The use of high-power, short-pulse lasers in order to achieve fusion conditions in a D-T plasma was suggested as early as 1963 by N.G. Basov and others. It was not until nearly a decade later, however, that significant efforts at laser-fusion research were set up in various laboratories around the world.

Facilities for laser-plasma interaction studies were established in the Soviet Union at the Lebedev Research Institute, and in France at Limeil, in the late 1960's; but it was not until early in the present decade that major efforts to achieve significant compression of thermonuclear fuels were launched in the United States.

Today approximately a dozen major laboratories for laser-fusion research exist around the world. In the United States the largest efforts are being carried out under the aegis of the Energy Research and Development Administration at Lawrence Livermore Laboratory, Los Alamos Scientific Laboratory, KMS Fusion in Ann Arbor, the University of Rochester, and the Naval Research Laboratory. Laser-fusion laboratories exist in France, Germany, the USSR, the United Kingdom, and Japan. Clearly, laser fusion has the appearance of an idea whose time has come, or to some observers, a bandwagon. What has changed in the past five years to make laser-fusion research suddenly so attractive?

Undoubtedly there are political elements involved in the decision to pursue laser fusion. The enormously increased awareness, on the part of both governments and individuals, of the need for an ultimate energy source has spurred research of all kinds. The desire on the part of scientists to do something relevant...
has also been a factor in encouraging laser-fusion research, since laser fusion affords the opportunity to apply sophisticated technology and difficult science to the solution of a social problem of global consequence. Apart from these factors, however, the main reason why laser-fusion research has suddenly blossomed is the improved performance of large, Nd-glass laser systems and the advance in understanding and controlling the problems of beam propagation at high power levels in such systems.

A typical large laser for fusion research is shown in Figure 1. This is the CYCLOPS laser at Lawrence Livermore Laboratory. This laser, which generates 100 J of light at 1.06 µm in a pulse of 100-psec duration for a peak power of 1 TW, consists of a Nd: YAG oscillator, a series of YAG and glass rod preamplifiers, and a series of disk amplifiers of increasing aperture, up to 200-mm diameter at the exit. There are about 100 optical surfaces in the beam, many of them coated with multilayer dielectric coatings, either AR coatings or high reflectivity coatings, on mirrors and on polarizers. The necessity for interstage isolation in a high-gain amplifier leads to the introduction of Faraday rotators, along with their concomitant polarizers and analyzers, at several points in the optical path. Spatial filters are introduced to limit the development of high spatial-frequency noise components on the beam. Fusion-laser design involves far more than simply staging amplifiers to achieve the desired gain. It involves a full understanding of the propagation of light at high intensity and of laser-damage phenomena, and an abiding appreciation of the difficulties of fabrication of large-aperture optics for use at high power levels.

The ultimate requirement of a fusion laser is that the energy be focusable on a fusion target, which is generally of the order of 100 µm in diameter. As any microscopist will testify, resolving a 100-µm object in visible or near-infrared light is not an insurmountable task. As we shall see in the subsequent discussion, however, there are special problems that arise in the design of fast-focusing optics for laser fusion that are outside the realm of conventional optical design. Thus the heading "optics for laser fusion" embodies two specialized areas of concern. One is the design of the laser amplifier and the other is the design of the focusing optics.

In designing a Nd-glass laser to generate terawatts of optical power, the primary factor influencing the design is the nonlinear response of optical materials to the intense optical field. The refractive index of any transparent dielectric can be expressed as $n = n_0 + n_2 <E^2>$, where the coefficient $n_2$ is the index nonlinearity of the medium. In Nd glass, for example, at a power density of $10^{10}$ watts/cm$^2$, the refractive index is increased by five parts per million (ppm) over its zero-field value. The nonlinearity of BK-7, a common optical glass, is of the same magnitude. A 5-ppm change in refractive index might not seem too consequential, especially considering the fact that the fluctu-

Figure 1. CYCLOPS: A terawatt laser used for Laser Fusion Research at the Lawrence Livermore Laboratory.
ations in the index of good optical glass are of that magnitude. The difference is that the index nonlinearity leads to a retardation of phase associated with regions of high intensity, which is of great significance. In one meter of optical material, one ppm of nonlinear index change, at 1.06 µm, leads to one full wave of retardation. This retardation is not uniform, but instead has the shape of the intensity distribution. Thus even this small amount of index nonlinearity can easily give rise to a large amount of intensity-induced aberration.

This intensity-induced aberration is called whole-beam self-focusing. In designing a fusion laser, it is essential that the extent of self-focusing be carefully controlled. A measure of the maximum whole-beam self-focusing that has come into popular use is the $B$ integral, defined as the on-axis phase retardation caused by index nonlinearity, expressed in radians. Thus one wave of nonlinear retardation corresponds to a $B$ of $2\pi = 6.3$. The net effect of a $B$ value depends on the intensity profile of the laser beam. A Gaussian profile leads to severe aberration, since the curvature of the nonlinear phase retardation changes sign at the inflection point of the Gaussian. A parabolic intensity profile, on the other hand, leads simply to an intensity-dependent shift in the focal point, a sort of self-induced zoom lens, but insofar as the profile is truly quadratic, to no higher order aberrations. It is for this reason that the quadratic profile is favored for fusion lasers.

In principle, one would like to eliminate whole-beam self-focusing effects altogether. An interesting approach has recently been investigated by R. Lehmberg and co-workers at the Naval Research Laboratory. In a cell of cesium vapor, at temperatures high enough that atomic cesium is the dominant species, light at 1.06 µm experiences a negative index nonlinearity ($n_2 < 0$). This is due to a near coincidence with a strong two-photon resonance in the vapor. If the beam is passed through such a cell, it undergoes a phase advance. Such a cell could conceivably be used to provide dynamic compensation for whole-beam self-focusing. Dynamic compensation using positive $n_2$ materials, but tailoring the path length to produce phase advance, has also been proposed.

The effects of uncompensated whole-beam self-focusing can be further minimized by the correct choice of focusing optics. Here we begin to see the systems aspects of fusion-laser design. The focusing optics cannot be designed without regard for the properties of the incoming beam, which are in turn dependent on the specific design of the laser system. For a quadratic intensity profile (which is, admittedly, an idealization, since the beam profile must be smoothly apodized at the edges to avoid diffraction effects), the phase distortion at the focusing lens is simply given by $B\lambda^2/2\pi r_0^2$, where $r_0$ is the full-aperture radius. Thus the radius of curvature of the phase front at the lens is just $n r_0/\lambda$. The resultant focal shift (displacement of the image plane) is given by $\Delta z = (4/\pi)\cdot B\lambda (f/\#)^2$, where $f/\#$ is the $f$ number of the focusing lens. Thus, in the CYCLOPS system, with a $B$ value of 1.5 waves ($B = 3\pi$), the focal shift is 75 µm with an $f/2.5$ lens, but only 12 µm with an $f/1$ lens. The laser-fusion target generally is placed in the near field of the lens, so that only geometrical-optics considerations apply. Simple trigonometry yields the result that for a 50-µm target radius and a $B$ of $3\pi, f/1$ optics (or faster) is required.

The parameter $B$ is also a measure of the tendency of a large laser beam to break up into a myriad of small filaments, an effect called small-scale self-focusing. This effect was first analyzed by Bespalov and Talanov. They pointed out that, in the presence of an intense light beam in a nonlinear medium, small spatial ripples on the phase or amplitude of the light beam tend to grow exponentially, and that the growth rate is a function of the spatial frequency of the ripple and the intensity of the background beam. The most unstable spatial frequency grows by a factor $\exp (B)$, where $B$ is the same $B$ integral described above. It has been found empirically that when spatial filtering is introduced, the beam is unstable over a path in which $B$ exceeds about $3\pi$, or one and one-half waves.

Spatial filtering is accomplished in one of two ways. The vacuum spatial filter consists of a telescope of unit magnification with a pinhole aperture at the common focus. High spatial frequencies are focused off axis at the aperture, and are blocked. Thus the emerging beam is smoothed compared with the input. An example of a spatially filtered beam is shown in Figure 2. As an alternative approach to spatial filtering, long air paths can be introduced in the laser system between successive stages. If the path length is long compared to the Fresnel length corresponding to the ripple size, the ripples will diffract out of the beam. For 100-µm ripples, the Fresnel length is 6 cm, but for 1-mm ripples, it is 6 m.

This raises the question of what the dominant ripple frequency is expected to be. Phase and amplitude ripples grow from minute imperfections in the glass, from diffraction around bubbles, dirt on surfaces, the ever-present damage sites, and imperfections in surface figure. Although the most unstable frequencies are expected to correspond to 100-µm dimensions, in actual fact ripples of mm dimensions grow to significant size, as is seen in Figure 2. Vacuum spatial filters are now a common feature of most large fusion lasers.

There is clearly an interplay between whole-beam effects and spatial filtering. Spatial filters are designed with $f$ numbers of 10 or more to obtain good rejection of high spatial frequencies. This in turn leads to a great sensitivity to focal shift. The performance of a spatial filter degrades with increasing cumulative,
whole-beam $B$. This is further motivation for the development of active compensation devices to suppress whole-beam effects.

The ultimate measure of performance for a fusion laser is the amount of energy that can be brought to focus on a fusion target, generally of the order of 100 µm in dimension. The design of the focusing optics to accomplish this is of crucial importance in determining the overall system performance, cost, and reliability. In order to achieve adiabatic compression of the target without the onset of deleterious hydrodynamic instabilities, the radiation from the laser must be focused on the target as uniformly as possible, and, to ensure that the impinging radiation is uniformly absorbed in the evolving plasma, the light must be incident as near to normally as possible. These dual requirements of uniformity and near-normality are the overriding concerns of the fusion-optics designer.

C. E. Thomas of KMS Fusion has devised an ingenious optical configuration to provide uniform, near-normal illumination from two beams of incident light. The fusion target sits at the common focus of two ellipsoidal mirrors of eccentricity one-third. Each mirror images the target at the axis of the opposing mirror. A small hole is drilled in each mirror, and each of the two laser beams is focused by a fast lens (NA 0.73) through that hole. This catadioptric system is a clever modification of the concept of the reflecting microscope. In fact we see that all laser-fusion illumination optics bear strong resemblance to microscope objectives, but microscope objectives of 200–300-mm aperture!

As the aperture of the illumination system increases at constant numerical aperture, the thickness of glass in the focusing lens increases apace. This introduces the specter of beam breakup or small-scale self-focusing in the lens itself. To avoid this, either the beam may be ex-
panded to reduce the intensity, or the required power of the refracting elements may be reduced by the introduction of cascades of reflecting elements. The latter measure, although effective in reducing the $B$ integral through the optics, greatly increases the cost and complexity of the optical system. Such a cascaded reflector has been designed, and is being fabricated at Lawrence Livermore Laboratory for use on the ARGUS laser.

As the number of apertures of the laser is increased (each aperture is limited to about one terawatt of output power), one can envision multiple-beam illumination using focusing lenses only. Thus, four lenses can provide tetrahedral illumination, six can be arranged at the faces of a cube, and so on. Unfortunately, suitable uniformity and near-normality cannot be achieved with a small number of lenses. Twelve or more lenses are required to satisfy the illumination requirements. Current planning at the Livermore Laboratory calls for twenty apertures on the SHIVA system, and the University of Rochester is planning twelve-beam illumination.

The combined requirements of large numerical aperture and minimum thickness of glass leads unavoidably to the use of aspheric surfaces. Improved methods of design and fabrication, with particular application to laser focusing optics, have been developed to fill this need. The reflecting surfaces are generally either plane or ellipsoidal, and the mirror substrates may be either Cer-Vit or metal. Of particular interest is the development of diamond-turned metal mirrors for laser focusing. A set of diamond-turned silver ellipsoids on a beryllium substrate is shown in Figure 3. These mirrors were produced for use with the JANUS system by J. Bryan of the Lawrence Livermore Laboratory. Diamond-turned metal surfaces have been found to be far more resistant to laser-induced damage than have polished metal surfaces. The diamond-turning process leaves behind a corrugated surface, which acts as a diffraction grating, but the fraction of incident energy diverted from the target can be held to below ten per cent.

The aspheric refracting elements present unique problems, both to the designer and to the optician. The lens systems are generally simple, involving only a few elements. The performance criterion for the system is expressed in terms of the distribution of intensity at the focus. In geometrical optics this can be translated into a mapping of a set of ray heights into a set of angles about the focus, corresponding to a single mathematical surface. This surface, called the principal surface or equivalent refracting surface, represents the desired performance of the lens. Conventional interactive lens-design programs can be used to find the lens that approximates this surface, but we can also approach the problem directly and simply solve for the desired surface once the curvatures and spacings of the spherical elements are fixed. In practice, a baseline design can be obtained by using conventional lens design methods, and the final aspheric determined by using direct calculation.

The utility of any design is limited by the cost and difficulty of fabrication. Advances in numerically controlled grinding for aspheric fabrication offer the promise of reducing the time and effort required in generating strongly aspheric optics. Overall, however, the optics industry has not had extensive experience in the fabrication and testing of fast, aspheric lenses of 200–300-mm aperture for laser use. The number of potential suppliers of these optics is very limited, and the total resources for fabrication can easily be saturated, leading to prolonged delay in the procurement of focusing optics. It is clear that the laser laboratories will have to work closely with the optics suppliers over the next few years to develop and put into practice new methods for aspheric design and fabrication for laser-fusion use.

This article provides only a very superficial glimpse of the totality of problems encountered in developing optics for laser fusion. The critical problems of optical materials for high-power laser use have not been discussed, simply because of lack of space. No mention has been made of the very active field of new laser development that may, over the next decade, lead to the introduction of some as yet unidentified laser system that does not employ a solid material as its laser host. Nevertheless, the problems of optical design will remain of paramount importance in any laser system developed for use in fusion research.

REFERENCES