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Antares Automatic Beam Alignment System*

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Antares is a 24-beam-line CO_2 laser system for controlled fusion research, under construction at Los Alamos Scientific Laboratory (LASL). Rapid automatic alignment of this system is required prior to each experiment shot. The alignment requirements, operational constraints, and a developed prototype system are discussed.

A visible-wavelength alignment technique is employed that uses a telescope-TV system to view point light sources appropriately located down the beamline. Auto-alignment is accomplished by means of a video centroid tracker, which determines the off-axis error of the point sources. The error is nulled by computer-driven, movable mirrors in a closed-loop system. The light sources are fiber-optic terminations located at key points in the optics path, primarily at the center of large copper mirrors, and remotely illuminated to reduce heating effects.

There are 2 power amplifiers, each containing 12 beams. One telescope/TV camera is needed per amplifier. The driver amplifier, power amplifier, and target system optics are collimated to the telescope/TV camera optical axes. The final alignment to the target is accomplished with the use of a special fixture.

The use of visible light for alignment, rather than infrared, requires less expensive components, gives a smaller diffraction blur, and permits more accurate pointing. The dispersion between 10.6- μm and visible light due to the NaCl windows is measured and compensated by the control system.

Introduction

Antares is a high-power (80-100), high-energy (35-40 kJ), pulsed CO_2 laser system for the investigation of inertial confinement fusion. The system consists of three major optical sections: the front end, the power amplifier, and the target chamber system (Fig. 1).

The front-end system (Fig. 2) consists of those components necessary to generate two separate laser beams that are fed into two main power amplifiers. The front-end system contains a multicavity, line-selectable oscillator (0.25 to 1 ns, four rotational lines in the 10.6 μm band), switchout and conditioning optics, preamplifiers and spatial filters, beam splitters and relay optics for coarse temporal synchronization of the propagation paths of the two power-amplifier beam lines. The two driver amplifiers (90 J, 1 ns, annular shaped beam) have saturable gas cells for additional contrast enhancement (10^7 contrast ratio) and parasitic oscillation control.

There are two main power amplifiers (Fig. 3). Internal to each power amplifier the annular beam from the front-end system driver amplifier is spatially split into 12 sectors. After passing through a spatial filter, each of the sector beams makes two passes through the gain medium. Each power amplifier has 12 trapezoidal-shaped output beams (0.5 ns, 1400 J, 40-cm chord dimension), which fit into an annular array. The 24 beams originating from the power amplifiers are independently controlled beams and must be automatically aligned through the system and independently centered and focused upon the target.

The 12 output sector beams of each of the 2 power amplifiers are relayed to the burning chambers in an annular array and then further relayed to the target chamber (Fig. 4). The final optical elements in the target chamber (F/6 off-axis parabolas) can independently center and focus the energy of each sector in a focal spot less than 280- μm in diameter.

The cost-effective beam-alignment technique employed to align the 24-beam system is shown in Fig. 5. The system consists of variable-focus telescope/TV cameras (operating in the visible wavelength spectrum) to view and boresight light sources appropriately located down each of the 24 sectors. The deviation errors of a point source are determined by a video centroid tracker and the error is nulled by a computer-controlled, closed-loop, mirror actuator system. The light sources are fiber-optic terminations located at key points in the optic path, primarily at the center of large copper mirrors, and remotely illuminated to reduce heating effects. The optical axis of the telescope is made collinear with the front end driver amplifier and, therefore, the output is collinear with the boresight line through the system optical network.

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Antares Beam Line Physical and Operational Constraints

The automatic beam-alignment system must manage a number of various shaped beam sizes in a number of environments. The front-end driver-amplifier output beam (annular 9-cm i.d., 15-cm o.d.) is directed along a 16-m temperature-controlled atmospheric path to the power-amplifier vacuum input window. In the vacuum (10^{-6} torr) input section of the power amplifier the annular beam is divided into 12 trapezoidal-shaped beams (3 cm by 4 cm) and directed 7 m along relay and focusing mirrors and through spatial filters to the input window of the 1800-torr CO_2/N_2 pressure vessel. Each of the 12 sectors are double passed through the four discharge regions, expanded, and shaped to a 30 cm by 41 cm trapezoidal cross section. The discharge-induced electric and magnetic fields are very high (750 kV/m, 5 kA/m) at the various mirror positions. Additionally, components are subjected to x rays generated by the half-million volt, 10,000-amp discharge gain regions. The slightly converging trapezoidal beams next exit through 46-cm-diameter output NaCl window and are relayed along a 70-m path (10^{-6} torr vacuum) and focused on the target. The electrical components in the target chamber will be subjected to large EMI and other target implosion-generated radiation.

The optical support structures have been designed to maximize the natural resonance frequency and minimize the response to the pressure and vacuum states of various sections. A worst-case analysis of pressure- and vacuum-induced movements of components indicates a ± 40 - μrad beam-pointing offset between the amplifier and target chamber. The power amplifier and target system structural designs were tailored to keep the structural lowest-resonance mode frequency above 40 Hz. The corresponding optical structure, vibration-induced rotations are less than 1 μrad at 40 Hz. The closed-loop, beam-alignment servo-system bandwidth is determined strictly by operational requirements.

The general operational constraints are governed by both total system and subsystem requirements. They are: (1) The power amplifier and target system should initially be aligned independently from the front end and interfaced prior to a shot. (2) Each beam line, an individual power amplifier and its corresponding target system optical network, should be independently aligned. (3) The entire Antares system should be automatically aligned within a half-hour period for target shots. (4) The automatic alignment system controls are to be configured so as to be compatible with the hierarchical, distributed, microcomputer control system and stepper-motor applications control scheme developed for Antares. (5) The basic alignment scheme must ensure that the beams enter, traverse, and exit the two power amplifiers and their corresponding target system relay optics without vignetting, and with final centering and focusing of the beam on target. Locating the two alignment stations between the driver and power amplifiers allows constraints (1) and (2) to be met.

General Requirements

The previously listed physical and operational constraints initially provided information for the general requirements. An optical sensitivity analysis was made of the Antares optical beam line. The study involved both geometrical and diffraction analyses to determine the beam-path parameters through the system (Fig. 6, Tables 1, 2, and 3). The total analysis included the effects of all geometrical beam aberrations, vignetting, diffraction losses, beam decentering and angle errors due to small mirror errors and the study of the beam focusing characteristics at the target plane.

The primary Antares system requirement is to deliver 80% of the power amplifier output energy into a 0.1-m-diameter spot at the focal plane. A diffraction analysis of the overall optical train performance was carried out in which the performance degradation resulting from individual tilt, decentering, separation changes, and measured figure errors of the optical elements were included. Degradation due to non-linear intensity effects in NaCl and to gas nonuniform medium phase distortions are expected to be minimal. The radial energy distribution (Fig. 7) for the degraded case without any final pointing errors shows that a conservative final centering error budget on target of $\pm 45 \mu\text{m}$ is appropriate. Table 2 shows the error budget for the final centering and pointing required for the target alignment system. As indicated in the table, the sources of alignment errors need to be constrained in order to meet the target system alignment requirements. Additionally, the error sources are, in general, mutually independent, so that the combined error can be approximated by the square root of the sum of the squares (RSS).

Working back from the target system alignment requirements, a number of system requirements are established throughout the remainder of the optical network. The details of elements' field of view, error budgets and requirements for the remainder of the optical network is presented in Table 3, and referenced to Fig. 6. The error budgets contain the possible vibrational and thermally induced offsets in beam centering, control system deadbands and computer/mirror actuator, motor-driver interface offset errors. These errors are RSSed or coherently added where appropriate. The motor controlled elements are shown in Fig. 6. The other elements are either fixed or manually adjusted. The decision as to which mirror positions should be motor controlled is determined from a sensitivity analysis and from practical engineering considerations like accessibility, susceptibility to environmentally induced tilts, and the particular EMI environments. For example, the back-reflector mirror, element 14, Fig. 6, is subjected to a pressure pulse (~ 3 psi) from the electrical discharge in the gain regions of the absorber window, element 13, as the pressure is released. In this case the back reflector, which directs the beam down to the target system, would most likely be misaligned and in need of a remote adjustment.

Table 1. Calculated Energies and Intensities

Station	Energy (J)	Pct. Loss	I_{Max} (J/cm ²)	$I_{\text{Max}}/I_{\text{Av}}$
Splitter	6.35	—	1.1	—
Spatial Filter	5.20	5.1 13.7 8.8	2750	—
Gas In	4.54	4.4 24.8*	0.5	3.0
Back Refl.	35	4.1 5.5**	0.4	1.3
Gas Out	1513	0.4 2.0	2.1	1.3
Turn	1439	1.6 1.0	3.4	1.6
Fold	1415	0.7 1.0	4.5	1.8
Focus	1400	0.0	4.7	1.8
Target	1400	—	2.3×10^7	—

*Loss prior to gain portion of first pass
(primarily loss in cold CO₂)

**Obscuration and window loss

Table 2. Target Pointing Error Budget Statistics

(1) Telescope/Camera/Target Interface	±17.0 arc
— Contributions from typical sources:	
T.V. raster drift	±3.0 arc
Telescope thermal drift	±5.0 arc
Image resolution granularity	±4.0 arc
Tracker position granularity	±4.0 arc
Stepper motor granularity	±5.0 arc
Centroid location error	±5.0 arc
Large and small mirror vibrations	±5.0 arc
(2) Target Fixture Positioning and Vibration	±17.0 arc
(3) Target Positioning and Vibration	±5.0 arc
(4) Orthogonal Telescope Target Orientation	±17.0 arc
	95% ±33.0 arc

The major task in the system alignment is mostly that of centering the beam on the various optical elements as seen in Table 3. The exceptions are:

1. The collinearization of the telescope axis with the driver amplifier output beam.
2. The polyhedron mirror, element 3, Fig. 6, requires a pointing and centering task. Any centering errors at the polyhedron mirror are magnified by a factor of 10 at the back reflector mirror, element 16, Fig. 6, and pointing errors are respectively decreased by a factor of 10.
3. The range of pointing angles on the target system focusing parabola will be determined with a double path interferometer to minimize alignment-induced aberrations, and thereafter will be controlled by centering adjustments on the parabola.

The Antares optical train is designed to eliminate stray, wide-angle optical paths from the network so as to avoid parasitic oscillation paths. As a consequence, the severe vignetting at the edge of the mirrors on the edge of the mirrors led to the use of biconcave holes in the center of mirrors with integrated fiber optics as illustrated in Fig. 5. With these few exceptions and any requirements for a target system was designed and tested which is functionally reliable, cost effective, and easily maintainable, and the total Antares optical network.

Alignment System Description

The visible-wavelength alignment technique uses a television camera to view point light sources located at key positions in the optics path. Automatic alignment is accomplished by means of a computerized tracker. Pointing and centering misalignments are registered as displacements on the TV tube, as shown in Fig. 8. These displacements are quantified by the tracker video, which, through a computer, moves the appropriate motorized mirror to null the misalignment. The result is a block diagram showing the alignment interface schematic. The TV camera is a standard 525-line CCV system using a silicon charge-coupled device.

Figure 5 is a schematic diagram showing all of the key alignment devices required to implement the alignment scheme into Antares. The key items are: the front-end alignment station, power amplifier assembly, polyhedron alignment device, back reflector, off-axis light source, mirror, and light source, mirrors with integral light sources, and the target-alignment fixture. All mechanical operations are stepper-motor driven so that positions can be retained in computer memory.

The heart of the alignment system is the front-end alignment station, as shown in detail in Fig. 10. This station is physically located in the front-end room where the initial alignment and trigger pulses are generated. There is one station per beam line, each with a variable-focus telescope system. The telescope views the point light source via the point mirror pair, which is mounted on a motorized stage just up-beam from the telescope. This enables the telescope to either look forward to the power amplifier or back towards the front-end driver amplifier. A third station of the telescope is available so that after alignment is complete, the beam from the front-end driver can pass between the point mirror pair and up the beam tube towards the power amplifier.

Visible and CO₂ alignment lasers are also on the front-end alignment station. The visible alignment laser (500-mW Krypton-Ion) is an aid in initial setup, mirror alignment, and to align the target. The alignment laser provides 10.6-μm radiation for initial setup alignment, while the CO₂ laser provides 10.6-μm and 10.6-μm alignment due to dispersion caused by water vapor in the beam path. Both of these laser beams are spatially filtered and collimated by the point mirror pair, which is also a part of the front-end alignment station.

Table 3. Element Field of Views, Acquisition Ranges, Decenter and tilt Residual errors

Element and No.	Instantaneous Field of View	Required Acquisition Range	Allowed Error	Predicted Error	Limiting Constraints
Angle at Power Amp. Driver Spatial Filter Input	± 4 mrad	± 9 mrad	± 5.6 mrad	± 5.14 mrad	± 90 μ rad at EL No. 3
Translation at Power Amp. Driver Output	± 3 mm	± 20 mm	± 0.2 mm	± 0.1 mm	± 0.4 mm at EL No. 3
Angle of Periscope Index	—	350°	± 1 mrad	± 300 μ rad	± 4 mm decenter at EL No. 14
Translation of Periscope Index	—	—	± 0.2 mm	± 0.1 mm	± 4 mm decenter at EL No. 14
Angle at Polyhedron, No. 3	± 0.6 mrad	± 4 mrad	± 90 μ rad	± 55 μ rad	± 9 μ m at target EL No. 21
Translation at Polyhedron, No. 3	± 12 mm	± 30 mm	± 0.2 mm	± 0.3 mm	± 4 mm decenter at EL No. 14
Translation at Spatial Filter No. 7	± 3 mm	± 13 mm	± 0.2 mm	± 0.09 mm	less than 1% loss in power transmission
Translation at Back Reflector, No. 14	± 40 mm	± 90 mm	± 5 mm	± 4 mm	less than 1% loss in power transmission
Translation at NaCl Window, No. 15	± 35 mm	± 70 mm	± 5 mm	± 4 mm	less than 1% loss in power transmission
Angle of Rotary Wedge	—	360°	± 250 μ rad	± 150 μ rad	± 1 mm at EL No. 14
Translation at Rotary Wedge	± 112 mm	± 3 mm	± 0.25 mm	± 0.25 mm	± 2 mm at EL No. 14
Translation at Turning Chamber Mirror, EL No. 18	± 77 mm	± 110 mm	± 1 mm	± 1 mm	To maintain field angle at EL No. 21 to be less than 0.5 mrad
Translation at Fold Mirror, EL No. 19	± 35 mm	± 61 mm	± 1 mm	± 1 mm	To maintain field angle at EL No. 21 to be less than 0.5 mrad
Angle at Focus Mirror, EL No. 20	± 1 mrad	± 4 mrad	± 0.5 mrad	± 0.25 mrad	To minimize aberrations
Translation at Focus Mirror, EL No. 20	± 62 mm	± 76 mm	± 1 mm	± 1 mm	To maintain field angle at EL No. 21 to be less than 0.5 mrad
Pointing Angle* at Target EL No. 21	± 0.5 mrad	± 0.5 mrad	± 20 μ rad	± 12 μ rad	insure 80% power transmission on 280- μ m-diam. spot

*Allowed pointing angle includes errors from target and alignment fixture centering and vibration.

The beam expander/spatial filter device uses zinc-selenite input/output lenses, which are mounted on stepper-motor driven slides so that they can accommodate both the visible and infrared light. Focusing and change the focus position of the output lens enables the alignment layers to be focused on any particular location of interest throughout the Antares optical system.

After the alignment beams exit the beam expander/spatial filter they pass through a series of steering mirrors on the front end of the output stage. The hole in this mirror is located so that the beam exiting from the front end driver amplifier has an annular shape (15 mm dia.) by the time it is

The polyhedron alignment device is located in the power amplifier attached and aligned to the polyhedron mirror. The polyhedron mirror, which has a hole in its center, accepts the annular beam generated in the front end and splits it into 12 trapezoidal shaped beam sectors, each of which follows its own path through to the target. The polyhedron alignment device consists of a lens that is illuminated with a point light source at its focal point. The telescope/TV camera is able to view this light source through the lens by viewing up the beam-path centerline through the hole in the polyhedron mirror. With the telescope focus set at infinity, the point-light source in the polyhedron alignment device can be viewed and angular pointing misalignments nulled by the appropriate mirror. By changing the telescope focus to image the lens in the polyhedron alignment device, it is possible to achieve a centering alignment to the polyhedron mirror, Fig. 8.

For alignment further into the system, it is necessary to sight off each of the 12 faces of the polyhedron mirror. To achieve this, the periscope/carousel is inserted into the beam path prior to the polyhedron mirror. This device consists of two parallel mirrors that are rotated around the centerline of the annular beam path. These mirrors have the proper offset so that the telescope/TV can view one of the 12 faces of the polyhedron mirror. By automatically indexing the periscope mirror pair it is possible to view sequentially (with the telescope/TV) through each of the 12 individual beam sectors in each power amp. of on.

The back reflector "flip-in" light source is located just before the back-reflector mirror in the power amplifier. It consists of a fiber-optic light source mounted on an arm, which can be retracted, retracted into position in front of the mirror. At this location, a "flip-in" light source was chosen in preference to mounting a light source in the mirror due to risk of parasitic oscillations in the power amplifier.

The rotary wedge device (Fig. 5) is located after the output NaCl window. The salt window has a slight wedge built into it (for diagnostic purposes); therefore, it was necessary to put in a compensating wedge to correct for angular dispersion between visible and 10.6- μ m radiations. This compensating wedge is mounted on a rotary arm that is stepper-motor driven so that it can be sequentially indexed between beam lines as is done with the periscope/carousel. Also mounted on the rotary wedge is a fiber-optic light source to serve as a target for the telescope/TV/tracker.

Next, alignment is done at the turning chamber, target-chamber fold flat, and target-chamber focus parabola mirrors. Alignment at each of these locations is similar since each of these mirrors has a fiber-optic light source installed in a hole in the center of the mirror.

Final alignment to the target is accomplished using an illuminated target-alignment fixture. This fixture is accurately located at the target position so that after alignment the target can be pointed off as mentioned via a pair of orthogonal telescopes. The target-alignment fixture is a hollow cylinder with internally reflective surfaces and apertures located at positions for final alignment. The target-alignment fixture is mounted to a single, large fiber-optic light pipe that provides the illumination. The telescope/TV/tracker then aligns to the light exiting the apertures in the target-alignment fixture.

A typical computer-controlled automatic alignment sequence is to first check the alignment of the telescope by viewing the pinhole in the beam-expander/spatial-filter device as a reference. Next, the telescope views the light sources in the front-end driver amplifier, and these sources are null aligned to the pointing mirrors on the front-end alignment station. The telescope then views the power amplifier, periscope, and pointing alignment is made to the polyhedron alignment device. After this, the periscope, the flip-in back reflector, the appropriate back reflector flip-in light source are inserted and alignment is made to the back reflector. At this time, the flip-in light source is retracted, the rotary wedge device is indexed into place, and alignment to it is accomplished. With the wedge still in place, but with the light source retracted, alignment is made sequentially to the turning-chamber mirror, to the fold flat in the target chamber, and then to the focus parabola in the target chamber. Next, the light source in the target-alignment fixture is illuminated and final pointing alignment to the target is achieved. Finally, a spatial filter device in the power amplifier is moved into position and alignment is achieved to a light source in the spatial filter. After alignment, the spatial filter device indexes a pre-determined distance from the reference light source position to the filter aperture. This completes the alignment of one of 12 sectors of the power amplifier. The periscope/carousel is then indexed to the next sector and the above procedure is repeated for more power amplifiers. Finally, the periscope/carousel, back reflector flip-in, and the rotary wedge are all retracted out of the beam path and the rotary focus in the front end is indexed out of the beam path. The target-alignment fixture is replaced by the target and the system is ready to fire.

Corrections based upon values obtained in a calibration procedure are applied, which remove errors between the visible and 10.6 μ m beam paths. The calibration values are obtained using a spatially coherent common-path interferometer³ at the target location. The interferometer is used in conjunction with the 10.6- μ m alignment laser to locate the position of the alignment beam and also to locate the 10.6- μ m coherent pulsed beam when it is used as an alignment laser. These positions are compared to the visible alignment beam pointing position at the target position, and the corrections can be quantified. As a result, to access the quality of a given beam, the common path interferometer can be used to locate the desired focal point and illuminated with a spatially filtered alignment laser. The beam with the resulting fringe pattern that shows defocus, lateral misalignment, and aberrations can be viewed and corrected. The beam corrections are minimized by tilting and translating the focus on the target chamber mirror with the preceding two flat mirrors.

Performance Analysis

The driving requirement from the standpoint of resolution/accuracy is the ± 1 mm centering on the fold mirror in the target chamber. A light source at this mirror is imaged by the laser optics at 23,000 mm from the telescope. The laser optics also have a linear/lateral magnification of 0.14% at this mirror so that a decentering of ± 1 mm translates to ± 0.14 mm at 23,000 mm or, equivalently, ± 6.1 μ rad. The limiting aperture for this image is the polyhedron beam splitter, which produces a diffraction angle of about 15 μ rad. Thus, the 6.1- μ rad resolution requirement can readily be achieved by resolving the diffraction spot to better than 1 part in 3, assuming that the source size does not significantly enlarge the diffraction spot.

Making the light source 1 mm in diameter adds 6 μ rad to the diffraction spot size, yielding a 12- μ rad image. This image requires a resolution of about 1 part in 4, but at the same time keeps the source brightness requirement reasonable.

The required source brightness (lumens/sr/ft²) is given by

$$B = H(A_{\text{spot}}/A_{\text{source}})T/\Omega$$

where

$H = 0.1$ lumen/ft² of 2935°K tungsten light (required silicon vidicon illumination for good resolution).

$\Omega = 9 \times 10^{-7}$ steradian = maximum collecting solid angle (limited by polyhedron aperture stop).

A_{spot} = Area of source image on vidicon.

A_{source} = Area of source at fold mirror.

T = Total transmittance of all optics between source and vidicon.

In order to obtain ± 3.5 μ rad of resolution (± 0.030 mm at the target), which allows for other system errors, the telescope magnification for this source must be 0.34. This result is based on using a standard 525-TV-line, 1-in. vidicon, and the numerical analysis 9.5 mm/350 resolution lines/0.030 mm. For $A_{\text{spot}} = 0.021$ m² for a 21- μ rad source. The transmittance of the optical train for a source at the fold mirror (Fig. 4) is approximately 0.07 at 6328 Å. For a 1-mm-diameter source the brightness, as calculated from the formula, must be 5×10^4 lumens/sr/ft². The output of fiber-optic light pipes coupled to tungsten halogen lamps have been measured at more than 6×10^4 lumens/sr/ft², which allows adequate margin for fiber-optic connector losses plus adjustment of A_{spot} to obtain more resolution if needed.

The 0.34 magnification factor implies a telescope focal length on the order of 5000 mm. When viewing sources at infinity, such as the target, resolution is not the driving requirement and the long focal length results in a system with marginal field of view at the target and requires a bright source. Thus, the desired requirement on the telescope design is a shorter focal length (smaller magnification) for infinite objects and a longer focal length (larger magnification) for 23,000-mm objects.

The target alignment total error budget is ± 92 μ rad at the telescope. This results from a 1.6-m focal length focus parabola and 7.4% angular magnification in the Antares laser optics, and alignment error budget at the target. A reasonable source size in a "jack-o-lantern" type target alignment fixture is 50 μ m, which is 2.0- μ rad angle at the telescope. The wedge compensator of 13-cm diameter is the limiting aperture for this source and results in 140- μ rad total diffraction angle at the telescope after a magnification of 0.46. If total source angular subtense is then 310 μ rad, as seen by the telescope, requiring resolution to 1 part in 4. A 5000-mm focal-length telescope would give a spot diameter of 1.73 mm on the vidicon requiring a source brightness of 4.7×10^5 lumens/sr/ft² ($\omega = 4.95 \times 10^{-2}$ sr, $T = 0.07$). This brightness is difficult to achieve from a "jack-o-lantern" type alignment fixture without resorting to high brightness lasers for illumination. A telescope focal length of 2500 mm would require less brightness, 1.4×10^5 lumens/sr/ft². The field of view at the target is 0.4 mm with the 5000-mm focal length, whereas with the 2500-mm focal length, the field of view is 0.9 mm, which allows more error in target location without resorting to search modes.

A telescope that provides a magnification of 0.326 for 22-m objects and a 2700 mm focal length for infinite objects has been designed with off-the-shelf components, and is presently being fabricated. This design, however, does not provide for viewing objects within 15 m (front end requirement) so other designs that focus to within 11 m (to also allow imaging front-end pit mirrors) are currently being evaluated.

Tests

Tests were performed using a mock-up of an Antares beam-line section, which essentially verified the performance predictions of the above analysis. The beam line mock-up used actual Antares mirrors and optical components and was complete except for Antares salt windows.

The following questions had to be answered:

1. Will the Antares beam line allow good viewing using visible light sources at the fold flat and at the target?
2. Will the reflectance of the copper mirrors allow for adequate system transmissivity?
3. Will pressure-induced bowing of the salt windows affect the optical characteristics of the system?
4. Will salt-window surface damage, due to high CO₂ flux and water vapor, degrade the system's performance noticeably?

The telescope used for the tests was a 7-in.-diameter Questar set-up with a focal length of 4900 mm. Fig. 11 shows the tracker error maximum/minimum outputs vs movement of a 1-mm-diameter source at the fold flat. This data shows the resolution to be approximately ± 1 m.

The light spot covered 6 TV scan lines compared to a predicted 5 TV lines using a 3-by-4 aspect-ratio raster, 3/8 in. high by 1/2 in. wide, 480 scan lines. The effective magnification for the Questar to view an object at 23,000 mm was 0.22. A telescope with a magnification of 0.34 for the fold flat source will provide even better resolution.

Figure 12 shows the same type of data for the target. In this case, resolution is about ± 5 m. The spot size in this case covered about 90 TV scan lines, whereas one would predict about 80 TV scan lines. This was due to aberrations resulting from deliberately inaccurate placement of beam-line optics to simulate worst-case component alignment, and also from atmospheric scintillation since the beam sector was not enclosed.

Initially, there was concern that the diamond-turned mirrors might spread the images of the point sources. These fears were dispelled by earlier MTF measurements and by the tests just mentioned. The MTF data is shown in Fig. 13. The beam line contains 7 diamond-turned copper mirrors and 11 polished copper mirrors between the alignment telescope and the target. The worst-case contrast transfer for seven diamond-turned mirrors is 0.91. The target at the equivalent resolution bar size corresponded to the spot size of 230 μ rad.

Reflectance measurements made on diamond-turned and polished-copper mirrors in the visible spectrum (0.63 μ m) showed the diamond-turned mirrors to be consistently better than 0.91 reflectance (the 2.0 loss included both absorption and scattering) while the reflectance of polished copper mirrors varied considerably, depending on the supplier (0.33 to 0.95). The polished copper mirrors used in the mock-up beam line were specified to have a reflectance higher than 0.88 at 0.633 μ m. Since the mirror reflectances were as high as expected, the actual source brightness requirements compared well with the predicted requirements.

Early in the program there was concern about the effects of the large NaCl output window bowing because of the 1800-torr pressure differential across the window faces. Tests were made on an Antares prototype window to measure the defocusing of a beam passing through the window for various pressure differential conditions. It was found that at 1800 torr the window experienced a very slight meniscus bending on the order of 10^{-3} λ at 633 nm, which corresponds to an equivalent focal length of 3.56×10^3 m and a wavefront sag of 1.2×10^{-3} λ at 633 nm.

Concern was also expressed as to a possible reduction of the alignment telescope camera image contrast due to the degradation of the salt window faces from damage sites and a haze formation that results from surface absorption of water. Tests were made of the point source contrast ratio as four degraded salt windows were added into the Antares single-sector test bed. The windows were more degraded, from open atmosphere degradation effects, than expected in the Antares system, which is a closed, clean system. The test results indicated that even in this worst-case measurement, the contrast ratio was decreased by only 4%. The result is not surprising, since the silicon diode array TV camera tubes used in these experiments respond well in the 0.8 to 0.1- μ m band where the forward scattering function of hazed surfaces falls off rapidly. The main effect of any possible haze in the Antares system is to reduce the transmission since the wide angle scatter from the haze would have to pass through the typical small solid angles, ± 1 mrad, to the telescope/TV camera system.

Summary

The automatic alignment system for the Antares CO₂ fusion laser is described. The visible-wavelength alignment technique meets the Antares beam-alignment requirements in a very cost-effective manner. The technique employed uses a telescope/TV system to view point light sources in situ at key points in the optics path. Automatic alignment is accomplished by means of a video control tracker, which nulls the error with a computer-controlled, closed-loop mirror actuator system.

System analysis shows the technique to be suitable for automatically correcting pointing and centering errors to the resolution required by the Antares optical system. This analysis was verified using a full-size mockup of one Antares beam-line sector. The beam-line mock-up employs a full Antares mirror and optical components and is complete from the front end to the target. The alignment technique is currently being refined using this mock-up, and hardware is being prepared for installation in an actual Antares power amplifier later this year.

References

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Fig. 1. Antares facility schematic.

Fig. 2. Antares front-end optical schematic.

Fig. 3. Antares power amplifier (1 of 6).

Fig. 4. Antares target system optical schematic.

Fig. 5. Antares automatic alignment system schematic.

Fig. 6. Antares power amplifier optical train.

Fig. 7. Incidence curve at target.

Fig. 8. Alignment concept.

Fig. 9. CCTV/Tracker alignment station.

Fig. 10. Front-end alignment station.

Fig. 11. Fold flat source movement vs. tracker error signal.

Fig. 12. Target source movement vs. tracker error signal.

Fig. 13. Contrast transfer of diamond-turned copper mirror for silicon x-ray and electron beam lithography.