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ANTARES POWER AMPLIFIER OPTICAL SYSTEM*

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Abstract

We describe the optical systems of the six Antares Laser Power Amplifiers. These assemblies are preceded by the front-end optics and followed by the target system. Each power amplifier receives an annular input beam and divides it into 12 beams which are then directed to double pass them through 12 gain regions surrounding a central electron gun.

Provisions are being made for spatially filtering each beam and for the possibility of adding saturable absorbers. Two keys to the successful completion of the power amplifier are: (1) the avoidance of unwanted lasing modes and hot spots in the wavefronts, and (2) the maintenance of alignment throughout the entire laser system, including the internal alignment of the Power Amplifier. The goal has been to minimize alignment problems by careful and simplistic design of the mountings, stressing modular assemblies and accessibility.

We have succeeded in designing to average energy densities of 2.0 J/cm^2 for salt windows and 3.0 J/cm^2 on copper mirrors, while extracting the largest possible energy from the volume of gas which is electrically pumped.

Introduction

The Los Alamos Scientific Laboratory (LASL) High-Energy Gas Laser Facility (HEGLF) is part of the U.S. Department of Energy's Inertial Confinement Fusion Program. Antares, the 100-kJ CO_2 laser system being designed for HEGLF, will require six power amplifiers (see Fig. 1) working in parallel to provide the required gain for the pulsed 10.6-μm radiation.

Section 1 describes the purpose of the Antares laser power amplifiers and briefly how they function in the Antares system.

Section 2 expands the description by listing the principal goals accompanying each by a brief description of the solution to the problems presented by that goal. Areas of particular strength are pointed out in addition to areas of concern.

Section 3 contains detailed descriptions of selected features of interest. These include the optical train, mirror substrates and mounts, salt windows, baffling, the prevention of retropulse damage, and diagnostic optics.

1. Purpose

The six Antares laser power amplifiers are each preceded by the front-end optics and are followed by the target system. Each power amplifier receives an annular input beam and divides it into 12 beams which are expanded and double passed through the 12 gain regions around an electron gun. The 12 sector beams are then formed into a tighter array by pairs of periscope mirrors and directed through the vacuum beam line tubes towards the target system.

2. Goals and Solutions

The listing of each of the principal goals is accompanied by a discussion of the solution to the problems presented by that goal. Areas of particular strength are pointed out in addition to areas of concern.

a. Initial Alignment. The goal of being able to achieve efficient, cost-effective initial alignment is being met by planning for:

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(1) Combining elements into modules such as the variable delay line mirrors (Fig. 2, Element 5), relay mirrors (Elements 9-12), and periscope mirrors (Elements 16-17) into rigid subassemblies that are reasonably invariant under alignment changes (secular or short term) produced by system deformation or vibration;

(2) Mounting the optics in modules which can be prealigned and tested before insertion into the power-amplifier major assembly.

The prealignment techniques and the use of invariant structures where feasible will definitely help in meeting the stated goal. There are, however, many instances where ordinary alignment techniques must be employed. The elements most sensitive to tilt and decentration are 12, 13, and 15 (the beam expander).

We plan to make maximum use of the latest optical tooling devices during the coalignment of these large assemblies. Centerlines will be 3 meters above the floor with individual elements up to 1.5 meters from centerline.

b. Parasitic Gain Standoff. The avoidance of parasitic oscillations is a goal which has been approached by studies of the possible stable specular-specular and specular-diffuse paths which might cause the power amplifier to self-oscillate prior to the arrival of a pulse from the front end. This is a difficult task, due to the number of possible paths. We have avoided a four-pass oscillation; with the help of the University of Arizona, we are checking for other likely paths. Also included in the area of parasitic suppression are considerations for baffles, stops, and antireflection coatings.

For the metal parts, coatings of LiF (dielectric) and Fe_3O_4 (conductor) will be used in appropriate places (see Section 3.d). These coatings have been found to be highly absorptive at 10.6 μm.

The spatial filters both help and present problems concerning parasitics. They act as field stops, limiting the solid angle between the driver amplifier and power amplifier for parasitic considerations, but the spatial filter must also be considered a potential source of parasitic oscillations, especially when a target is in place. Careful design can minimize this problem.

Should parasitics present a problem, the use of the saturable absorber cell (Fig. 3) can be invoked. For this, the absorber windows, Element 13, would be installed and the volume between Elements 13 and 14 to provide approximately a 0.7-m path length of SF_6. This would also improve the contrast ratio of the pulse and allow the use of higher gains. Implementation would depend upon experimental determination of parasitic levels and on funding for the additional salt windows.

A theoretical study[1] of parasitic oscillation criteria in previous systems and for Antares indicated that saturable gas absorbers will not be required in Antares, largely because of the great standoff distance between the laser and the target. In the prototype power amplifier, parasitic gain standoff in excess of Antares requirements was achieved.

c. Prevention of Material Damage. Attainment of this goal involves material selection and optical design to definite energy density limits. It was decided to make optimum use of existing materials with which we had extensive experience. Plated copper reflectors and forged polycrystalline NaCl windows were selected.

The components must be able to withstand pulses of high peak power but with a very low average power, i.e., short pulses with a very low repetition rate. This combination frees Antares from many thermal problems present in other high-power lasers.

The mirrors will all be made of plated copper for a number of reasons, including the purity of plated copper, which has a high damage threshold. The mirrors after the first pass will be large (900 cm2 beam area) and of irregular shape. They will be manufactured by single-point diamond turning (SPDT) -- literally cut on a lathe. SPDT is an evolving technology being developed on a large scale by the Union Carbide Y-12 Facility at Oak Ridge, Tennessee. Large components of quite impressive optical quality have already been produced. When one considers the alternative of conventional manufacture of the odd-shaped off-axis parabolic segments, single-point diamond turning is imperative for laser fusion at 10.6 μm.

The considerations leading to the choice of these materials include performance, cost, availability, and susceptibility to damage from the high-energy densities. Other materials such as ZnSe and Ge may be used in the preamplifier stages where energy densities can be kept sufficiently low, but they would be damaged in the fully-amplified beam.

Of the major materials used, NaCl plays the dominant role in determining the optical system configuration. The average energy density on NaCl must be kept below 2 $J\text{-}cm^{-2}$ if damage is not to occur. To obtain 100 kJ in the output beam without exceeding this energy density, a total aperture or beam area in excess of 5 m^2 is required. A 45-cm diameter represents the state-of-the-art for forging NaCl blanks. Thus, the very large total aperture required must be made up of many smaller apertures. The Antares solution became a configuration of 6 large annular amplifiers, approximately 2 meters in diameter, each divided into 12 smaller subapertures for a total of 72 subapertures.

Clearly, it is assumed that local intensities can be kept below actual damage thresholds. Components will show damage eventually, and great care must be taken to keep components clean and beam profiles as uniform as possible. Windows are kept a minimum of 1.5 m from the electrodes to avoid direct damage from the pressure pulse which follows the electrical discharge.

d. Retropulse Protection. Retropulse protection is a goal of all laser fusion systems. As the main output pulse from the laser strikes any target some fraction is reflected from the target back into the laser system. As this pulse traverses the system in reverse, it is compressed by the afocal ratio of the optics, and higher energy densities are possible than were contained in the forward-running pulse. Residual gain in the amplifiers severely compounds this problem. Some method of attenuating this backward pulse is essential if component damage is to be prevented.

After considering numerous options, it was decided that we would use a passive technique whereby most of the energy returned will be absorbed by inverse bremsstrahlung in the cold (unpumped) CO_2 of the power amplifier. To effectively protect the metal mirrors involved, it was necessary to fold the beam back on itself at an angle of 5° for additional absorption (Fig. 4). Expanding the beam slightly at the NaCl input windows then effectively protects these (lower damage threshold) components.

The spatial filter also gives the system additional retropulse protection: this can occur passively if the return retropulse is not perfectly retroreflected, there being significant beam steering where the beam overlaps itself, as described in the previous paragraph. In addition, active protection might be added here as the beam diameter is small (Section 3.e).

As a direct result of items c and d, we made a decision early in the design process to use a separate small input window (Element 8) rather than using the main output window also for input. There was concern that we might damage the expensive large windows either due to inadvertent parasitics or failure to attenuate a retropulse. This decision forced us to add small mirrors to direct the beam through the smaller input window located outboard of the main output window.

The energy density on the small input window has been carefully selected to avoid damage from retropulse or parasitics. This is a critical element for damage, as is the small copper mirror, Element 12.

e. Pulse Synchronism. Strict pulse synchronism would involve the simultaneous arrival of all the beams at the target. Compensation for the phase shifts caused by the window thickness variations, a form of phase error which has been termed random piston error, would require fractional wavelength equalization of beam paths -- an unrealistic goal. The net effect of the uncorrected random piston error is that the encircled energy is determined by the incoherent addition of distributions from the individual subapertures.[2]

To achieve a reasonable degree of pulse synchronization, preliminary path-length adjustment of the six beam paths is done in the front-end optics. Tolerances in the individual optical components and in their location make it necessary that we have the capability of further equalizing path differences in the power amplifier. We decided to perform this task using a three-mirror corner cube (Element 5) so that we can change path lengths without an alignment correction. There are also advantages from a vibration stability standpoint. We plan to equalize path lengths within a 2-cm extreme spread for all 72 segments. In addition, it may be desirable to delay or advance a given segment 30 cm in total optical path length from its nominal position. Path-length adjustment is considered a nonroutine adjustment and we do not intend to motor drive the mirrors, build in sensors, or attempt day-to-day adjustment. We will depend on system stability to maintain synchronization, once adjusted.

f. Maintenance of Alignment. This goal is being met by providing an automatic alignment system. Alignment of Antares is expected to be initiated in the laser laboratory. The subassemblies generated there will be transported to the major assembly where the alignment will be completed to a degree which will allow the automatic alignment system to operate.

Pressurization of the gain region and evacuation of the beam tubes will alter the initial alignment; the automatic alignment is expected to restore the system state, i.e., to eliminate any vignetting and output beam pointing errors and periodically cancel drifts in alignment.

Two aligment systems are presently being evaluated for use. One system provides movable sensors which can be placed into the beam path to sense the beam centering; this is called the "flip-in" scheme. The other scheme is called the "imaging see-through" approach. It involves visible-imaging, variable-focus telescope systems which can be focused on the different planes of mirrors, spatial filters, alignment devices, and the target. The angle of the retroreflected beam from a surrogate or real target is sensed and then the brightness of the return is maximized. For part of the alignment a collinear beam system is to be used.

For either of these schemes there will be numerous requirements for specialized imaging- and position-sensitive detectors. We are experimenting with various devices, commercial and LASL-built. These include silicon Seebeck, thin metal film, pyroelectric, and thermal detectors.

The elements which are planned to come under the automatic control system are Elements 2, 4, 7, and 17. Manual trimmer controls are to be furnished on Elements 6 and 12. All other elements are supposed to be fixed during the prealignment phase.

g. Efficient Use of Existing Materials and Fabrication Techniques. This goal influences the entire project, but is particularly evident in the selection of the optical parts.

The choice of copper-plated mirrors is related to material damage threshold (Section 2.c). Solid copper is ruled out for structural instability. Our smaller mirrors will have aluminum-bronze substrates to take advantage of the good match of structural stability and thermal expansion. The larger mirror substrates will be aluminum, because the bronze would be too heavy; the extra mass would drive down the natural vibration frequency of the assembly. The thermal environment of these larger mirrors will influence their figure; acceptable limits for temperature change will be determined and the necessary controls will be established.

The choice of window material (Section 2.c) is also dictated by material damage threshold.

The salt windows will be made of polycrystalline sodium chloride, forged from large single crystals to obtain an increased yield strength. This is important because many of the windows experience a 3-atmosphere pressure differential.

The fabrication technique for the large salt windows (trade name Polytran R) is fairly new. It is being developed by Harshaw Chemical Company, under contract to LASL. We are also supporting a Research and Development salt-polishing program at the Air Force Weapons Laboratory; the process is in an advanced state of development.

The optical problems which result from the selection of structural materials for the power amplifiers all appear to have been accounted for in the design. The pressure shell (steel) and internal optics support structure (aluminum) have high enough natural frequencies (higher than the design goal of 30 to 50 Hz) that vibration is not expected to be a problem. Finite-element analysis has been used to predict static loads and structural resonant conditions (frequencies and mode shapes). The static load calculations include structural deformations due to the gas pressure and vacuum loads. The deflections appear to be the optical alignment tolerances; if the optical system is aligned before these loads are applied, a small remotely-controlled adjustment of the automatic alignment system mirrors and the spatial filter mount will be sufficient to correct the beam alignment.

h. Maintenance of Beam Quality. This goal is very complex because of the large number of sources for beam degradation. The solutions to many of these are obvious, but some have no solution. We are considering degradation from the following:

(1) vignetting, which can be due to component tilt, decenter, or maladjustment f the alignment system input beam;
(2) defocus at the input beam (Elements 1-2); spatial filter (Element 8); and in the beam from the back reflector (Element 15);
(3) wavefront deformation from several causes; these include optical figure errors of all types (random and classifiable).

Induced error can come from mounting strains. A brief description of the mounting methods is given in Section 3.b.

Beam decenter on the optical elements has been investigated; fortunately, the system is relatively insensitive to this. Gas inhomogeneity arising from stratification or turbulence in the air paths and in the lasing medium can contribute to the phase differences. Other phase differences caused by cosmetic defects can randomly scatter the radiation; there is also directed diffraction from the diamond-turned mirrors.

Finally, there is the possibility of a fast deflection of the output beam due to the transverse gain gradients necessarily present in every real laser medium (gain steering).[3]

3. Selected Features

a. The Optical Train. Figure 2 schematically illustrates the present power amplifier optical design. An annular input beam from the front-end room is directed by a series of plane turning mirrors vertically up through the vacuum input window (1) into the in/out optics section. This region is evacuated and common to the target vacuum system. A plane turning mirror (2) directs the beam to the polyhedron mirror (3) which divides and reflects the annular input beam radially outboard to form 12 separate beam lines. From this point on we will describe only 1 of these 12 beam lines.

This method of dividing the beam into 12 segments was selected after considering numerous other options including the use of semi-transparent beam splitters and multiple beams from the front end. The prior decision to use large, double-pass driver amplifiers having a Cassegrainian optical configuration became the deciding factor in selecting this method of beam-splitting.

After leaving the beam divider, the beam is reflected by the plane mirror (4) to a three-mirror corner cube (5). This arrangement (shown as two mirrors in the illustration for simplicity) actually consists of three mirrors mounted at right angles to each other. The beam is reflected out of plane by the first mirror, back in plane by the second, and towards Element 6 by the third.

Provided that the mirrors are rigidly held relative to each other they may be translated parallel to their input beam to provide path length adjustment without disturbing beam alignment. The mirrors, in fact, form an invariant subset which is insensitive to angular misalignment and gives the required travel for path-length adjustment (pulse synchronization).

The collimated beam incident upon the concave spherical focusing mirror (6) is focused through the spatial filter (7) and allowed to expand through the input salt window (8) into the N_2+CO_2 gas region. The concave spherical mirror (9) converges the beam and directs it to the plane mirror (10) and to the convex mirror (11) where it is recollimated. Mirror (12) is convex and designed to diverge the beam such that it is expanded in size by a factor of 10 when incident upon the back reflector (14). The 10-to-1 expansion ratio was selected after considering energy density out of the front end, required drive, vignetting in the double-pass amplifier, and alignment sensitivity.

The beam is intended to be roughly the same size at Elements 4-6 and at 12. The beam is deliberately expanded at the NaCl window (8) to reduce the energy density at this point by a factor of 2, insuring that this window is not damaged by the retropulse. The angle of incidence on mirror (12) is approximately 2.5°. This provides an overlap region which will have high absorption for the retropulse due to inverse bremsstrahlung.

The beam leaving the back reflector (14) is nearly collimated with just enough convergence to provide the proper (reduced) beam size in the target chamber. The output salt window (15) separates the laser gas from the target vacuum system. The plane mirrors (16) and (17) translate the beam segments radially inward to reduce the beam array diameter prior to the beams entering the long beam tubes to the target chamber. Provision for the absorber window (13) makes possible the use of a gas saturable absorber which would be obviously double-passed.

When calculations were performed for the LASL Antares optical system, a net wavefront error of between $\lambda/15$ rms and $\lambda/20$ rms was predicted. This corresponds to a diffraction-limited system by most definitions and means that slightly more than 80% of the energy will be within a 400-μm-diameter focused spot.

b. Mirrors, Substrates, and Mounts. As was described in Section 2.g, the smaller mirror substrates will be of aluminum-bronze, and the larger ones of aluminum. These will all have plated copper faces approximately 1- to 1.5-mm thick.

The smaller mirrors (spheres and flats) will be pitch polished using conventional processes: the larger pieces will be SPDT. Distortion-free mounting of the optical elements is a challenging task. Requirements include high stability for almost all mirrors as well as precise motorized adjustment on many of the mounts, which must be operated under vacuum conditions. The irregular shape of many of the mirrors, as well as tight clearances, precludes the use of standard mounts in all but a few places.

Strain-free mounting of these mirrors is being done via three different mounting methods according to the specific needs. Cell-mounted mirrors are held between three directly opposed contact points (front and back faces). Rear-mounted mirrors are attached to a backing plate by three studs which are epoxied into holes tapped into the mirror substrate. Between the mirror and the backing plate are three pairs of spherically seated washers which automatically take out any wedge in the mechanical assembly.

The larger mirrors are supported on specially designed flexure mounts. The precise description of these mounts, which are in the final design and testing stages, is a subject for a future paper.

c. Salt Windows. The large salt windows, 45 cm in diameter and 8.8 cm thick, are state-of-the-art components, both in the production of the stock and in fabrication technique. As mentioned in Section 2.b, they can be antireflection coated where necessary. With the need to use the normal Fresnel reflection for diagnostics in a few cases, combined with the technical difficulties of coating the larger windows, we have decided, pro tem, to coat one side of the vacuum input window and both sides of the absorber window (if used). The latter will be done mainly for defense against parasitics. Fresnel losses elsewhere can be compensated by increasing the gain of the lasing medium, but that increases the possibility of initiating parasitics.

Each window functions to separate different media, with pressure differentials. Thus, the mounting must also contain gas-tight seals. We have chosen to sandwich the element between O-ring seals. The largest differential is between the 1800-torr (2.37 atm) laser gas and the beam-tube vacuum region. The mounting distortions will be monitored by interferometer tests as part of our quality assurance program.

d. Baffling. An important part of the parasitics gain stand-off effort involves devising suitable baffles. In part, this helps to limit the optical system to function in the designed optical path.

As mentioned in Section 2.b, other possible paths which have large enough reflectance can support oscillations prior to the main pulse from the front end. These oscillations can be suppressed by (1) decreasing specular and diffuse reflections to the maximum extent possible, and (2) use of "clever" geometry. For example, one can replace a smooth glossy surface (even though painted black) with one having a broken or more highly curved geometry and a highly absorbing (rough) finish.

Baffles for the main beam are planned at the polyhedron beam divider (Element 3) near Elements 9 through 13, at Element 17, and at certain of the diagnostic optics (Section 3.f).

e. Retropulse Prevention. Protections (passive) against retropulse were discussed in Section 2.d. Here, an active method is described which can be used if the other methods fail to provide sufficient protection.

At a place where the beam is small, e.g., in the vicinity of the spatial filter, a simple coaxial gap comprised of an array of exploding wires can deliver, a given length of time after the passage of the main pulse, an isolating plasma a few millimeters in diameter. The timing is such that the retropulse is blocked, but not the input pulse.

f. Diagnostic Optics. Retropulse diagnostics will be done on samples of the radiation reflected from the vacuum input window (Element 1).

The main pulse power will be calibrated by a calorimeter fed by the reflected radiation from the small input window (Element 8).

Beam quality and other diagnostics will be done with sampling optics to be mounted in the diagnostics spool (that section shown at the extreme right end of the assembly, Fig. 1).

Conclusions

The Antares optical train consists chiefly of plane windows, plane mirrors, and weak spherical mirrors. As an optical design problem, it is straightforward. As an optical systems problem, designing and fabricating the entire train for successful operation, it is extremely challenging. Success will probably depend on the ability of the systems designer to anticipate and make provisions for the multitude of problems that are so difficult to fix after the fact.

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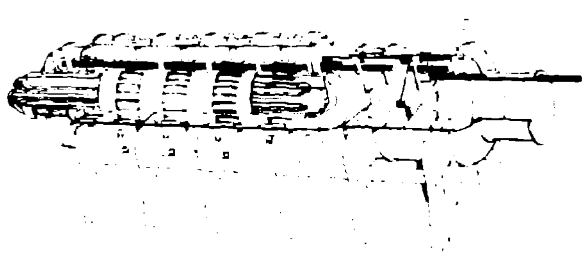

Fig. 1. The Antares laser power amplifier.

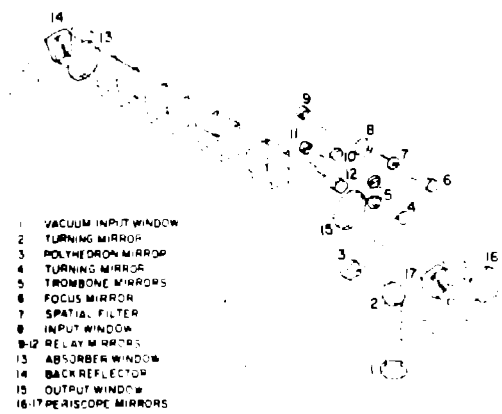

Fig. 2. Optical Schematic. One of the twelve beams from the beamsplitter is traced.

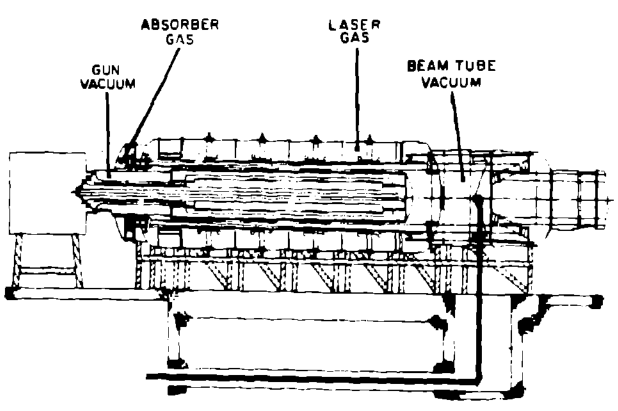

Fig. 3. Power amplifier vacuum and gas volumes. The absorber gas is shown as a possible option.

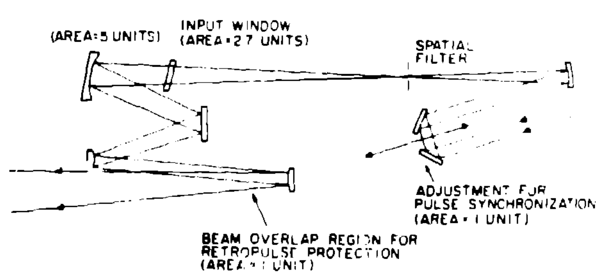

Fig. 4. Antares power amplifier input beam.