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Class KrF Laser

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The Aurora Project: optical design
for a kilojoule class KrF laser

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Introduction

Aurora is a 248-nm, 10-kilojoule laser system being built at Los Alamos National Laboratory to demonstrate the feasibility of large KrF laser systems for laser fusion. It was designed as a test bed to demonstrate: 1) efficient energy extraction at 248 nm; 2) an angularly multiplexed optical system that is scaleable to large system designs; 3) the control of parasitics and ASE (amplified spontaneous emission); 4) long path pulse propagation at uv wavelengths; 5) alignment systems for multibeam systems; and 6) new or novel approaches to optical hardware that can lead to cost reduction on large systems. In this paper only issues pertinent to the optical system are addressed.

First, a description of the entire system is given. The design constraints on the optical system are explained, concurrent with a discussion of the final design. This is followed by a very brief discussion of coatings; in particular, the use of sol-gels for antireflection coatings is presented.

System description

The Aurora optical system is designed to match the long, 480 ns amplifier electrical pulse time required for efficient KrF energy extraction to the much shorter, 5 ns optical pulse time required for efficient fusion target interaction. Aurora is designed to demonstrate the critical technologies and to serve as an engineering test bed for megajoule-class laser fusion systems. For the very large megajoule-class lasers, electrical pump times will be in the 300-500 ns range, and the optical pulse times will be in the 5-10 ns range.

The heart of the Aurora System is the large aperture module (LAM), which has a gain region of 1 m x 1 m x 2 m size. It provides nearly all of the energy and sets many of the system design constraints.

The optical system uses angle and time multiplexing to meet the system requirements. The basic building blocks of the system are the following: 1) an oscillator that produces a 5 ns pulse; 2) an optical encoder that replicates the 5 ns pulse 96 times to give 96 separate beams stacked head-to-tail in time producing a 96x5 ns or 480 ns long pulse; 3) an angle encoder and centered optical system that directs each of the beams through the amplifiers, and 4) an optical decoder, which is now being designed, that appropriately delays each of the amplified 5 ns pulses to arrive at the target simultaneously. Figure 1 illustrates the conceptual system design, leaving out the decoder. Figure 2 shows the system layout in the building.

Temporal encoding

The 5 ns square beam from the oscillator is first divided spatially into right and left halves. One half is delayed by 30 ns with respect to the other. Each half is expanded to about a 15 by 13 cm beam. This expanded beam is divided spatially into six parts and each part given a 5 ns delay. The twelve beams resulting from this sequence of aperture division have a total duration of 60 ns and are directed through a two-pass amplifier of 10 by 12 cm aperture. This can be done simply with flat mirrors because the beam size of 7 cm is a good match for the amplifier aperture. After amplification an array of twelve mirrors creates a bundle of twelve parallel beams. This bundle is handled as a unit for three stages of 50/50-intensity-division beamsplitting, which produce an eight-fold replication, to 96 beams. The time delays required to obtain the final 480 ns composite pulse-width are obtained by judicious location of the beamsplitters.

Angular multiplexing

In the temporal encoder the beams are collimated, and spatially distinct. They do not follow the same path, but follow parallel paths to 96 mirrors in an 8 by 12 array, called the input pupil array. There each of these beams is independently aimed at the input pupil of the centered, symmetric optical relay system. Thus the segments are angularly multiplexed. Each beam is of square cross section, 7 cm across. The effective f/number of the input pupil array is 4.03. It is given by the stand-off distance, from the input pupil to the input array, divided by the diagonal dimension taken to the extreme of the beam. The angle of an of an extreme ray is 6.5 degrees from the beam centerline. The input pupil is a square 4 cm on an edge. Thus the beams are 1.5 cm oversize, to allow quite generous tolerances for the alignment system and diffraction losses.

Centered symmetric relay optical train

The primary function of the relay optical train is to use the amplifiers efficiently. The first two amplifiers are single-pass so that the beams use common optical elements, thereby reducing the cost and complexity of the beam train. Relaying the pupil provides the best possible amplifier fill factor. The lenses between the input pupil and the first amplifier relay the pupil to the back of the first amplifier. The beam angles are largest in this section of the beam train (6.5 degrees half-angle for the extreme ray). Since the components are small in this section most of the third-order correction is done here. Negative lenses are used to compensate the Petzval curvature introduced by the total system.

LAM input array

Following the second long-pulse amplifier there is a long flight path, sufficient to separate the 96 beams. At this location there is a 96-fold array of small convex mirrors. These redirect all of the beams into the center of the final amplifier at the full 1 meter aperture size.

Large aperture module

The large aperture module or LAM is an electron beam pumped amplifier, similar to but much larger than the other amplifiers in the system. While the other long-pulse amplifiers are single pass, the LAM is double pass to improve efficiency. The general size can be appreciated by looking at Figure 2, which shows each system component to scale. The output aperture is square, 1 meter on an edge.

Design constraints

The temporal encoder has been one of the major design efforts in building this system. A multistage, intensity division beamsplitter places stringent requirements on the accuracy of the split achieved by each stage. With three stages, it was necessary to specify a 1% beam split, even when working into saturated amplifiers. A seven-stage system was also considered for obtaining 96 beams, but was abandoned because it seemed unrealistic. The decision to place the aperture division section first was based on the following four considerations: 1) immediate expansion would reduce divergence and aiming problems inherent in the front end; 2) this sequence provided a convenient station for the input-output array for the small amplifier; 3) having intensity division first would require either a huge expansion telescope or several in parallel; and 4) intensity division provides more flexibility in fitting the longest delays into the building. The delay action of the beamsplitters alternates; the reflection is delayed at the first, the transmission at the second, and the reflection again at the third, all to fit the building. It is not possible to pack the beamsplitters tightly, as is done in the mirror arrays, because the mount cannot be hidden behind the component. This leads to the use of large beamsplitters, on 11 by 41 cm substrates, each handling 12 beams, to keep the beam array compact. Mechanical mounting of the large beamsplitters proved a major challenge, since it requires the rigidity of a mirror mount in an open window frame.

The relay optical system must work over a rather large field angle. This requires balanced correction of coma and astigmatism as well as spherical aberration, which is the only significant aberration in the usual afocal laser system. In order to make the LAM input array buildable, the optical design must produce a low distortion field with zero Petzval curvature. Another major constraint was to fit the laser into the building. This later constraint largely set the first order properties of the system. The two hard feet resulted from the pupil imaging. By so doing, the number of optical parts was minimized. The feet may also be used as aids to alignment, and for spatial filtering. Because of the expected fluences, all regions of hard focus require a maximum ambient pressure of 10^{-3} torr, to avoid air breakdown. In order to satisfy all the constraints mentioned above, nine lenses were required. Of these, five have surfaces which are cone sections, two of

them are oblate, and the remainder are prolate. The same correction might be achieved by more spherical surfaces; However, this is not attractive, due to the cost of large uv lenses.

The most complex part of the system, optically, is the section between the input pupil and the first amplifier. The third-order aberrations were dealt with here because the parts are small and less expensive. This resulted in a very unusual design, one with strong negative components.

The first element is plano-concave with a fairly severe aspheric surface. The next two elements are balanced plano-convex convexo-plane lenses, though one is a mild prolate spheroid. Perhaps the most difficult lens to fabricate in the system is the bi-concave fourth element. The first surface is a simple sphere of fairly long radius of curvature. However, the rear surface is fairly steep and is an oblate spheroid with a positive conic constant of 2.3. There is an intermediate focus which requires a modest vacuum. The lenses also act as vacuum windows. They distort up to 4 μ m, but this bending has little effect on the beam quality. The final lens is essentially a concavo-convex meniscus. A layout is shown in Figure 3.

The beams are relayed thru the preamplifier to the exit window, which is a pupil. The next lens in the system also has an aspheric surface. In order to fit into the building, a turn mirror is required. The next pair of lenses in the system provides an intermediate hard focus, which is in a nearly-telecentric space, that can be used for alignment and spatial filtering. These lenses act to relay the pupil from the back of the preamplifier to the back of the intermediate amplifier.

The lens after the intermediate amplifier focuses the beams to a surface behind a 96-mirror array called the LAM input array. However, there are two intermediate turn mirrors in the system. Both are of novel design. These mirrors employ blanks made with pyrex face plates fused to pyrex tubing stacked in a hexagonal close packed array, to achieve about 80% lightweighting. These mirror blanks are a fraction of the cost of a conventional mirror blank of quartz, zerodur, or ULE. Since they face a fairly benign thermal environment, their virtue lies in their rapid equilibration time, due to their low thermal mass.

The LAM input array consists of an 8 by 12 array of small mirrors the same size as the input array. The supporting structures are identical, resulting in some economy. However, these mirrors are convex to avoid air breakdown. The radius is chosen to cause each beam to fill the aperture of the LAM, which is 1 meter square. An initial attempt was made to carry the pupil image thru the LAM, but the angles were then so large in the optical section in front of the first amplifier that third-order correction appeared hopeless, and the attempt was abandoned. Also, the lenses in the last relay would have had 85-cm apertures. The cost savings by not having such large lenses more than pays for the construction of the LAM input array.

Alignment

The input pupil array, which does the angular multiplexing, is fully motorized and computer controlled to insure that each beam is aimed in its assigned multiplex direction with an accuracy of about 30 microradians. Error information is acquired by a sophisticated computer analysis of the video signal produced by a far field image of the beams at the entrance pupil. The alignment error information for all 96 beams is processed at the same time, which leads to a very short alignment time, 13 minutes for 96 beams. The method of image analysis is described elsewhere. The far field image is continuously available without interrupting the ultraviolet beam by using two dichroic beamsplitters. One of these inserts a visible CW laser before the temporal encoder, the second diverts it again at the input pupil. Since each beam overfills the input pupil by a large margin, it is not necessary to control the positions of the beams, only their angle. Mounts for encoder optics will hold alignment to within this overfill tolerance for long periods. The stability of the relay train optics is adequate for the immediate task of filling the LAM. A second aiming system, near the target chamber, will have to be added when a decoder and target chamber are installed.

Materials Issues

Some mirrors in the encoder are pressed pyrex; they are well annealed, but full of striae. The substrates require holes in the back to accept the mounting structure. Conventional biscuit cutting techniques to cut these holes resulted in a very low yield of good parts. The use of ultrasonic machining gave 100% good parts.

The material for transmission optics is limited to synthetic fused silica. In general, Corning 7940 of homogeneity grade C, inclusion class II was used throughout. For the mirrors, a variety of substrates were used: The smaller elements are pyrex, one of the larger turning mirrors is zerodur, and two are the novel lightweighted pyrex. The LAM mirror is cervit, made from a blank for a telescope project that was never built.

Coatings^{3,4}

Antireflection coatings which are not required to withstand fluorine can be made by conventional vacuum deposition or with sol-gels.⁵ In preliminary tests the sol-gels have produced damage thresholds of 14 J/cm^2 for 15 ns pulses at 248 nm, about 3 times the damage threshold produced by any other technique. The AR coating on the LAM mirror has a damage threshold on the order of 1.0 J/cm^2 and samples appear serviceable after 200 hours exposure in 0.5% fluorine laser mix. The AR coatings which are exposed to fluorine have damage thresholds around 1.6 J/cm^2 and samples appear serviceable after 200 hours exposure to the fluorine atmosphere. Many of the mirrors in the beam train that are not exposed to fluorine use an aluminum undercoat to give a high reflectance for visible-beam alignment.

Conclusion

The Aurora project pulls together many diverse fields in a technology test bed to prove the practicability of large-scale excimer laser systems. The hardware will all be in place by September 1985. Final energy optimization is due to take place in the autumn of 1985.

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Figure 1. Conceptual diagram showing the Aurora laser system, not including the decoder.

CENTERED SYMMETRIC OPTICAL TRAIN BETWEEN INPUT PUPIL AND PREAMPLIFIER

Figure 2. Plan view of the Aurora laser system layout. a diagnostic station is shown in place of the decoder.

Figure 3. The centered symmetric optical relay train between the input pupil and the preamplifier.