KrF Laser: the advance toward shorter wavelengths

by Reed J. Jensen

If energy is added to water in a swimming pool by using wavelengths comparable to the dimensions of the pool, water quickly peaks and sloshes over the edge, If, however. shorter wavelengths are used, the water. though rippling with motion. remains in the pool. There is an analogous problem when one uses laser energy to drive the implosion of a small fusion pellet. If longer wavelengths, say in the infrared, are used, then a portion of the energy "sloshes over" into undesirable modes (such as a few very hot electrons) that dissipate rather than drive the implosion. As our understanding of the physics of laser fusion has increased, awareness of the importance of fusion drivers with shorter wavelengths has likewise increased.

However. building an efficient, high-intensity laser that emits short-wavelength photons is a difficult balancing act for a number of reasons. The balancing becomes obvious when we look at the expression for laser gain. In a simple two-level laser, the gain coefficient g obeys the relationship

$$g \propto \lambda^2 / t_{\text{spont}} ,$$

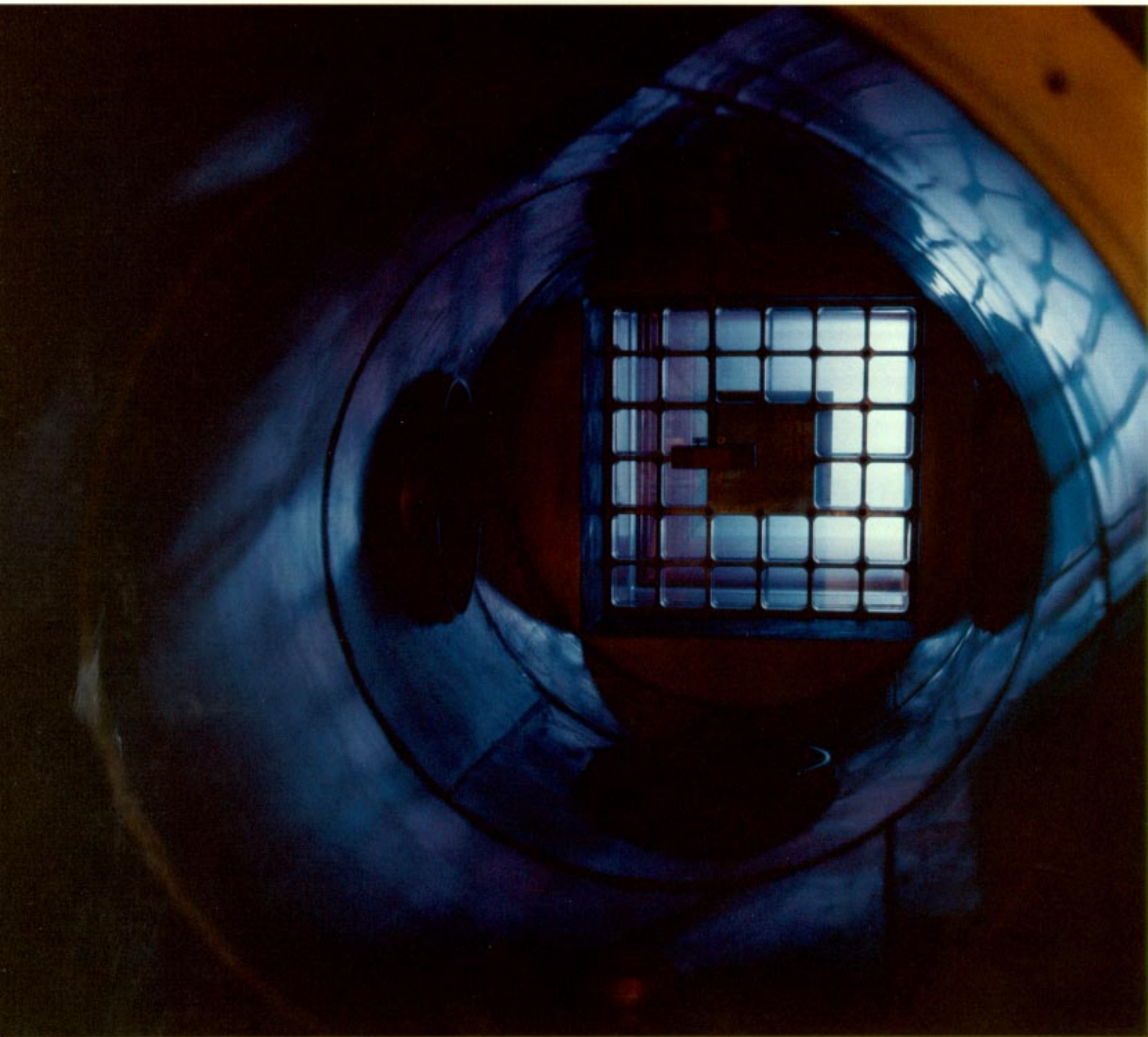
in which t_{spont} is the lifetime of the excited state against spontaneous emission and λ is the wavelength of the emitted photons. The gain itself is proportional to the factor e^g.

As we go to the high excitation levels needed for shorter wavelengths, the lifetimes of excited states tend, in general, to become short. This means the gain coefficient increases—an apparent advantage (although transition strengths can reverse this trend). But a short lifetime also means the excited atoms spontaneously emit their energy quickly. This latter fact is a disadvantage because the emitted photons stimulate further emissions. resulting in a phenomenon called *amplified spontaneous* emission. In large-volume systems. such emission is parasitic. draining energy away too quickly and reducing system efficiency. In other words, it becomes difficult to store large amounts of energy in the lasing medium.

Because of the factor λ^2, this trend can be resisted by locating a system that emits short-wavelength photons from an excited state with a moderate lifetime. For example, a system that emits at a wavelength of O. I micrometer (yin) can have a spontaneous emission lifetime ten thousand times shorter than that of the CO_2 laser and still have about the same gain.

Promising laser systems exist in the mid-ultraviolet, but in this region technical difficulties with optics and windows add to the difficult> of the balancing act. For example. common optical materials absorb strongly at wavelengths shorter than 0.24 μm.

A large KrF amplifier, the LAM, is discharged to generate ultraviolet power at a wavelength of one-quarter of a micrometer. *(Photo by Fred Rick.)*



We are currently developing at Los Alamos the krypton fluoride (KrF) laser—a system that balances these properties to yield a highly efficient laser able to emit intense bursts of short-wavelength photons. For example, the KrF laser operates at ¼ μm, close to the short-wavelength limit for optics but, fortunately, just on the conventional-optics side. The excited-state lifetime of the system is short—due both to spontaneous emission and to deactivation from collisions—making it impossible to store significant energy in the lasing medium. Counterbalancing this disadvantage is the laser's high gain, which yields a system able to amplify efficiently a rapid series of short pulses. As a result. considerable energy can be stored *outside* the laser during the beam's flight to the target. Such storage is accomplished by using a novel multiplexing scheme in which time-of-flight differences cause the series of pulses to meet simultaneously at the target. Thus we are developing a system that will be able to generate short, intense pulses of ¼-μm light highly desirable for the study of the physics of laser fusion at short wavelengths.

An Overview of the Laser

In early 1975 J. E. Velazco and D. W. Setser at Kansas State (University suggested using a mixture of krypton and fluorine gases as a lasing medium, and in June 1975 J. J. Ewing and C. A. Brau at Avco Everett Research Laboratory reported the first laser oscillation for the highly efficient KrF system. The potential energy curves shown in Fig. 1 illustrate the major reason for the high efficiency. The ground state of the KrF system is really a trio of states ($X\ ^2\Sigma_{1/2}$ and $A\ ^2\Pi_{1/2,\ 3/2}$) that are covalent but repulsive. and the "molecule" readily dissociates into neutral krypton and fluorine atoms. As a result, there is no accumulation of molecules in the lower laser level, and a significant population inversion can be achieved. The main laser transition occurs between the $B\ ^2\Sigma_{1/2}$ excited state, made up of an attractive Kr^+F^- ion pair, and the $X\ ^2\Sigma_{1/2}$ ground state.

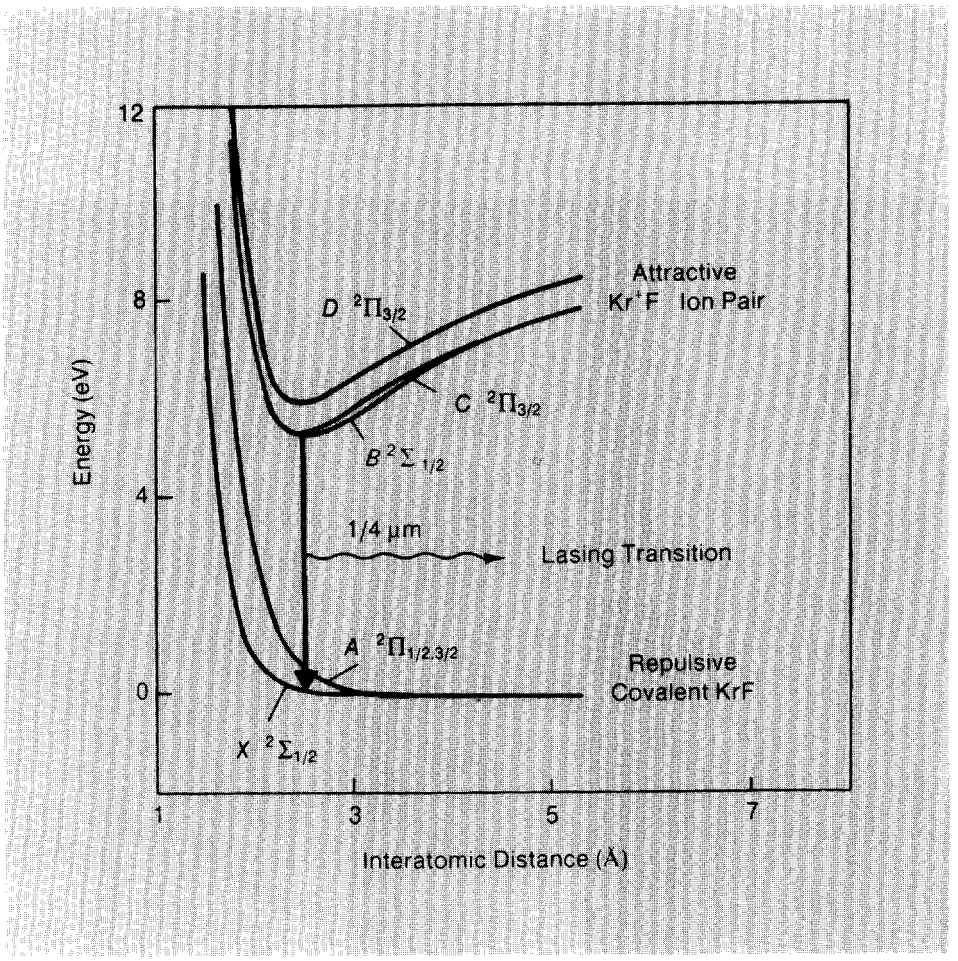


Fig. 1. The potential energy diagram for the KrF laser. The upper state of the lasing transition ($B\ ^2\Sigma_{1/2}$) is one of the states for the Kr^+F^- ion pair. The lower state ($X\ ^2\Sigma_{1/2}$) is one of two covalent states that are repulsive and so dissociate, eliminating KrF molecules from the lower level and ensuring a large population inversion. (Adapted from P. J. Hay and T. H. Dunning, Jr., **Journal of Chemical Physics** ***66 (1977):1306.)***

This transition can be pictured as the ion pair reverting back to the dissociating molecule by transferal of an electron from F^- to Kr^+ and emission of a photon with a wavelength of ¼ μm.

Gain. Measured gain coefficients for the KrF lascr arc in excess of 10 per cent per centimeter. so that a l-meter amplifier would have a gain of e^{10}, or about 20,000, per pass through the amplifier. As pointed out above, such huge gains will not allow storage of large amounts of energy in the lasing medium as a population inversion; the excessive gains cause a loss of upper-level population by amplified spontaneous emission. By using a multiplexing scheme, however, we are able to extract the energy as a series of short

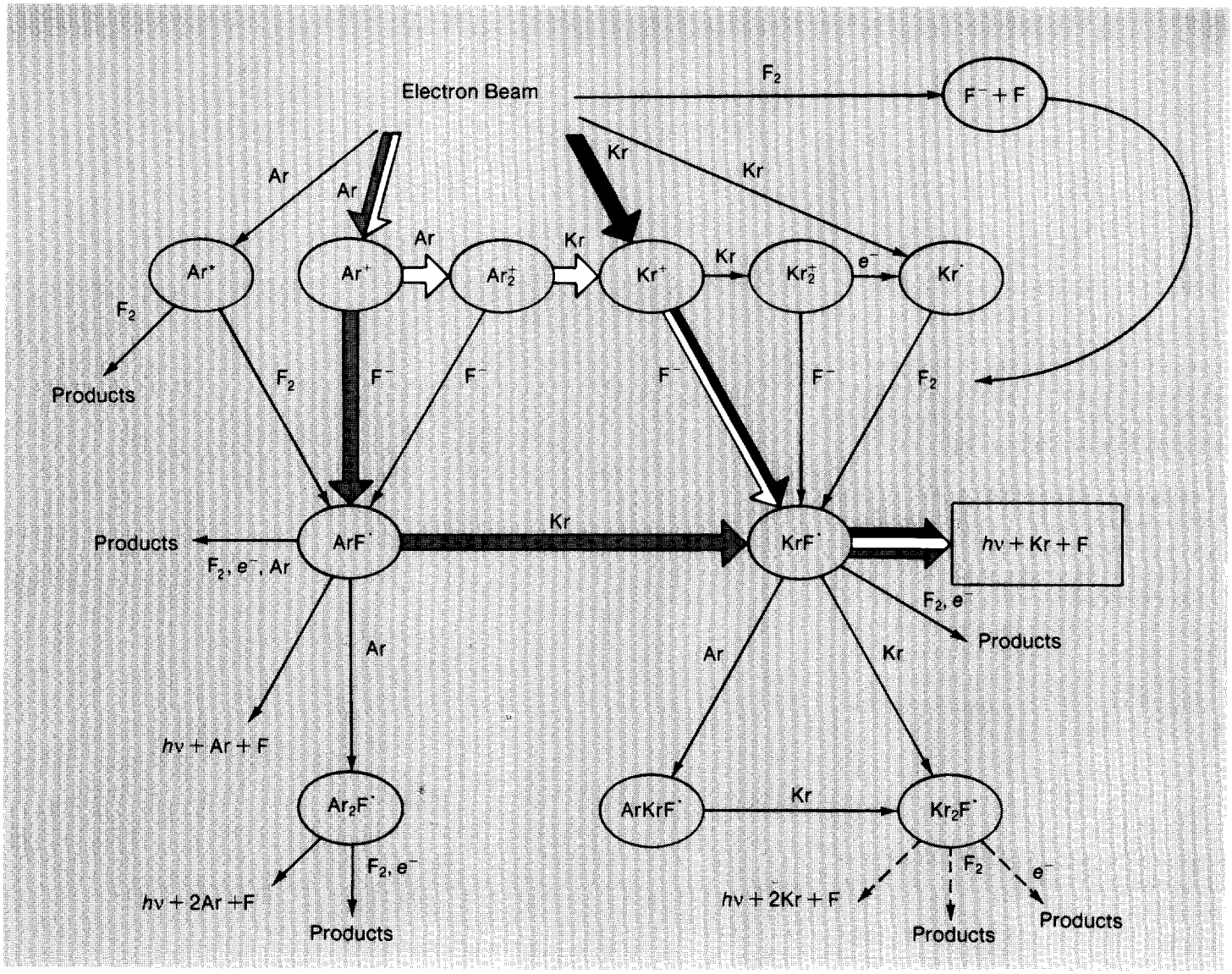


Fig. 2. Kinetic pathways for the KrF laser. Initially, all three atoms in the Ar-Kr-F_2 gas mix are ionized, but the most important path (white) to the KrF ion pair (KrF*) passes through Ar^+ and Ar_2^+ intermediates before a krypton atom is ionized. The Kr^+ ion then combines with a previously ionized fluorine atom. The second most important path (gray) also starts with Ar^+ but then forms on ArF ion pair (ArF*) before exchanging with a krypton atom. The path in black is energetically favorable because krypton ionizes easily but becomes important only as the amount of krypton gas in the mix is increased.

pulses *while* the laser is being pumped. This extraction suppresses the gain by reducing the gain coefficient according to the equation

$$g = \frac{g_0}{1 + \frac{I}{I_{sat}}} ,$$

where g_0 is the gain coefficient at low intensities (the small-signal gain), I is the laser intensity in the medium, and I_{sat} is the so-called saturation intensity (an intensity based on photon energy, the stimulated emission cross section, and the upper-state lifetime of the lasing medium).

It is apparent that if energy is extracted from the amplifiers while the laser is running at an intensity three times I_{sat}, there will be a fourfold decrease in the actual gain coefficient. This reduction will bring the system gain down from about twenty thousand to a few hundred.

Gas Kinetics. In a practical sense, the efficiency possible in the system is determincd by how atoms are pumped into the upper laser level. Typically, the energy is added by ionizing a gaseous mixture that includes argon. The argon atoms play an active role by forming intermediate species, as shown in Fig. 2, a simplified flow chart for the gas kinetics of the Ar-Kr-F_2 system, Initially, all three types of atoms are ionized (here by using an electron beam), but the path (shown in white) that produces the largest population of KrF ion pairs (KrF*) in the upper laser level involves Ar_2^+. The second most important path (shown in gray) involves the ArF ion pair (ArF*). Once KrF* is reached, the desired exit channel is, of course, dissociation to Kr and F and emission of a photon.

The efficiency for conversion of pump energy to upper-state population could conceivably be increased by using more direct or lower energy channels to KrF*. In fact, im-

mediate gains in efficiency can be realized by increasing the amount of krypton in the mixture, although this gas is more costly. Such an approach would emphasize the path (shown in black) in which krypton is ionized directly-a more efficient route because of krypton's lower ionization energy,

Undesirable Absorption. Many of the species pictured in Fig, 2 absorb light of the KrF lasing frequency. What constraint does this place on the design of the KrF laser? Generally, for any absorbing species there is an intensity at which the absorption saturates—that is, the light overpowers the absorption process and starts to pass freely through the system. The fluence for this condition is given by

$$\mathfrak{p}_{sat} = \frac{1}{\tau\sigma} ,$$

where τ is the relaxation time and σ is the absorption cross section for the absorbing species.

Unfortunately, some of the absorbing species in the KrF laser gas have low values of $\tau\sigma$ and do not saturate at fluences used for the design of this laser, The systcm, therefore. has a practical upper limit on the growth of fluence in the lasing medium. In other words, wc have another balancing task: as intensity or fluence increases. the gain saturates but absorption by other species does not. It is believed that the limiting fluence for the KrF system is about 10 to 130 megawatts per square centimeter. Greater intensities can only be reached by using optical focusing and other techniques that arc applied beyond the last amplifier.

Electron Beam. Ionization of the laser gas mix also has its difficulties, The gas contains fluorine. a halogen. which is an efficient electron scavenger. In fact. the formation of' F by electron attachment plays a key role in the pumping scheme of Fig. 2. However, standard gas-discharge techniques used with many gas lasers generate electrons with energies of a few tenths of an electron volt

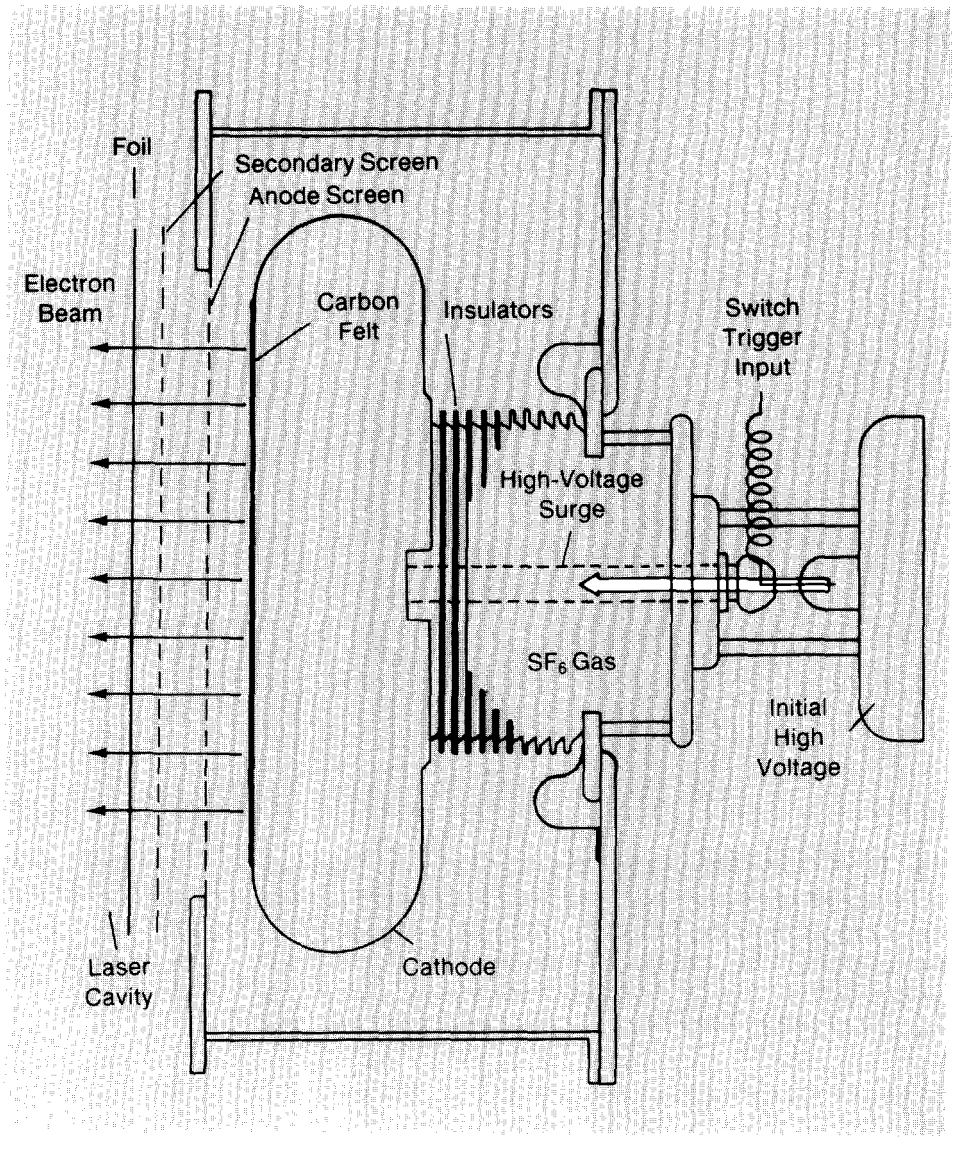


Fig. 3. ***A schematic of the diode for generating the electron beam. When the switch trigger is activated, high voltage surges from right to left on the cathode, where electrons are ejected toward the anode screen. These electrons also flow through a screen that eliminates stray secondary electrons and then through 2-mil titanium foil into the volume of the laser cavity. The electrons are emitted at energies of several hundred keV, and about 95 per cent are transmitted through the foil, where they uniformly excite the laser gas. Critical to the design is the cylindrical high-voltage bushing between the switch and the cathode. This bushing of insulators and SF_6 prevents undesirable arcing back toward the switch. To give an idea of the size of these electron-beam devices, the emitting surface of one of the cathodes in our recent large KrF amplifier (the Aurora system) measures 1 by 2 meters.***

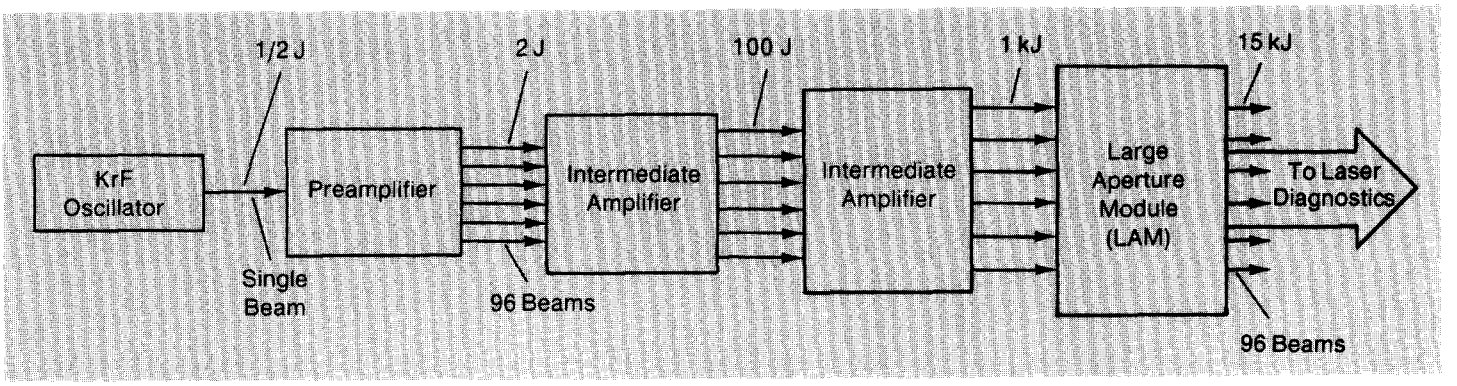


Fig. 4. The power amplifier chain for the Aurora KrF laser system starts with a single 1/2-joule beam and ends with about 15 kilojoules divided among 96 beams.

(eV). Because attachment energies are also of this order, such a discharge has trouble sustaining itself if electron scavengers are present.

Further, in a standard ionization-stabilized discharge system, there is a tendency for the discharge to constrict into a few very hot arcs. This phenomenon leaves most of the gas unpumped, whereas the gas in the vicinity of the arcs is far overpumped and overheated. Even though a preionization device may help generate more homogeneous current flow, the discharge still tends to constrict into hot arcs because of the large positive temperature dependence of the coefficient β in the electron replenishment equation,

$$e^- + M \rightarrow M^- + \beta e^- .$$

In other words, the number of secondary electrons generated when a primary electron collides with atoms in the medium increases rapidly with temperature, and any area of enhanced conduction quickly forms an arc.

The solution to these problems. which would be especially severe at the higher intensities required in amplifiers, is to ionize the gas directly by pumping with an electron beam. In this case, the electrons enter the laser volume with energies of several hundred keV, and any difficulties with electron attachment are simply overpowered.

In addition, an electron beam device avoids runaway arcs by injecting electrons directly into the gas through thin foil windows (Fig. 3). Electron homogeneity is established by field emission and propagation physics in the vacuum region around the cathode. The resulting even distribution of the primary electron current from the electron beam dominates all physics in the laser volume. Thus, the primary current in any particular volume of gas does not depend upon the conductivity of that gas.

Typically, electrons enter the laser volume at energies of 400 to 800 keV. In primary collisions, gas ionization generates secondary electrons with an energy loss to the primary electron of about 30 eV per ionization. Thus each primary electron requires thousands of collisions to deposit its energy in the gas. Both primary and secondary electrons participate in the various pumping and attachment processes shown in Fig. 2.

With this pumping technique we find that for Ar-Kr-F_2 mixes about 24 per cent of the energy of the electron beam appears as population of the upper laser level. With more Kr in the gas mixture and using proper pumping and extraction techniques, the efficiency should be higher. Once again, we see that the KrF laser has high intrinsic efficiency. The exact value depends, of course, on the conditions of the gas and the pumping circuit. So far, an overall efficiency from wall plug to laser beam of 4 per cent has been achieved. Such efficiency is still a little less than is achieved for the $C0_2$ laser, but, even so, more of the energy will be absorbed by the fusion target (about 90 per cent for KrF versus 40 per cent for $C0_2$) and considerably more should end up driving the implosion.

High Repetition Rate. Because KrF is a gas laser with relatively high efficiency, it can be pulsed at high repetition frequencies, To prepare for a subsequent pulse, the gas needs time for all intermediate fluorides to revert back to the elements and for electron-beam-induced shock waves to damp out. This is achieved by exchanging the gas between pulses with modestly sized pumps. Also, spurious impurities, formed by fluorine attack on surrounding materials, are removed during the exchange with filters and "getters" (metals, such as sodium or calcium, that react with the impurities). With these techniques. KrF lasers have been operated at repetition frequencies greater than a kilohertz. Such high repetition rates are the key to the eventual successful development of a laser-driven fusion power plant.

The Los Alamos Program

Los Alamos has been heavily involved in the development and use of KrF and other rare-gas-halide lasers since 1976. The work was done originally for the laser isotope-separation program, and in the first year KrF lasers were used to generate macroscopic samples of photolytic UF_5 from UF_6. At that point we were developing high beam quality, multijoule gas-discharge (rather than electron-beam) lasers. In the late 1970s Los Alamos pioneered gas cleanup schemes that paved the way to the long-lived rare-gas-halide lasers. These efforts culminated in a KrF laser that ran at 1 joule per pulse and 500 pulses per second. We also developed, jointly with Rocketdyne, another KrF laser that had double this repetition rate.

At present we arc constructing a prototype KrF laser system that uses electron-beam pumping in the amplifiers and that will demonstrate the production and extraction of laser energy and the optical techniques needed for a KrF fusion laser. The system is called Aurora, and its various components—from the KrF oscillator through four stages of amplification-arc shown schematically in Figs. 4 and 5. The gas-discharge oscillator will emit a single beam consisting of a 5-nanosecond, 'h-joule pulse. To achieve optical multiplexing, the original beam will be split into 96 beams before being sent through the various stages of amplification. The final amplifier, called the Large Aperture Module (LAM), will have a lasing volume that is 1 meter by 1 meter by 2 meters long and an output totaling about 15 kilojoules (kJ) in the 96 beams.

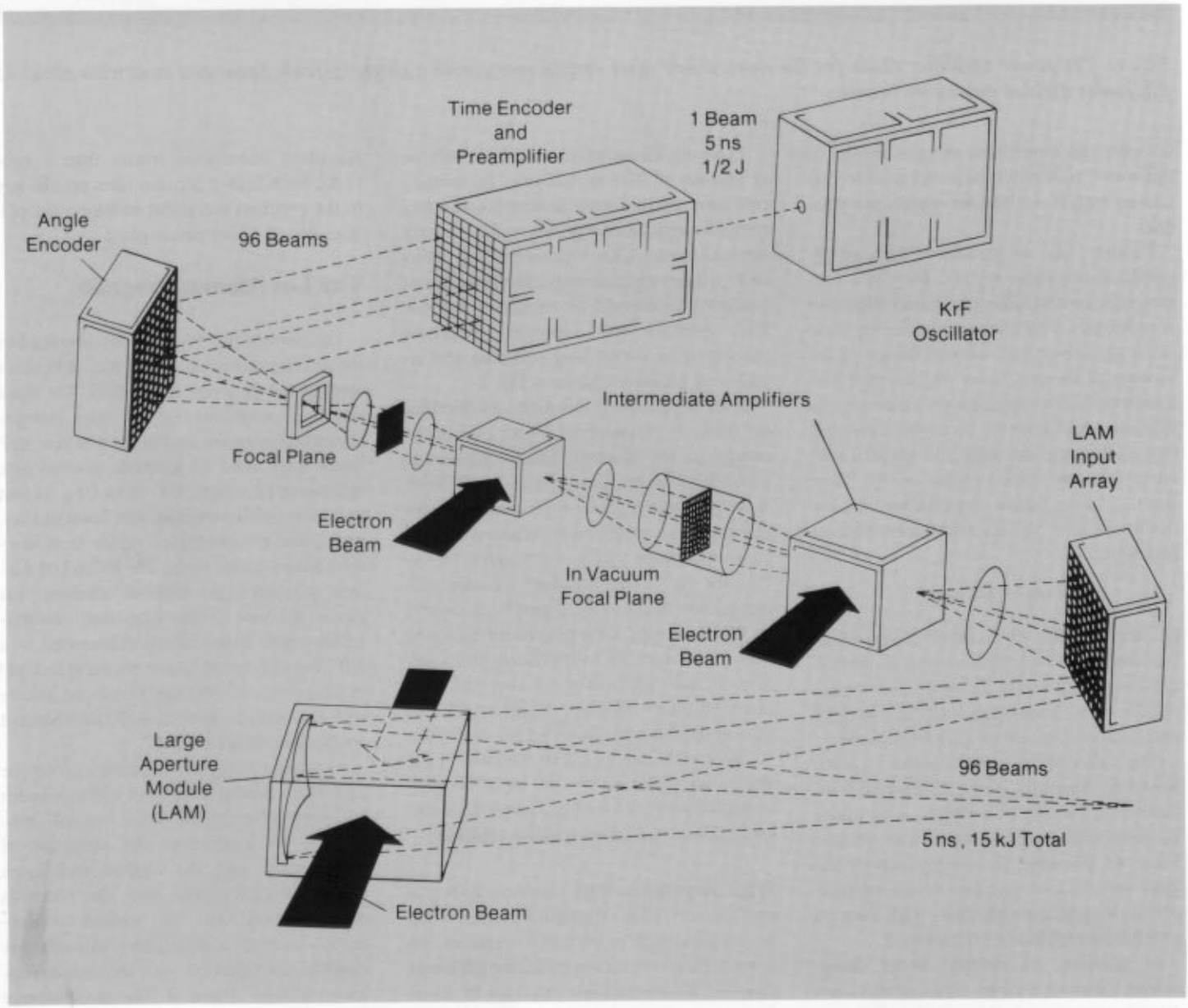


Fig. 5. A conceptual layout for the Aurora laser system. The single beam with 5-nanosecond pulsewidth from the KrF oscillator is divided by the time encoder into a train of 96 temporally separated beams. This splitting is accomplished with aperture dividing, partially reflective mirrors called beam splitters, and different path lengths for each beam. Preamplification also takes place in the same apparatus. The angle encoder aims each beam so that it will pass through the central region of both intermediate amplifiers. Final amplification to 15 kilojoules takes place in the large aperture module. The oscillator is driven by gas-discharge techniques, but the higher intensities in the amplifiers require pumping by electron beam. A demultiplexing arrangement is needed after the LAM to bring the 96 beams to the target simultaneously (see Fig. 6).

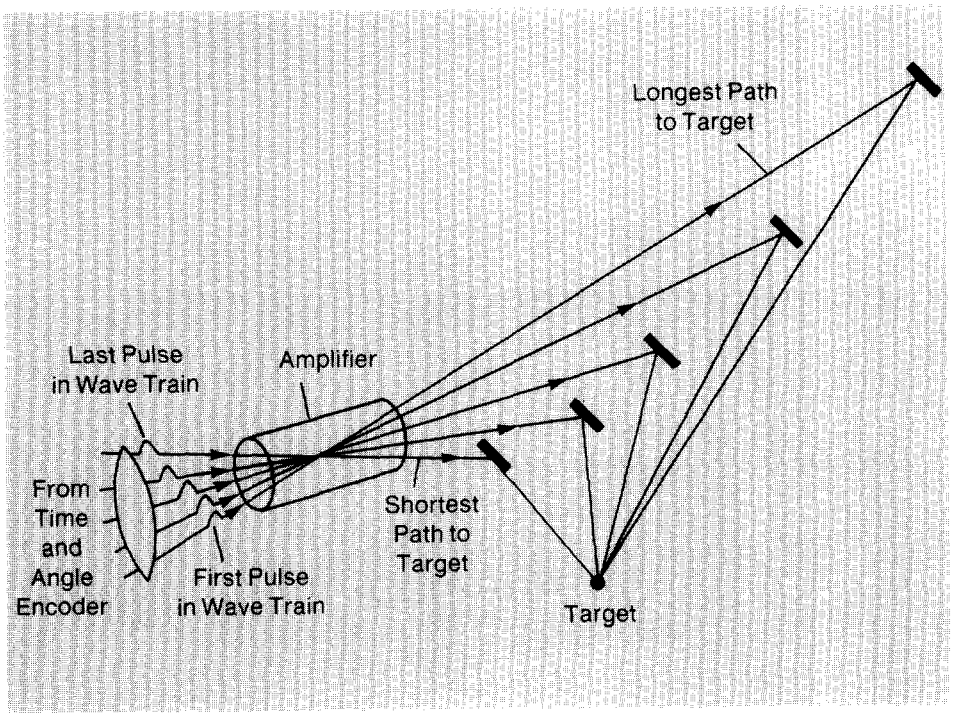


Fig. 6. A simplified optical angular multiplexing device. TheJive beams from the decoder represent a train of pulses that are separated in time. By adjusting path lengths so that the earliest pulse (crossing from bottom left to upper right) has the longest time-of-flight and the last pulse (crossing horizontally) has the smallest time-of-flight, the pulses can be brought together at the target simultaneously.

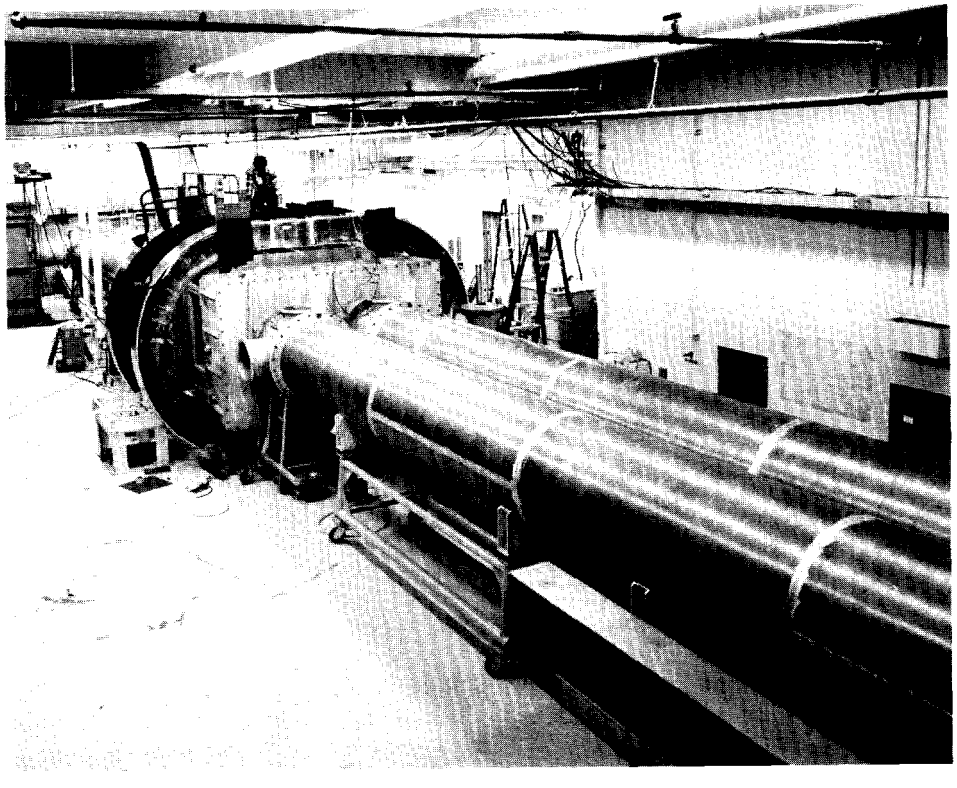


Fig. 7. The KrF laser system 's final amplifier, the LAM, under construction.

Multiplexing. A prime motive for optical multiplexing is cost. It has been estimated that a cost minimum can be achieved for KrF laser fusion if there arc from 50 to 100 beams, each less than 5 nanoseconds in duration, derived from a single electrical pulse. Rather than build 100 systems. we intend to usc a single optically multiplexed system-a key concept to be demonstrated by the Aurora laser.

Multiplexing starts with the time and angle encoders (Fig. 5), which split the original 5-nanosecond pulse into 96 angularly separated beams. Each beam travels a different distance so that each is delayed differently; the resulting output consists of a train of 5-nanosecond pulses. Because the pulses arc angularly separated, each passes through the amplifiers from a slightly different direction. The amplifiers are pumped for a relatively long time—about 600 nanoseconds—while the train of short pulses traverses their volumes

The same time-delay concept can be applied in reverse after the final amplification to cause all the beams to arrive at the target at once. A simplified version of this part of the system is shown in Fig. 6, illustrating how the time-of-flight for each beam differs so that all beams meet simultaneously at the target.

As noted earlier, the multiplexing technique allows us to take advantage of the high gain and high efficiency of the KrF gas laser to generate a short, high-energy pulse on target. The energy of the electron beam discharge is stored in the variously delayed flights of the 96 beams. Moreover, low-cost laser energy is provided by using one system in which the amplifiers run for a relatively long time rather than by using many short-pulse systems.

Figure 7 is a photograph of the final amplifier under construction. The large oval-shapcd features arc magnets that provide a 3-kilogauss guide field to direct the electron beam straight into the laser chamber. The two large cylindrical tubes arc water dielectric transmission lines that transmit the 1.3-megavolt electrical pulse to the cathode. One

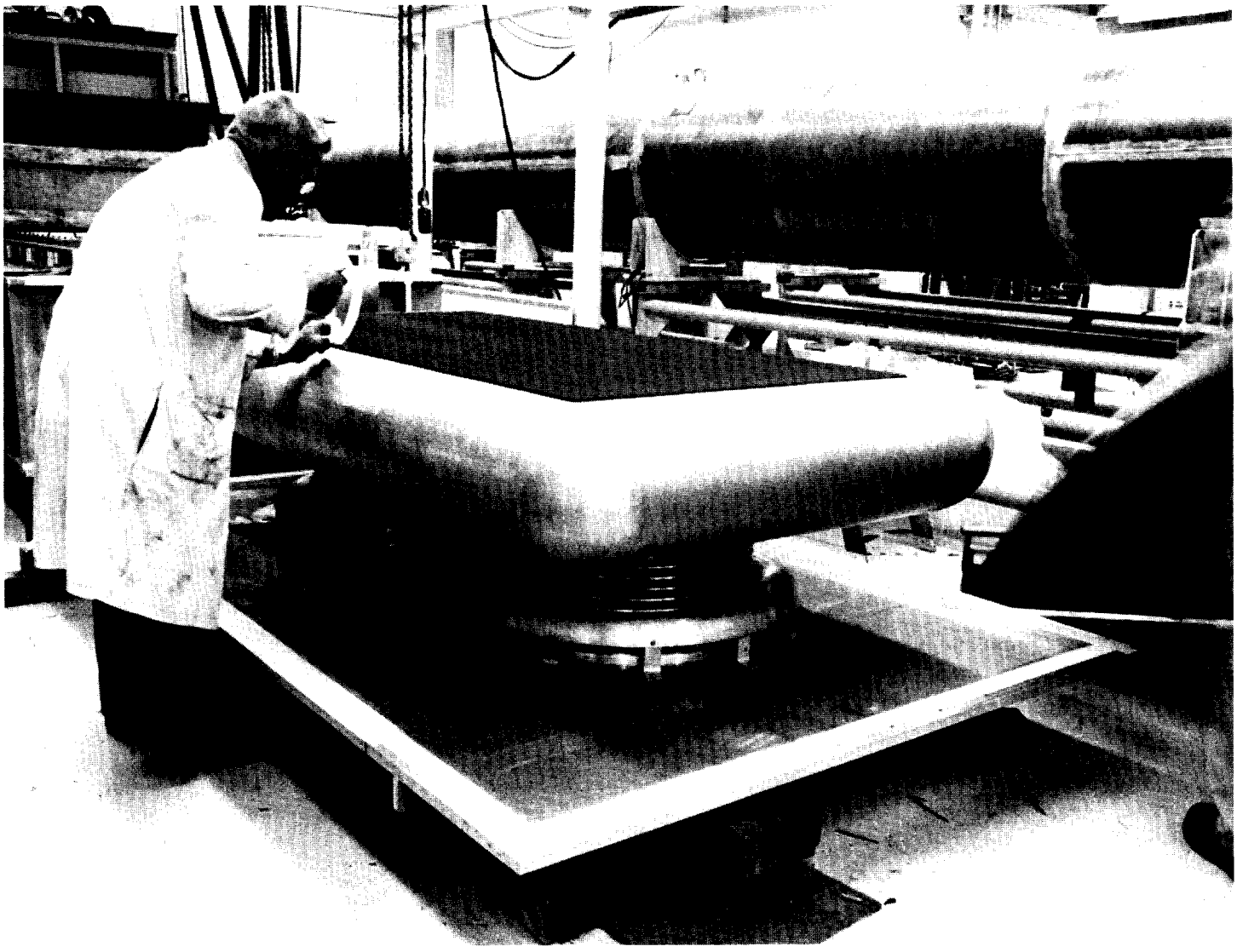


Fig. 8. One of the electron-beam cathodes for the LAM with the emitting surface upright.

of those cathodes is pictured in Fig. 8 lying on a workbench with the carbon felt emitter surface upright. Discharge of this amplifier produces ultraviolet power like that shown in the opening phonograph.

The Aurora lascr system will provide experience in nearly all of the issues involved in building a very large KrF laser fusion driver. We will gain experience not only in large KrF amplifier construction and operation but also in running a whole series of amplifiers with final flux close to the limiting flux for the system. A major issue in this, or any large KrF laser system is damage to the windows and mirrors. We must develop coatings with good reflective or transmissive properties that also arc resistant to fluorine attack and optical damage. At present, the size of apertures and, therefore, the overall system cost-depends very sensitively on the threshold for optical damage.

Results. Recent key results from Aurora include operation of the large final stage amplifier (LAM) at partial charge voltage. We were able to produce 5 kJ of high-quality laser output at the amplifier. This measure-

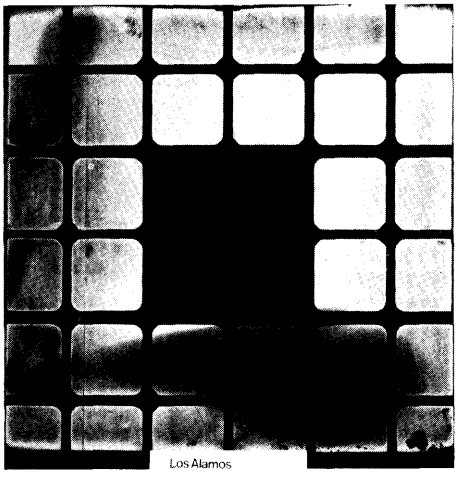
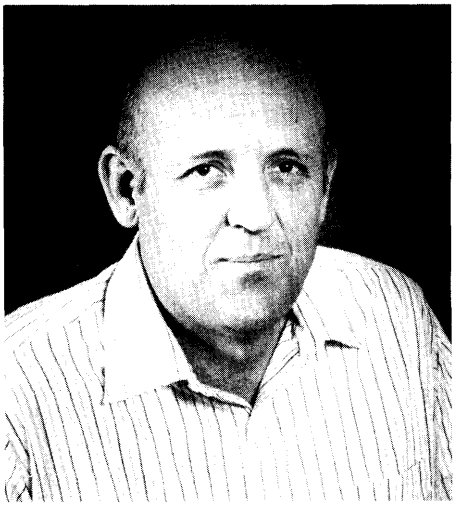


Fig. 9. A burn pattern produced by the LAM running as an oscillator. About 3 kJ of light produced this burn.

ment was made running the LAM as a resonator with a long build-up time rather than as an amplifier. The 5-kJ output was developed during the last 400 nanoseconds of the pump pulse. A typical burn pattern is shown in Fig. 9. The preliminary tests indicate that the goal of a 10-kJ output from Aurora should be exceeded when all of the preamplifiers are in full service.

The automatic alignment system needed to direct the 96 individual beamlets through the amplifier system to a target is based upon beam position sensing. Our technique uses rather ordinary television technology linked to inexpensive small computers. Key tests of the concept have been performed, and we expect to align all the beams simultaneously in a matter of minutes as part of our shot preparation procedure.

When we have successfully operated the complete Aurora system, most of the key issues in the use of efficient KrF lasers for fusion will have been resolved. We will then outfit the Laboratory's existing laser fusion facility (Antares) with the KrF ultraviolet laser system to begin to explore the promising realm of short-wavelength laser-driven fusion. ■



Reed J. Jensen received his Ph.D. in physical chemistry from Brigham Young University in 1965. After a postdoctoral appointment at the University of California, Berkeley, he joined the Laboratory's GMX Division. Following a two-year teaching experience at Brigham Young University, he returned to Los Alamos to initiate a program in chemical laser research. He played a key role in advancing the technology of high-energy pulsed chemical lasers. His experience with the interaction of-laser radiation and chemical kinetics led him directly into the field of laser isotope separation. During this period he, along with several coworkers, advanced the concept for molecular laser isotope separation. His promotion to the post of Assistant Division Leader of the Laser Division was followed in 1976 by an appointment as Alternate Division Leader of the newly formed Applied Photochemistry Division. In 1981 he was named Division Leader of the Applied Photochemistry Division and Program Manager for molecular laser isotope separation. Under his direction approximately 225 scientists and technicians pursued research and development in laser isotope separation, laser-induced chemistry, applied photochemistry, spectroscopy, and related fields. In 1983 he became Associate Physics Division Leader and Program Manager for advanced fusion lasers. Current work includes efficient scaling of lasers to giant pulses for laser fusion.

Further Reading

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