. 	2	4	32	No	Require set up target	Difficult assembly Poor magnet clearance	Diamond turn	Mirrors ~$30k Mounts $20k 2 windows ~$10k 2 arms Alignment ~$32k	$92k
6. 	3	5	75	Yes	Require set up target	Center mirror in pellet path Center mirror cannot be mounted to optical bench Difficult assembly	Diamond turn	Mirrors ~$40k Mounts $25k 3 windows ~$15k 3 arms? ~$10k Alignment ~$75k	$165k
7. 	3	3	27	Yes	Require set up target		Conventional "state of art"	Mirrors ~$100k Mounts ~$15k 2 windows ~$10k 2 arms Alignment ~$27k	$152k
8. 	2	4 2 lens 2 mirror		Yes	Must align at 10.6 μ	Thermal stability questionable Titanium coating would cause laser damage	Conventional	Lenses would be extremely thin and fragile .. design study covering; thermal shock, laser damage would require experimental verification Lens costs ~$30k Mounts ~20k 2 windows ~$10k 2 arms Alignment ~$32k	$122k

(ALIGNMENT COMPLEXITY FACTOR = (OPTICS COUNT)[2] x NO. PATHS)

Fig. 2. Optics trade-off study.

parabolas in numbers 2, 3, 4, and 7; and lenses in number 8. In those cases using the off-axis mirrors, no secondary flat-beam turning mirrors are required.

The number of paths is the number of beams incident on the pellet. To hit the pellet symmetrically, two or more beams are required. When two beams are used, their angle of coincidence must be 180° for symmetry; therefore, on-axis parabolas cannot be used. The asymmetry of the two-arm, on-axis, parabola approach could be overcome by adding a third beam. The requirement of mounting all optical components to a common structure appears to preclude adding a third beam in this way.

The labor and difficulty of alignment are dependent on the number of optical elements as well as the number of paths which must be co-aligned. Only those optical elements inside the chamber are considered here because of the extreme physical difficulty of making any adjustments. An alignment complexity factor is an estimate of the labor and time involved in alignment. This factor is defined as the square of the internal optics count, times the number of co-aligned paths, and experience has shown it to be reasonably valid. The location and adjustability of beam-splitting are important in balancing multiple beams for symmetry.

Alignment approaches and procedures are tied to the optical configuration. The symmetric two-arm approaches have a considerable advantage in that they allow interferometric alignment, which is the only self-consistent technique applicable. The asymmetric configurations must rely on an alignment target. Interferometric alignment is useful for real-time external monitoring and servo-control. The spectral dependence of the refractive index of the lenses in the system would preclude the use of visible alignment techniques without auxiliary optics and additional complexity.

The very limited physical space inside the magnet but outside the magnetic mirror points rapidly becomes a problem with an increasing optics count. The necessity of supporting all the optics from a common external structure rapidly fills available space and ports. Certain diagnostic instruments must be reworked to accommodate even a single mirror. Additional optics either require more extensive rework or they completely obscure instruments such as the energy analyzer.

Some titanium coating of mirrors is acceptable; however, it is absolutely fatal on lenses. Protection from the titanium sublimators for the mirrors requires only elimination of direct lines of sight, whereas, protection of lenses is considerably more difficult.

The approach chosen uses two off-axis parabolas (Fig. 2, number 3). This approach is by far the simplest to implement within the confines of Baseball II and overshadows the expense and difficulty of mirror fabrication.

The design of the focusing mirrors is summarized in Fig. 3. Annealed OFHC copper was chosen for the mirror material because of its known fabrication properties, high 10.6-μ reflectivity, and homogeneous behavior with thermal cycling to 77 K.

Reference mirror surfaces are located normal to the optical axis of the incident beam. These surfaces are essential for defining the optical axis during fabrication and alignment.

The fabrication of the copper parabolas was contracted to the Perkin-Elmer Corporation* of Norwalk,

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

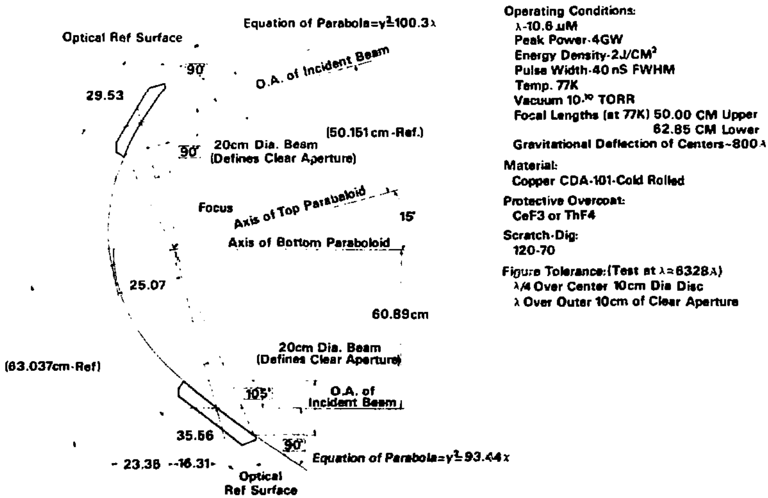


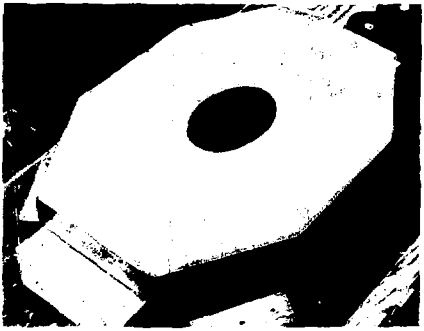
Fig. 3. Design of focusing mirrors.

Connecticut with a subcontract to Frank Cooke Inc. of North Brookfield, Massachusetts. A special machine was constructed for the rough curve generation[2] by Frank Cooke Inc. The mirrors are being polished using conventional machine and hand techniques. The strong deviation from spherical and steep curvature makes this approach extremely difficult and has caused significant delay in the mirror delivery.

Single crystal sodium chloride and zinc selenide are the only commercially available optical window materials capable of withstanding the CO_2-laser beam without damage. The order of magnitude difference in cost eliminates the zinc selenide despite some other slight advantages.

The index of refraction of sodium chloride is 1.5, giving a window loss of 8%. This loss can be reduced to under 3% using an antireflection coating developed in the LLL optics shop.

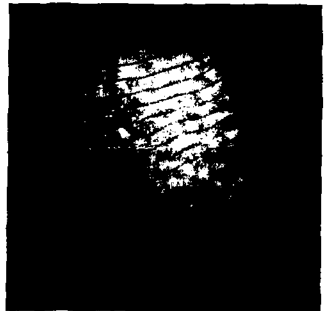
Laser damage has occurred in the coating of one surface in the test bed experiment. Although this could be associated with caustic images unique to that one surface, it does bring up questions as to the



(a)

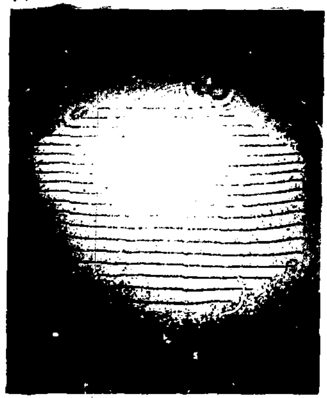
(b)

Fig. 4. Flat-turning mirrors; (a) with aperture for combining with auxiliary laser beams, (b) beam splitter, also with aperture.



(a)

(b)



(c)

Fig. 5. Interferograms of diamond turned mirrors: (a) turned mirror, (b) center zone of turned mirror showing residual spindle runout, (c) fly cut mirror.

durability and damage threshold of the coatings. This is an area not yet sufficiently understood for reliable lifetime analysis.

The laser damage threshold for the optical components (copper and NaCl), is generally accepted to be at or above 2 J cm^{-2} $ns^{-1/2}$ or about 14 J cm^{-2} for a 50 ns pulse. The 20-cm diameter of the laser beam is sufficiently large that damage is not a problem except as indicated above.

Beam splitting is presently being accomplished by physically cutting the beam with a half-mirror. The alternatives include using a grating or two lasers. The grating has the advantage of doubling the energy density in a diffraction limited focal spot. However, this advantage is significantly diminished by dispersion of the laser and the limitations of the optics and budget. Laser damage to a grating also remains an unanswered question.

Using two lasers as an alternative to splitting has significant drawbacks. There is sufficient jitter and uncertainty in the laser triggering to preclude reliable simultaneous firing of optically independent units. Using a common laser oscillator to drive two parallel amplifiers is less efficient and significantly more complex than the approach currently used.

Flat turning mirrors handling this CO_2 beam are all OFHC copper (Fig. 4). These mirrors were fabricated by direct diamond machining in the LLL metrology shop.[3] Direct machining produces surfaces that are significantly more resistant to laser damage than conventionally polished copper. The diamond turning machine was used as a fly-cutter to eliminate the spindle runout errors at the center of the mirrors (Fig. 5). Diamond machined mirrors scatter coherently at visible wavelengths (grating effect), however these effects are negligible at 10.6 μ.[4]

The auxiliary optical systems (interferometer, timing, and diagnostic) take advantage of the toroidal geometry of the CO_2 unstable resonator (Fig. 6). Central apertures have been cut in the beam splitter and first turning mirrors to allow the co-axial insertion of the auxiliary lasers. The use of visible wavelength lasers requires tighter figure requirements over the central portions of all the optics.

In addition to the co-axial lasers, the auxiliary systems include continuous CO_2 and HeNe lasers. These are alignment lasers, which are inserted through an aperture in the rear optic of the unstable resonator. These beams walk through the unstable resonator and emerge with the same optical characteristics as the pulsed laser. They are used for beam

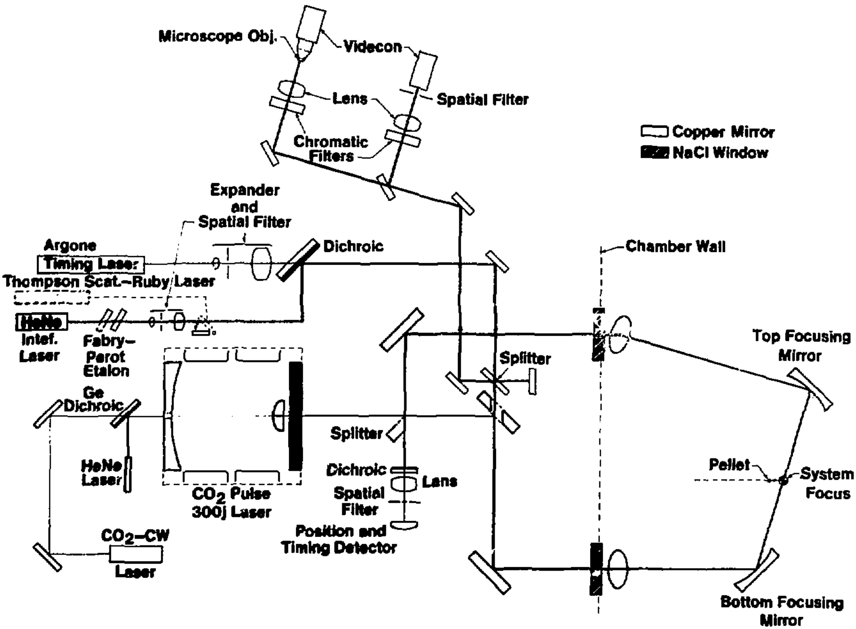


Fig. 6. Schematic of optical system.

characterization and co-aligning the pulse laser with interferometer and timing lasers.

The interferometer system takes advantage of the symmetry of the focusing optics to provide analysis of the optical alignment. The focusing mirrors are the only nonflat elements in beam handling optics. Consequently, they are the only elements that can produce optical aberrations. Focusing errors produce curved or circular fringes, whereas alignment errors produce astigmatic fringes. The figure errors in the optical elements are fixed and can be eliminated from the data.

The interferometer is read out on a TV monitor in the control room and continuously monitors the optical alignment. A second TV read-out looks at the focused image of the interferometer beam and provides autocollimation data. This second read-out also provides an image of the system focal zone, which is useful with fixed-target alignment procedures.

The timing laser is defocused to illuminate a 5-mm diameter region at the system focus. The beam is refocused externally onto a zeroth order spatial filter. This filter eliminates the laser beam except for a diffraction image of the pellet that forms in the image of the system focal plane behind the spatial filter. Both a silicon quadrant-detector and a charge-coupled device are placed in the pellet image plane to provide timing and position information on the pellet. The 40-m/s velocity of the pellet requires that a decision to fire the laser be made 5 µs before the pellet arrives in the system focal zone. Consequently, the position and timing detectors are centered about 0.5 mm before the image of the system focus in the pellet trajectory.

Provision has been made in the system for handling a high-power pulsed ruby laser for a Thompson scattering source. A beam expander will be used to reduce the energy density of the ruby to prevent damage to the optical components. The Thompson scattering system is expected to be implemented next year.

The physical and thermal stability requirements of the structure are derived from the 10-µ alignment tolerance at the pellet. Optical paths in excess of 5 m and a pellet trajectory of 3 m put stringent stability requirements on the structure. The mechanical excursions of the magnet are larger than the frozen pellet; consequently, an independent inertial reference frame had to be established for the laser/pellet system. All components of this system are mounted on a common granite slab and are mechanically isolated from the magnet, vacuum chamber and ground. The vibrational characteristics of the structure were analyzed using finite element procedures.[5] The entire laser/pellet gun package is housed in a thermally controlled clean-room. Thermal excursions during cool-down will be monitored through the interferometer and will be tracked by the external adjustments for the focusing mirror mounts.

Power Density Analysis

The power density at the pellet is primarily limited by the divergence of the laser, the wave front distortion of the optical system, and the diffraction of the focused beam. These effects all limit the diameter of the focal spot, whereas secondary effects, such as window transmission and mirror reflectivity, simply reduce incident intensity.

The uncorrectable divergence of the laser and the wave front distortion of the optics both introduce angular errors of 0.1-0.2 mrad. The focal spot size is, therefore, limited to the angular error times the optical focal length.

Diffraction also limits the size of the focal spot and removes energy from the central spot to a pattern of satellite rings and spots. To analyze the power distribution in the focal plane, we follow the analysis of J. W. Goodman[6] of the Fourier transforming property of a lens (focusing mirror). If the amplitude function of the disturbance is $U(x,y)$, then, in the focal plane (f) the disturbance is proportional to the two-dimensional Fourier transform:

$$U(x_f,y_f) \propto \iint_{-\infty}^{\infty} U(x,y)\, e^{-i\,2\pi(xx_f + yy_f)}\, dx\, dy \; .$$

We neglected both normalization and quadratic phase factors as these fall out in the subsequent analysis. The intensity in the focal plane is found by squaring the amplitude or:

$$I(x_f,y_f) = U(x_f,y_f)\; U^*(x_f,y_f) \; .$$

The power in a given region (region P) can be found by integrating the intensity over the region, normalizing by integrating over all space, and multiplying by the power input P_{in}. Therefore,

$$P_{region} = \left[\frac{\iint_{region} I(x_f,y_f)\, dx\, dy}{\iint_{-\infty}^{+\infty} I(x_f,y_f)\, dx\, dy}\right] P_{in} \; .$$

The intensity distribution of the laser output (Fig. 7) is not a function that could be easily handled analytically. Modeling the system optically

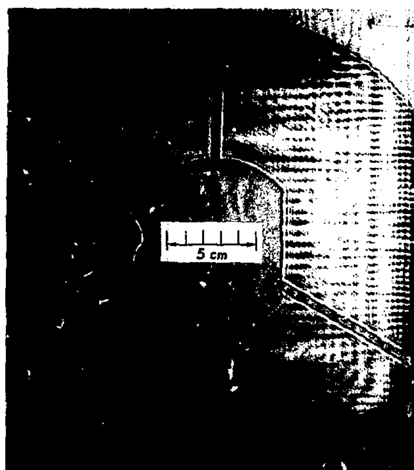


Fig. 7. Burn pattern of 300-J CO_2 laser showing the characteristic shape of the unstable resonator.

at visible wavelengths gives good qualitative results, but direct numerical analysis is necessary for quantitative information. The intensity distributions of the optical and numerical simulations, shown in Fig. 8, are for actual cases where the laser output is physically split in half. The central spot has dimensions of about 48 × 96 μ and contains about 50% of the energy in the beam.

Comparing the diffraction results with the angular dispersion limits, we expect an irregular central spot with a maximum dimension of about 150 μ and an average power density in excess of 3×10^{13} W/cm^2 for each arm. Measurements of the actual intensity distribution are currently in progress.

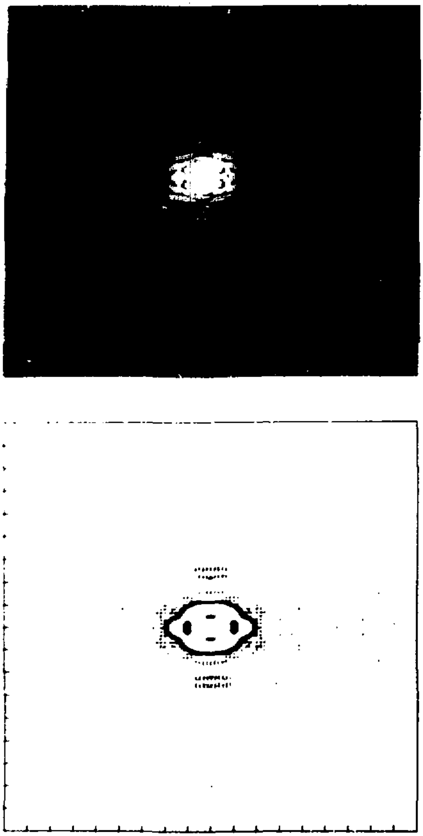


Fig. 8. Intensity distribution of the optical and the numerical model of the split CO_2 laser beam.

Energy that misses the pellet is directed back into the laser and will cause the laser to go multimode. However, the length of the optical path causes a 50 ns delay in the multimoding, placing it in the tail of the laser pulse, and should not cause any problems.

System transmission losses are virtually negligible compared to the above effects. The reflectivity of polished copper at 10.6 μ is typically greater than 99%. Therefore, the loss in four reflections is less than 4%. Window losses for sodium chloride result mostly from reflections at each surface. With good coatings, these losses can be held under 3%, whereas a bare window would lose 8%. Because the coating's resistance to laser damage is questionable, bare-window operation is a possibility. Therefore, total system transmission losses will run between 7% and 12%.

Considerations for Future Systems

The upgrading of the laser startup concept for a reactor-scale mirror machine appears to be a straightforward task. If the Baseball startup conditions are correct, then laser power density requirements will remain essentially the same, 10^{13}-10^{14} W/cm^2. Plasma volumes will increase, thereby requiring a proportionally larger pellet, larger laser focal spot, and longer burn-through time, and therefore, increased total laser energy. For example, a 100-ℓ target plasma would require a 500-μ diameter pellet and a laser energy of 5-10 kJ, and burn-through would take about 10^{-7} s.

A highly efficient electron beam, gas-dynamic laser with a 4.2-kJ output has recently been demonstrated by Sandia Laboratories.[7] The large double-headed CO_2 laser now being tested at LASL[8] would also have a similar output if it operated in the required "long" pulse regime.

The larger lasers will require larger optics, i.e., a 40-cm diameter beam for 10 kJ. The optical fabrication techniques and facilities now being developed for the laser fusion program will handle the reactor optical requirements. For example, the 84-in. swing diamond turning machine at Oak Ridge is being upgraded to do optical fabrication of comparable quality to the LLL 18-in. facility.

Window technology is also being pursued in the laser fusion effort. New and larger crystal growing equipment is being developed by Harshaw Chemical Co. (the principal sodium chloride supplier) to enlarge the maximum available crystals from 35 to 43 cm in diameter, then later to 75 cm.[9] Polycrystalline NaCl is also being investigated as a possible window material.

It is apparent that as Baseball II-T has used currently available optical technology, so will a reactor scale system. Thus, from the laser and optical engineering view, laser start-up for mirror machines appears to be a feasible technique.

References

1. J. Osher and G. Porter, "Laser-Pellet Heating Studies for Plasma Target Production," Lawrence Livermore Laboratory Rept. UCRL-77133 (1975).
2. R. Parks, "Machining a Copper Off-Axis Parabola," Appl. Op. 14 (4), Aug. (1975).
3. T. Saito, "Machining of Optics," Appl. Op. 14 (4) Aug. (1975).

4. R. E. Sladky, "The Results of Optical Measurements of Surface Quality of Diamond Turned Mirrors," presented at ASTM Symposium on Damage in Laser Materials, Boulder, Colorado, July 29-31, 1975, Proceedings pending.

5. A. Chargin, et al., "Vibration, Thermal, and Alignment Considerations of the Laser System for Baseball II-T," Lawrence Livermore Laboratory Rept. UCRL-77260 (1975).

6. J. W. Goodman, Introduction to Fourier Optics, (McGraw-Hill, San Francisco, 1968).

7. J. B. Gerardo, "Electron Beam Driven Chemical Lasers," presented at 1975 Conference on Laser Engineering Applications.

8. W. Reichelt and S. Singer, LASL private communications, 1975.

9. Harshaw Chemical Co., private communications, 1975.