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OPTO-MECHANICAL DEVICES FOR THE
ANTARES AUTOMATIC BEAM ALIGNMENT SYSTEM*

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Abstract

Antares is a 24-beam CO₂ laser system for controlled fusion research, under construction at Los Alamos National Laboratory. Rapid automatic alignment of this system is required prior to each experimental shot. Unique opto-mechanical alignment devices, which have been developed specifically for this automatic alignment system, are discussed. A variable focus alignment telescope views point light sources. A beam expander/spatial filter processes both a visible Krypton Ion and a 10.6 μ m CO₂ alignment laser. The periscope/carousel device provides the means by which the alignment telescope can sequentially view each of twelve optical trains in each power amplifier. The polyhedron alignment device projects a point-light source for both centering and pointing alignment at the polyhedron mirror. The rotating wedge alignment device provides a sequencing point-light source and also compensates for dispersion between visible and 10.6 μ m radiation. The back reflector "flip in" remotely positions point-light sources at the back reflector mirrors. A light source box illuminates optic fibers with high intensity white light which is distributed to the various point-light sources in the system.

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Introduction

Antares is a high-power (20-TW), high-energy (35-40 kJ), pulsed CO₂ 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 (Figure 1).

The front-end system 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 (1 ns, four rotational lines in the 10.6 μ m 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. 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 (1.0 ns, 1600 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 turning chambers in an annular array and then further relayed to the target chamber. The final optical elements in the target chamber (F/6 off-axis parabolas) can independently center and focus 80% of the energy of each sector in a focal spot less than 280 μ m in diameter.

The beam-alignment technique employed to align the 24-beam 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 decentration 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. Therefore, when the optical network is collinearized with the telescope axis, the driver output is then collinear with the boresight line through the system optical network.

Automatic Alignment System Description

Figure 2 presents a schematic diagram of the automatic alignment system. The system design, including physical and operational constraints, general operational requirements, performance analyses, testing, etc., are discussed elsewhere in detail.^{1,2} A brief description of the system operation and the functions of the individual pieces of opto-mechanical hardware in the system are discussed in the following paragraphs.

The visible-wavelength alignment technique uses a telescope/TV camera to view point-light sources located at key positions in the optics path. Automatic alignment is accomplished by means of a video centroid tracker. Pointing and centering misalignments are registered as displacements on the TV tube, as shown in Figure 3. These displacements are quantified by the tracker device, which, through a computer, drives the appropriate motorized mirror to null the misalignment.

The heart of the alignment system is the alignment station, as shown in detail in Figure 4. This station is physically located in the front-end room where the initial oscillator and driver-amplifier pulses are generated. There is one station per beam line, each with a variable-focus telescope/TV camera. The telescope views the point-light source via the penta-mirror pair, which is mounted on a rotary table 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 position of the rotary table is available so that after alignment is complete, the beam from the front-end driver can pass between the penta-mirror pair and up the beam tube towards the power amplifier.

Visible and CO₂ alignment lasers are also on the alignment station. The visible-alignment laser (500 mW Krypton-Ion) is an aid in initial setup, manual alignment, and trouble-shooting. The CO₂ alignment laser provides 10.6 μ m radiation for initial set-up alignments, calibration of errors between visible and 10.6 μ m alignment due to dispersion caused by wedge in salt windows, and for use with a common path interferometer.³ Both of these laser beams are spatially filtered and expanded by the beam expander/spatial filter device, which is also a part of the alignment station.

The beam expander/spatial filter device uses zinc-selenide input/output lenses, which are mounted on stepper-motor driven slides so that they can accommodate both the visible and 10.6 μ m light. Being able to change the focus position of the output lens enables the alignment lasers to be focused at any particular location of interest throughout the Antares optical system.

After the alignment beams exit the beam expander/spatial filter they pass through a hole in one of the steering mirrors on the front-end alignment station. The hole in this mirror is allowed because the laser beam exiting from the front-end driver amplifier has an annular shape (15 cm o.d. by 9 cm i.d.)

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.

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 amplifier.

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 remotely rotated 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 oscillation in the power amplifier.

The rotary wedge device 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 μm radiation. This compensating wedge is mounted on a rotary arm that is stepper-motor driven so that it can be sequentially indexed to the 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 precisely positioned via a pair of orthogonal telescopes. The target alignment fixture is a hollow gold sphere with internally reflective surfaces and apertures located at positions of desired alignment, like a jack-o-lantern. The 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

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 misalignments are nulled using the two steering mirrors on the front end alignment station. The telescope then views the power amplifier, and centering and pointing alignment is made to the polyhedron alignment device. After this, the periscope/carousel and the appropriate back reflector flip-in light source are inserted and alignment is accomplished to the back reflector. At this time, the flip-in light source is retracted, the rotary wedge device is moved into place, and alignment to it is accomplished. With the wedge still in place, but with its light source turned off, 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 on the spatial filter. After alignment, the spatial filter device indexes a predetermined distance from the centered 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 11 more times per power amplifier. Finally, the periscope/carousel, back reflector flip-in, and the rotary wedge are all retracted out of the beam path and the rotary table 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 μm beam paths. The calibration values are obtained using a gimbal mounted common-path interferometer³ at the target location. The interferometer is used in conjunction with the 10.6 μm alignment laser to locate the position of the alignment beam and also to locate the low power, oscillator-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. Additionally, to assess the quality of a given beam, the common path (point diffraction) interferometer can be located at 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 almost fully corrected. The beam corrections are minimized by tilting and translating the beam on the target focusing mirror with the preceding two flat mirrors.

Opto-Mechanical Device Descriptions

Descriptions of the major pieces of opto-mechanical hardware designed for the automatic alignment system are discussed in detail in the following sections.

Variable Focus Alignment Telescope

The variable focus alignment telescope described here was designed with "off-the-shelf" optical components. It will be used for initial testing and evaluation of the automatic alignment system. This design, however, does not provide for viewing objects within 18 meters (front-end requirement). Therefore, a second design is currently underway (under subcontract to Space Optics Research Laboratory) for a telescope that will focus to the required 11 meters.

A sketch of the telescope is shown in Figure 5. Optically, it consists of a fixed 15 cm diameter objective lens, a manually adjustable 5 cm diameter secondary lens spaced approximately 104 cm behind the objective, and a corner cube formed by 3 mirrors which folds the optical path back to a silicon vidicon camera which mounts along side the secondary lens.

The main structural component is an optical breadboard 48 cm wide x 213 cm long x 6 cm thick. This breadboard is supported above the Front End Alignment Station Optical Table (Figure 4) by six 5 cm diameter Invar Steel legs 30 cm long. The objective lens holder is mounted to an aluminum angle plate attached to the front of the breadboard. The secondary lens is mounted on a series of translational/rotational stages (for ease of alignment) midway along the length of the breadboard. A second breadboard (30 cm wide x 122 cm long x 6 cm thick), which can be leveled with respect to the first breadboard, holds a slide mechanism. Attached to the slide mechanism is the corner-cube assembly. The slide mechanism is driven by a stepper motor through a flexible plastic chain to a step resolution of .50 mm. Movement of the corner cube on this slide mechanism results in the required change in focus of the telescope. The vidicon camera is mounted on a bracket which is attached to the base of the slide mechanism. The camera, on its mount, is fully adjustable. Attached to the front face of the camera is an eyepiece assembly which, through a prism which slides over the camera aperture, allows for direct viewing with the eye through the telescope.

The entire telescope is covered with a sheet metal cover to keep out stray light and dust. Electrical feed-throughs are provided and panels are included for accessing the secondary lens and camera for adjustments.

The telescope was precision aligned and tested. It achieved a focus range from 18 meters to infinity while holding a boresight alignment of .2 mm throughout its focus range.

Beam Expander/Spatial Filter

Alignment lasers in use (Figure 4) for manual alignment include a Krypton-Ion laser which provides light at a visible wavelength and a CO₂ laser which provides invisible 10.6 μ radiation. It was decided to process the visible laser through the same optics as the CO₂ laser to assure colinearity between the 10.6 μ and visible lasers. Few materials transmit radiation both in the visible and at 10.6 μ . One such material is salt. Another is zinc selenide (ZnSe). It was decided to

build a device using ZnSe lenses which would provide spatial filtering for both visible and CO₂ alignment lasers and also provide substantial (20 x) beam expansion for both alignment lasers.

Figure 6 is a sketch showing the key features of the device which has been developed. Its optical components consist of 1) an input ZnSe lens (1.25-cm dia.) which brings the input laser beam to a focus, 2) a precision pinhole for spatial filtering at the focus of the input lens, and 3) an output ZnSe lens (8.0 cm dia.) which accepts the diverging beam emitted from the pinhole and recollimates the light at a new larger diameter. The output beam diameter is larger than the input beam diameter by the ratio of the focal lengths of the input and output lenses. Extending the distance between the output lens and the pinhole causes the beam to be brought to a focus. This feature is a valuable aid in manual alignment since the beam can be focused onto the element being aligned.

The lenses are both mounted on motor driven slide assemblies so that the focal position of each lens can be changed. This is necessary because the index of refraction of ZnSe is a function of the wavelength being passed; and the focal length of the lens is a function of its index of refraction. Therefore, when changing from a visible laser to a 10.6 μ m laser it is necessary to change the position of both lenses. The mechanism is precisely aligned to achieve accurate tracking of the optical path as the lenses are moved.

A prototype unit has been in use in the Antares single beam line mock-up for over one year and has proven to be an invaluable tool in aligning this extensive optical setup.

Periscope/Carousel

Each power amplifier in Antares accepts a single annular shaped beam (15 cm o.d. x 9 cm i.d.) from the Front End and splits the beam into 12 distinct trapezoidal shaped beams by means of a faceted "Polyhedron" mirror. Each trapezoidal beam then follows its own optics path through amplification in the power amplifier, to the turning chamber and finally the target chamber (Figure 1). In order for the alignment telescope to view each of these 12 optics paths, it is necessary to provide a means by which the telescope, which is initially set up collinear with the annular beam from the front end, can sight off each of the 12 facets of the Polyhedron mirror. To achieve this, the Periscope/Carousel device is inserted into the beam path prior to the Polyhedron mirror in each power amplifier.

A sketch of the Periscope/Carousel is shown in Figure 7. Optically, it consists of two parallel mirrors that are set at 45° to, and rotated about the center line of the annular beam path. These mirrors are spaced so that the telescope/TV can view the center of one of the 12 facets 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 lines in each power amplifier. The Periscope mirrors are aluminized glass and rectangular shaped in order to increase the field of view through the device.

The main structural component of the device is a steel box-beam weldment which is firmly anchored to the floor below each power amplifier. The rotary carousel subassembly is mounted on a carriage which can be retracted from the beam path after alignment via a stepper-motor driven lead screw. Insertion positioning resolution is .006 mm per step. The rotary carousel subassembly rides on a single large diameter precision bearing and is positioned by a special large diameter ring gear and worm also driven by a stepper-motor. Rotary step resolution is 15.7 arc sec.

The carousel also contains a diagnostic "beam blocker" device which allows the full power annular beam to hit the carousel with only 1/12 of it allowed to pass. In order to minimize retroreflections into the front end, surfaces of the carousel exposed to the full power beam have been coated with flame or plasma sprayed Lithium Fluoride which is an excellent absorber at 10.6 μm

Polyhedron Alignment Device

Prior to alignment of each of the 12 individual beam lines in each power amplifier, it is necessary to align (both centering and pointing) to the faceted polyhedron mirror. To achieve this, the Polyhedron Alignment Device attaches to the rear of the polyhedron mirror. It provides, through a hole in the center of the polyhedron mirror, an illuminated aperture for centering and provides a point-light source for pointing.

A sketch of the Polyhedron Alignment Device is shown in Figure 8. Optically, it consists of a 5 mm diameter aperture, an acromatic lens, an adjustable steering mirror, and a 25 μm diameter pinhole which is illuminated by a fiber-optic pigtail. The lens is illuminated by the 25 μm point-light source located at its focal point. The telescope/TV camera is able to view this light source (through the lens) by viewing up the beam path center line through the hole in the polyhedron mirror. With the telescope focus set at infinity, the point-light source is viewed, through the lens, and angular (pointing) misalignments can be nulled by the appropriate mirror. With the telescope focus set to image the lens, which is illuminated by the point-light source, it is possible to achieve centering alignment.

The basic structural member of the Polyhedron Alignment Device is a welded aluminum housing which provides for attachment to the polyhedron mirror and a holder for the lens and the adjustable turning mirror. A rear end cap also attaches to the housing via a slip fit which can be locked in place with a collar. This cap holds the fiber-optic pigtail and pinhole which can be focused via the slip fit and locking collar feature. The adjustable turning mirror is used together with a large aperture auto collimator to align the pinhole so that the line-of-sight generated is truly perpendicular to the flat front face of the polyhedron mirror.

Rotary Wedge Alignment Device

Each of the 12 optics paths in each power amplifier contains a large (46 cm diameter) salt window. These salt windows have a slight wedge built into them for re-directing first surface internal reflections into calorimeters for diagnostic purposes. Since automatic alignment is done in the visible, while the actual laser pulse occurs at 10.6 μm , it was necessary to somehow compensate for the error which would occur due to the difference in dispersion for salt between the visible light and 10.6 μm radiation. To achieve this correction, it was decided to insert a compensating wedged window, for alignments only, into each beam path. The logical location for this compensating wedge, which was just a couple of meters past the salt window, was also a logical choice for locating a point-light source for the telescope/TV to align against. In order to keep cost to a minimum, and since only one beam path could be aligned at a time anyway due to the Periscope/Carousel indexing feature described earlier, it was decided to have one compensating wedge with a light source per each power amplifier. The resulting design is called the Rotary Wedge Alignment Device. It consists of the compensating wedge and light source 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.

Figure 9 is a sketch of the Rotary Wedge Alignment Device. Optically, it consists of a compensating wedge made of BK-7 glass which is 15 cm in diameter, approximately 2.4 cm thick and has a 91 arc sec. wedge built into it. This wedged window is suspended on 3 points in its ring mount. It was tested interferometrically before and after mounting and no distortion was observed due to the mount. The light source on the device consists of a 1 mm diameter fiber-optic input which is run up the center of the axis of rotation of the rotary wedge arm and fixed in place. A second optical fiber is mounted to the rotary arm. One end is mounted in a holder positioned at the center line of the axis of rotation of the arm. This holder is spring loaded to assure contact between itself and the fixed fiber. The other end of the fiber on the arm has a micro prism (2 mm x 2 mm) attached. This prism has an aluminized hypotenuse and is bonded to the fiber with an optical coupling adhesive.

Mechanically, the base of the rotary wedge is attached to the support stand which also holds the polyhedron mirror and polyhedron alignment device discussed earlier. The arm rotates on a pair of angular contact bearings and is positioned by a special ring gear and worm combination. The gear is stepper-motor driven to a resolution of .16 mm per step at the light source. Repeatability was measured to be .10 mm, also at the light source on the arm. The arm itself is aluminum and is tapered. Weight is also reduced by removing material in appropriate areas. Even so, the arm had to be counter balanced in order not to exceed the torque capabilities of the stepper-motor. The device includes a multitude of manual setup and alignment adjustment features. Also, the device has been designed for vacuum compatibility to 10⁻⁶ Torr, which necessitates sealing of the stepper-motor within a canister.

Back Reflector "Flip-In" Light Source

At several locations in each optical path, the light source which the telescope/TV aligns against consists of fiber optics mounted in the center of mirrors. However, at one location; the back reflector mirror in the power amplifier; it was decided not to mount a light source in the mirror due to risk of parasitic oscillations in the power amplifier. For this mirror it was decided to "flip-in" a light source for alignment and then retract it after alignment is complete. The device designed to achieve this is called the Back Reflector "Flip-In" Light Source. The device is placed between two back reflector mirrors; one device serving as an alignment point for two mirrors. It consists of an arm which holds the fiber-optic light source and is normally "parked" between two beam paths. It is stepper-motor driven from the park position either clockwise or counter-clockwise, depending on the beam path being aligned.

Figure 10 is a sketch of the Back Reflector "Flip-In" Light Source. Optically, it consists of a 1 mm diameter optical fiber which runs in a stainless steel tube up the arm of the device. The end is terminated with a micro prism that is 2 mm x 2 mm with an aluminized hypotenuse. This prism directs the light up the beam path towards the telescope.

Mechanically, the base of the device attaches to the power amplifier shell. The arm is driven via a stepper motor through a worm gear. Resolution at the light source on the arm is .33 mm per step. This device operates in the laser gas portion of the power amplifier. Consequently its motor and gear train have been sealed into a canister to prevent contaminants escaping into the laser gas. There is a limit switch on the device to verify the "park" position on the arm so that it would not inadvertently be left in the beam path during an actual shot.

Fiber Optic Light Source Box

The various alignment devices discussed earlier, which have fiber-optic assemblies serving as light sources for the telescope/TV to align against, do not have their own internal illumination sources. Light is "piped" to these devices by optical fibers running inside copper tubing and through vacuum feed-throughs to light source boxes mounted externally to the power amplifiers, turning chambers, and target chambers.⁴ These light source boxes were each designed to illuminate up to thirteen 1 mm diameter optical fibers.

Figure 11 is a sketch of the light source box. It consists of a high intensity projector bulb which illuminates up to 13 optical fibers mounted in an adjustable holder. Twelve fibers are for service to the various alignment devices. The thirteenth fiber is run to a connector on the rear panel of the light box. It interfaces to a control system fiber which, via the control computer, monitors the bulb for burn out. The box is air cooled with a fan and has a thermostat to keep it running after bulb shut off until the bulb holder cools off. Each box is wired with a relay for remote turn on via the computer; or it can be manually turned on via a key switch. A transformer is also included to reduce the voltage for the bulb. The main structural component of the box is an extruded aluminum channel. A sheet metal cover, with louvers, encloses

Summary

The automatic alignment system for the Antares CO₂ fusion laser is briefly described. The visible wavelength alignment technique includes a number of unique opto-mechanical devices, which have been developed specifically for this automatic alignment system. The optical, mechanical and electrical features of each device are described and sketches showing their key features and construction are presented.

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Fig. 1 ~~Alignment Station~~ Alignment Station

Fig. 5. Variable Focus Alignment Telescope

Fig. 6. Beam Expander/Spatial Filter

Fig. 7. Carousel Assembly

Fig. 8. Polyhedron Alignment Device

Primary Wedge Alignment Device