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A LASER START-UP SYSTEM FOR MAGNETIC MIRROR FUSION*

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ABSTRACT

A CO₂ laser system has been developed at LLL to provide hot start-up plasmas for magnetic mirror fusion experiments. A frozen ammonia pellet is irradiated with a laser power density in excess of 10^{13} W/cm² in a 50-ns pulse. This system uses commercially available laser system. Optical components were fabricated both by direct machining and standard techniques. The technologies used in this system are directly applicable to reactor scale systems.

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. Once formed, such a plasma is sufficiently dense to be heated and sustained with neutral beams. Recent results at LLL^{1,2} and the United Technology Research Center^{3,4} have separately demonstrated the necessary processes.

At LLL, Baseball II-T⁺ is being prepared for a combined experiment (Fig. 1). The start-up of Baseball II-T requires a plasma that has an ion

⁺"T" was added to designate laser target plasma start-up.

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

Operating Conditions:

λ 10.6 μ m
 Peak Power 4GW
 Energy Density 2J/cm²
 Pulse Width 40 nS FWHM
 Temp. 77K
 Vacuum 10⁻³⁰ TORR
 Focal Lengths (at 77K) 50.00 CM Upper
 62.85 CM Lower
 Gravitational Deflection of Centers 800 λ

Material:

Copper CDA-101-Cold Rolled

Protective Overcoat:

CeF3 or ThF4

Scratch-Dig:

120-70

Figure Tolerance: (Test at λ = 6328 λ)

$\lambda/4$ Over Center 10cm Dia Disc

λ Over Outer 10cm of Clear Aperture

Figure 2. Design of Focusing Mirrors

temperature of about 1 keV and will fill a two-litre volume with a density of $10^{14}/\text{cm}^3$. This requirement is fulfilled by hitting a 150- μm -diameter frozen ammonia (NH_3) pellet with a laser-power density on the order of $10^{13} \text{ W}/\text{cm}^2$. At this power density, the pellet burns through in about 50 ns and absorbs about 50 J of the laser energy. The laser is a 20-cm diameter, unstable resonator, transversely excited (TEA) oscillator that produces 300 J in a 50-ns pulse. 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 uses commercially available laser systems. Optical elements were fabricated both by direct machining and standard polishing techniques.

A pellet generator developed at LLL⁵ produces a stream of charged frozen ammonia (NH_3). A microprocessor-based guidance system using electrostatic deflection plates delivers the pellets to the laser focal zone. The pellets are 100 μm to 200 μm in diameter and traverse a flight path of 3 m with a final velocity of 30 to 40 m/s. The presently functional system delivers several pellets a minute through the focal zone. Improvements to the guidance system will substantially increase the delivered pellet rate.

The magnetic confinement will be accomplished in the existing Baseball II superconducting magnet facility with a central magnetic field of 1.5 T and a 2:1 mirror ratio.⁶ Neutral beam sources, nominally 50 A at 20 keV, developed by Lawrence Berkeley Laboratory (LBL), will be used.^{7,8} Sources at 50 keV are currently under development at LBL, and these will be used to sustain the plasma in later experiments.

The technology for such laser start-up systems is substantially less demanding than direct laser fusion. A full-scale reactor start-up system could be built using current technologies. Both the magnetic confinement and neutral beam technology are sufficiently far advanced that reactor-scale systems are being contemplated.^{9,10}

LASER SYSTEM

A commercially available CO₂ 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 CO₂ 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 beam pumped device to minimize the interference from the strong magnetic fields.

Focusing one or more laser beams 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 for the optics and pellet systems preclude mounting any component to the magnet or main chamber, thereby making a separate optical structure necessary. Cryogenic and vacuum requirements also constrain the system. A test bed experiment¹ showed that pellet rocketing in a single-arm system is unacceptable; consequently a symmetric distribution of the energy is required.

This symmetry requirement is far less stringent than for inertial confinement. In this case, the goal is to provide an expanding hot plasma rather than an implosion.

The horizontal axes of the magnet were 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. These constraints limited the system to only two beams.

The magnetic mirror points of the plasma extend about half a metre from the center of the magnet. This limits the closest approach of the last optical element. The diffraction of a 20-cm-diameter beam limits the focal length of the focusing element to a maximum of about 75 cm.

All these requirements limit the final optical elements to either a flat mirror-lens combination or off-axis parabolas. Lenses were ruled out because of the materials problems with 10.6- μ m optical materials in the cryogenic environment of the magnet. The presence of titanium from gettering sources and the requirement for visible alignment were also arguments against using lenses. The off-axis parabola approach is by far the simplest to implement within the confines of Baseball II; these advantages overshadow the expense and difficulty of mirror fabrication. The design of the focusing mirrors is summarized in Fig. 2. Annealed OFHC copper was chosen for the mirror material because of its known fabrication properties, high 10.6- μ m 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, Connecticut, with a subcontract to Frank Cooke Inc. of North Brookfield, Massachusetts. A special machine was constructed for the rough curve generation by Frank Cooke Inc. The mirrors were polished by conventional machine and hand techniques. The strong deviation from spherical and steep curvature make this approach extremely difficult and caused significant delay in the mirror delivery. Mirror fabrication took nearly a full year, with more than six months of polishing required for each mirror. The mirror figures (Fig. 3) were somewhat poorer than originally specified. However, the focal spots are sufficiently small (under 150 μm) to provide the required energy density. The central portions of the mirrors are good enough to allow interferometric alignment and reasonable imaging of the focal region.

The mirror surface, although within the 120-70 scratch-dig finish specification, is covered with very fine streaks and also has a few larger pits (an "orange peel" effect shown in Fig. 4). Since such effects form centers for laser damage,¹² several samples were tested for damage. Samples were polished to a slightly poorer finish (Fig. 5a) than the parabolas using the same techniques. A single 80- μm scratch was scribed into each surface to provide an example of a severe defect. The samples were then irradiated with 10 shots from a CO_2 laser with pulse width 50 ns and the beam focused to varying energy densities. The Nomarski micrograph of the

*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 and Development Administration to the exclusion of others that may be suitable.

Figure 3. Interferogram of upper focusing mirror over 20 cm diameter clear aperture. One fringe equals a quarter wave at 6328Å.

Figure 4. Nomarski micrograph (157x) of lower Focusing Mirror showing typical surface finish.

(a)

(b)

Figure 5. Low power Nomarski micrograph (40x) of: a) undamaged and b) laser damaged areas of ZrO_2 sample. Sample was irradiated with 10 shots of $1.3\text{J}/\text{cm}^2$ average from a CO_2 laser with a pulse width of 50 ns.

sample irradiated at 1.3 J/cm^2 reveals the onset of laser¹ damage (Fig. 5b).^{*} The results of the experiments showed that the real damage threshold of the mirrors was only slightly above the output density of the 300 J laser. As expected, the streaks and pits did act as damage centers; however, the 80- μm scratch did not.

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

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 the budget). Laser damage to a grating also remains unknown.

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.

^{*}This energy density is average over a beam with the same spatial and temporal characteristics as the 300-J laser and cannot be extrapolated to other situations.

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 the CO_2 beam are all OFHC copper (Fig. 6). These mirrors were fabricated by direct diamond machining in the LLL metrology shop.¹³ 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. 7). Diamond-machined mirrors scatter coherently at visible wavelengths (grating effect); however these effects are negligible at $10.6 \mu\text{m}$.¹⁴

The auxiliary optical systems (interferometer, timing, and diagnostic) take advantage of the toroidal geometry of the CO_2 unstable resonator (Fig. 8). Central apertures have been cut in the beam splitter and first turning mirrors to allow the coaxial 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 coaxial lasers, the auxiliary systems include continuous CO_2 and He-Ne 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 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

(a)

(b)

Figure 6. Flat-turning mirrors; (a) with aperture for combining with auxiliary laser beams, (b) beam splitter, also with aperture.

(a)

(b)

(c)

Figure 7. Interferograms of diamond turned mirrors: (a) turned mirror, (b) center zone of turned mirror showing residual spindle runout, (c) fly cut mirror.

Figure 8. Schematic of Optical System.

Figure 9. Burn pattern of 300-J CO₂ laser showing the characteristic shape of the unstable resonator.

they are the only elements that can produce optical aberrations. Focusing errors produce curved or circular fringes, whereas alignment errors produce astigmatic and comatic fringe patterns.

The interferometer continuously monitors the optical alignment. It is read out on a TV monitor in the control room; a second TV readout looks at the focused image of the interferometer beam and provides autocollimation data. This second readout 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 0th 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 μ s 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 Thomson scattering source. A beam expander will be used to reduce the energy density of the ruby to prevent damage to the optical components. The Thomson scattering system is expected to be implemented next year.

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 each introduce angular errors of 0.1 to 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 of the Fourier transforming property of a lens (focusing mirror).¹⁵ 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:

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

We neglect 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, P_{region} , can be found by integrating the intensity over the region, normalizing by the integral over all space, and then multiplying by the power input, P_{in} . Therefore,

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

The intensity distribution of the laser output (Fig. 9) is not a function that could be easily handled analytically. Modeling the system optically 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. 10, are for actual cases where the laser output is physically split in half. The central spot has dimensions of about $48 \times 96 \, \mu\text{m}$ 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 $150 \, \mu\text{m}$ and an average power density in excess of $3 \times 10^{13} \, \text{W/cm}^2$ for each arm. Measurements of the actual intensity distribution are currently in progress.

Some of the energy missing 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; the multimoding should not cause any problems.

(a)

(b)

Figure 10. Intensity distribution of the optical and the numerical models of the split CO₂ laser beam.

System transmission losses are virtually negligible compared to the above effects. The reflectivity of polished copper at $10.6\text{ }\mu\text{m}$ 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%.

MECHANICAL DESIGN PARAMETERS

In designing the structure for the laser system, we had to consider its location. Mechanical vibration is present throughout the facility, primarily from mechanical vacuum pumps, air compressors, water pumps, building ventilator fans, and the helium compressor for our liquefaction plant. Measurements show that these sources emit vibrations at 17 Hz, or its multiples, with amplitudes of 0.2 to 0.5 μm . Acoustical vibrations from the same sources have been measured at amplitudes of 69 dB (re 0.02 mPa). Finally, the experiment is situated in a large-bay area of the building, where large fluctuations in temperature, relative humidity, and dust are common.

After considering alternate optical approaches, we designed a two-armed, cantilevered assembly to guide and focus the various laser beams, support against the vacuum load, and eliminate any thermal shorts to the magnet. The cantilevers are asymmetrically oriented on the vertical axis of the Baseball magnet because of the cryogenic plumbing associated with it.

Figure 11 shows the laser system. It consists of a support structure on which are mounted the two cantilevered focusing mirror assemblies; a vertical granite slab supporting four large CO_2 laser optics and a number of smaller diagnostic optics; a mezzanine supporting the diagnostic lasers and their associated optics; the large CO_2 laser; and the pellet generator. These are all mounted on a 5.5 x 2 x 0.5 m granite table. The table surface has a maximum flatness runout of .25 mm and its thickness is sufficient to make the deflection from the supported weight negligible with respect to the surface flatness.

The laser system, weighing approximately 21,000 kg, is supported on eight vibration isolators. They are pneumatically controlled by three independent actuators, which define a reference plane. Two horizontal isolators, each with separate actuators, are also mounted along the vertical plane of the cantilevers to dampen any mechanical vibration transmitted by vacuum loading. Based on dampening coefficients of 0.12 to 0.17 and natural frequencies of 1.5 to 3.0 Hz, simple one-degree-of-freedom calculations showed the transmissibility to be no more than 6.3%. The amplitude of the 17-Hz vibration at each of the focusing mirrors would then be less than 0.01 μm . With estimated component weights, designed component locations on the granite table, and the 17-Hz excitation, a later dynamic computer analysis of the entire isolated laser system indicated responses as follows: a vertical natural frequency of 1.53 Hz; horizontal natural frequencies of 2.45 Hz and 2.02 Hz; a 5% transmissibility at 10 Hz; and a 1% transmissibility at 100 Hz. Tests have been run on the isolation system with almost all the equipment in place and with vacuum loading. Data show the transmissibility to be actually about 10%. A comparison of typical floor and granite table signals is shown in Fig. 12.

Figure 11. Baseball II-T Laser System.

Figure 12. A comparison of actual floor (A) and granite table (B) velocities.

The support-structure design was supplemented with a finite-element structural analysis program, SAP IV. Figure 13 shows the elemental model used in the program. Assuming 17 Hz excitation, the structure was designed not to be a mechanical amplifier. The design natural frequency of the support structure is 34 Hz, 10 Hz above the maximum frequency at which amplification occurs.

Many parts of the large CO₂ laser mirror mounts and the support structure are made of 304 stainless steel, used for its magnetic properties and strength. Some of the large CO₂ laser mirror mount assemblies weigh as much as 45 kg. Each of the cantilever assemblies weighs over 340 kg. The cantilevers themselves are made of 316 stainless steel because of its desirable behavior at cryogenic temperatures.

The mezzanine is made of 6061 aluminum. This gives it the stiffness required to be an optical table for the diagnostic lasers yet minimizes the change in height of the laser system center of gravity. Aluminum's good machinability also makes it easy to modify the mezzanine deck with changes in laser diagnostics. Its natural frequency has been measured at approximately 150 Hz. Observations with the alignment interferometer show maximum vibrations of about one-half wave ($\lambda = 632.8$ nm) with a frequency near the natural frequency of the cantilever structure. This is adequate for optical interferometry and more than adequate for reliable pellet irradiation.

ENVIRONMENTAL CONTROL

To ensure maintenance of dimensional stability of all laser paths, we built a temperature-controlled room to house the entire laser structure. It is thermally stable at $22 \pm 0.2^\circ \text{C}$ for a designed internal load of 2.5 kW.

Figure 13. The support structure and its elemental model.

Figure 14. Typical large CO_2 laser mirror mount used on the vertical granite slab.

Relative humidity is maintained at $30 \pm 5\%$. In conformance with Federal Standard No. 209a, air particulate matter is kept to less than 10,000 ppft³ at 0.5 μ m. This is necessary to minimize laser damage caused by dust on mirror surfaces. Room air is completely recirculated once every three minutes.

The room is constructed of wood, sheet rock, and polyurethane panels. For added structural integrity, these panels are jacketed in either aluminum or steel sheet metal, depending on their proximity to the Baseball magnet. Removable roof panels allow access to the laser system with an overhead crane during any major assembly or disassembly. All environmental control equipment for the room is mechanically isolated and the duct work is acoustically dampened.

Because of the 10.6- μ m wavelength of the large CO₂ laser, sodium chloride windows were necessary to seal the laser gas and vacuum chamber of the Baseball magnet. These windows require a relative humidity less than 10%. For this reason, an acrylic plastic enclosure was constructed to envelope the sodium chloride windows and all of the large CO₂ laser optics mounted on the vertical slab. It is continuously purged with dry nitrogen gas.

VACUUM AND CRYOGENIC COMPATIBILITY

We gave considerable thought to the mechanical stability of the sodium chloride vacuum windows, as their failure would result in a catastrophic shutdown. The windows were designed with a nominal fracture safety factor of 6 and were each tested to two atmospheres before use. The windows are mounted outside the cantilever turning mirrors so that in the event of

failure, the shrapnel would have one collision with the turning mirror and a long flight path before impacting the focusing mirrors. This would minimize the energy of the shrapnel and thus the damage to the focusing mirrors. Automatically operated valves are located outside each window to minimize thermal shock and ice accumulation on the Baseball magnet in the event of window breakage.

The focusing mirrors and outer extremities of the cantilevers are maintained at 80 K. This interface with the Baseball II cryogenic system is done with long thermal paths and liquid nitrogen cooling lines. Under steady-state operations, each cantilever represents a 45-W heat load on the liquid nitrogen system. Because of the symmetrical focusing of the laser beam in the Baseball vacuum chamber, there are only negligible heat loads on the Baseball magnet from 300-K radiation through the 200-mm apertures made by the cantilevers. Each of the focusing mirrors reflects the room temperature radiation onto the other and back out the vacuum chamber. As the focusing mirrors are cooled through cantilever conduction, their alignment will be tracked with the He-Ne interferometer laser. The dimensional changes of these mirrors were considered in their design and any changes in focal length can be corrected with remote manipulators.

OPTICAL MOUNT DESIGN

All laser optical mounts are designed with kinematic, three-point suspensions. Such a design was sufficient to establish the plane of the optical surfaces. The large CO₂ laser uses eight mirror mounts, four per beam path. The four mounts on the vertical granite slab operate at 300 K and 1 atm. Each mount has five degrees of freedom in adjustable motion

(Fig. 14). A sixth degree of freedom is not necessary because the axes of all these mirrors must lie in the same plane.

On the inner ends of the cantilevers, the turning mirrors operate under vacuum at 300 K and have two degrees of freedom, both in rotation. More degrees of freedom are not necessary because the projected mirror surface is larger than the 200-mm aperture of the cantilever. On the outer ends of the cantilevers, the focusing mirror mounts have four degrees of freedom and operate in the vacuum at 80 K. In addition to the eight large CO₂ laser mirror mounts, there are also approximately 20 smaller diagnostic laser optical mounts.

The large CO₂ laser mirror mounts on the vertical granite slab have an alignment resolution of 20 μ rad. The turning mirror mounts on the cantilever fronts and the focusing mirror mounts on the cantilever ends have an alignment resolution of 50 μ rad. Focusing bars can resolve a motion of 200 μ m at the focusing mirrors in the direction of the focal axis. Because of the cylindrical shape of the focal waist, this should be sufficient resolution.

CURRENT STATUS

The total output of the laser is about 750 J. Of this, about 300 J occurs in the 50-ns initial pulse, with the remainder distributed over 1 μ s. The performance of the laser has been satisfactory, although some problems have occurred.

The 400-kV discharge of the Marx generators across the laser cavity created several unforeseen problems. Parasitics caused electronic damage to the argon ion laser, clean room controllers, and pellet guidance systems; and EMI blanketed the data collection system. The construction of a Faraday Cage about the laser and the elimination of ground loops appear to have corrected the problem. High voltage breakdown to structures or equipment too close to the laser has twice punctured the acrylic cavity vessel.

The gold-coated aluminum cavity mirrors supplied with the laser are showing considerable damage after about 500 shots, but the copper optics are showing little or no signs of damage. A pair of diamond-turned copper mirrors is being prepared to replace the original cavity. No damage has occurred to the sodium chloride vacuum windows, although an apparent cavity misalignment destroyed the laser output window.

The acoustic shock of the laser firing is causing some shot-to-shot misalignments, primarily in auxiliary optics. These are currently being corrected.

A series of shakedown experiments was completed on May 8 of the laser and pellet systems without the magnet. We hit several pellets with the CO_2 laser beam, plasmas were produced and the results were encouraging. These initial tests were made with the magnet out of the chamber to facilitate the shakedown. The magnet, streaming plasma gun, and a single 20-keV, 50-A neutral beam module are operational and were tested together earlier in the year. The magnet is currently being put into the system and full-scale experiments are expected to begin in July.

CONSIDERATIONS FOR FUTURE SYSTEMS

The upgrading of the laser start-up concept for a reactor-scale mirror machine appears to be a straightforward task. If the Poseidon start-up conditions are correct, then laser power density requirements will remain essentially the same (10^{13} to 10^{14} W/cm²). Plasma volumes will increase, thereby requiring a proportionally larger pellet, a larger laser focal spot, longer burn-through time, and therefore increased total laser energy. For example, a 100-μ target plasma would require a 500-μm-diameter pellet and a laser energy of 5 to 10 kJ. Burn-through would take about 0.1 μs.

A highly efficient electron-beam, gas-dynamic laser with a 4.2-kJ output has recently been demonstrated by Sandia Laboratories.¹⁸ The large double-headed CO₂ laser now being tested at the Los Alamos Scientific Laboratory¹⁹ would also have a similar output if it operated in the required "long" pulse regime.

The larger lasers will require larger optics, e.g., 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 2.1-m swing diamond-turning machine at Oak Ridge is being upgraded to do optical fabrication of comparable quality to the LLL 1-m 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. (a principal sodium chloride supplier) to enlarge the maximum available crystals from 35 to 43 cm in diameter and later to 75 cm.²⁰ Polycrystalline sodium chloride is also being investigated as a possible window material.

Pellet system technology will be developed for the laser fusion program. In the future, frozen H_2 , D_2 , and D-T pellets may be required. These pellet systems will require liquid helium refrigeration but will be no different in principal than the current NH_3 system.

The recent discovery of streaming plasma start-up techniques² has opened the question of relative merits of the two approaches. However, from the laser and optical engineering view, laser start-up for magnetic mirror machines is a feasible technique.

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REFERENCES

1. J. Osher and G. Porter, Laser-Pellet Heating Studies for Plasma Target Production, Lawrence Livermore Laboratory Rept. UCRL-77133, presented at 17th Annual Meeting of the Division of Plasma Physics, St. Petersburg, Florida, Nov. 1975 (1975).
2. F. H. Coensgen et al., Phys. Ref. Lett. 35 (22), 1501 (1975).
3. A. F. Haught and D. H. Polk, Phys. Fluids 13 (11), (1970).
4. A. F. Haught et al., "Laser Initiated Target Experiment (LITE)," in Proc. 5th IAEA Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, 1974 (IAEA, Vienna, 1975).
5. G. D. Porter, R. K. Goodman, and A. L. Hunt, Ammonia Pellet Production and Delivery for the Baseball II-T, Lawrence Livermore Laboratory, presented at 17th Annual Meeting of the Division of Plasma Physics, St. Petersburg, Florida, Nov. 1975.
6. C. D. Henning, R. L. Nelson, A. K. Chargin, B. S. Denhoy, and F. Marschbarger, "Engineering the Baseball Magnet System," in Proc. 4th Symp. of Engineering Problems of Fusion Research, Washington, (Naval Research Laboratory, Washington, D. C., 1971).
7. W. R. Baker, et al., "Intense Neutral Beam Research and Development," in Proc. 5th Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo (1974).
8. A. K. Chargin and C. J. Anderson, "Solving Problems of Neutral Beam Injectors at LLL," in Proc. 5th Symp. on Engineering Problems of Fusion Research, Princeton (Princeton University, Princeton, N. J., 1973).

9. T. H. Batzer et al., Concept Design of a Mirror Reactor for a Fusion Engineering Research Facility, Lawrence Livermore Laboratory Rept. UCRL-51617 (1974).
10. G. A. Carlson et al., Progress on the Reference Mirror Fusion Reactor Design, Lawrence Livermore Laboratory Rept. UCID-17022 (1976).
11. R. Parks, Appl. Optics 14 (4), 1753-1755, (1975).
12. N. Bloombergin, Appl. Optics 12 (4), (1973).
13. T. Saito, Appl. Optics 14 (4), 1773-1776, (1975).
14. 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.
15. J. W. Goodman, Introduction to Fourier Optics, (McGraw-Hill, San Francisco, 1968).
16. K. J. Bathe, E. L. Wilson, and F. E. Peterson, SAP IV, A Structural Analysis Program for Static and Dynamic Responses of Linear Systems Lawrence Berkeley Laboratory, Berkeley, California, Rept. EERC 73-11 (1973).
17. General Services Administration, Clean Room and Work Station Requirements, Controlled Environment, Federal Standard No. 209a, Washington, D. C. (August 10, 1966).
18. J. B. Gerardo, "Electron Beam Driven Chemical Lasers," presented at 1975 Conference on Laser Engineering Applications.
19. W. Reichelt and S. Singer, Los Alamos Scientific Laboratory, private communications (1975).
20. Harshaw Chemical Co., private communications (1975).