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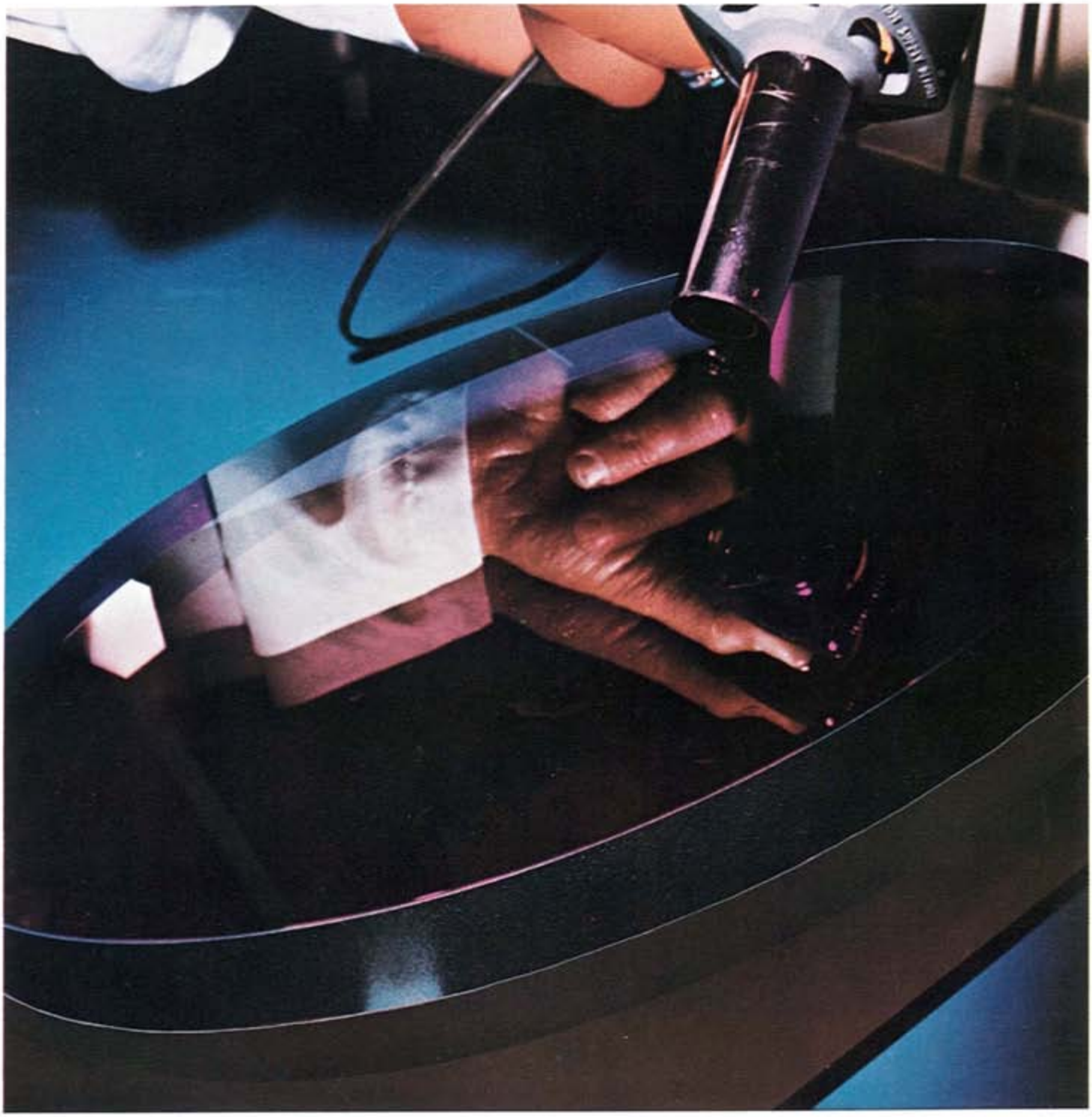

Contamination-control technology

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The advent of very-high-powered solid-state lasers for fusion research has created a need to keep large optical components extremely clean. A tiny speck of dust or a thin film of contamination can cause expensive laser-induced damage. The control and elimination of contamination has therefore become a vital adjunct to the laser program.

Contamination of optical surfaces can limit the performance of high-power lasers in two major areas. Within the laser amplifiers, the high-intensity flashlamps can heat contaminants on optical surfaces enough to cause local melting and damage. The presence of contaminants can also initiate intensity modulations on the laser beam that can cause self-focusing of the laser light, local heating further down the optical train, and local beam intensities that exceed the damage threshold of high-quality optical coatings—all effects that tend to prevent the precision focusing required for laser fusion applications.

We have developed a large body of standards, measurements, and techniques that enables us to define a clean surface, determine the degree of contamination, and provide optical surfaces of suitable cleanliness. This contamination-control technology attempts to keep optical surfaces free of particulate matter before coating, during installation, and throughout their useful lifetime. It has practically eliminated contamination-related failures in the Shiva laser system.

Clean surfaces are needed in many areas of science, such as on high-vacuum devices, optics, integrated circuits, and high-speed digital recording equipment. Clean surfaces are of particular significance in relation to high-power lasers because of the potential damage to expensive optics that can result from even a few micrograms of contamination and the intensity modulations (noise) that such contamination initiates on the laser beam.

Obtaining a clean surface has always been more of an art than a science. Part of the problem is defining what is clean, or what is clean enough, and then attempting to obtain the desired degree of cleanliness reproducibly. Since its inception, the laser program has been developing contamination-control technology and studying contamination and its effects on optical components.

Effects of contamination

The main requirement on an optical surface is that it be uniform and consistent in its effect on light. Any speck or film, by absorbing, refracting, scattering, or reflecting light differently than the surface, reduces the quality of the optical surface. At the very least, such effects will reduce transmission of light. At worst, in high-power lasers they can also cause local overheating, damage to coated optical surfaces, and beam spatial intensity modulations (noise). Spatial intensity modulations can lead to beam breakup, self-focusing, and

local hot spots and also can ultimately limit the ability to focus a laser beam to a small enough spot for laser fusion experiments.

Damage may be defined as any alteration of an optical element that modifies the transmission of the laser beam through the optical element. Typical effects are attenuation, scattering, or deflection of the beam. The three principal causes of damage to laser optics are:

- Flashlamp heating of contaminant particles, which damages the surface of the laser disks.
- Laser beam noise, which damages the optical coating.
- Films on the optical surfaces, which attenuate the beam.

Small particles on laser disk surfaces, when heated by flashlamp pump light in excess of 10 J/cm^2, can cause local overheating, surface melting, and permanent damage to the glass. The optics can be repolished to remove this damage, but in this situation prevention is far less expensive than regrinding and repolishing flat to within about 50 nm. Repolishing all the disks in a disk amplifier would currently cost $5100 plus the manpower to perform the maintenance.

Even particles nearby but not directly on optical surfaces are of concern because forces resulting from nonuniform heating during flashlamp firing can make them migrate toward the glass surfaces. The large optical surfaces and the even larger mechanical surfaces of a laser disk amplifier must be maintained clean throughout the life of the component to prevent this form of damage.

Optical coating damage, on the other hand, arises from beam modulation (hot spots in what would otherwise be a uniformly intense beam). In operation we keep the average fluence level (J/cm^2) of the laser at about one-half the intrinsic single-shot damage threshold for freshly cleaned optical components. Damage occurs, in general, when the peak-to-average beam modulation exceeds this threshold.

Figure 1 shows a damaged spatial filter lens. This lens was accidentally damaged by a very intense beam during the initial operation of the laser. Beam modulation, resulting in spot intensities exceeding the damage threshold, has permanently etched the antireflection coating. Concentric circles are whole-beam diffraction rings and smaller damage sites are due to diffraction from random beam perturbations. This form of damage results, not from contaminants on the coated optical surface itself, but from diffraction effects begun by contaminated or damaged surfaces earlier in the optic train.

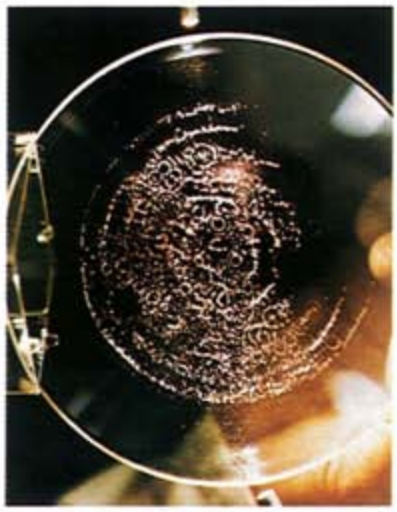

Fig. 1 ***An antireflection-coated spatial filter lens damaged by spatial noise on the laser beam. Wherever the peak ripple intensity exceeds the damage threshold, it blasts the coating off. This lens will require regrinding, repolishing, and recoating.***

The 20-kJ Shiva laser has 50 disk surfaces in each of its 20 arms that are exposed to flashlamp radiation. Since damage to one surface can cause damage to others downstream, the amount of damage per surface must be kept very low. To prevent even a 1% (200-J) loss in energy due to scattering, there must be fewer than 1200 damage sites larger than 100 μm in diameter per arm.

By examining many sites, we have found that a damaged area may be from 5 to 10 times larger than the particle that caused it. Thus, to avoid a 1% energy loss, we must start with fewer than 24 000 dust particles 10 μm or more in diameter *in the whole laser.* By comparison, a single clean home window on which no particles are visible to the naked eye may still harbor fifty times as many particles in the same size range per square metre.

Using knowledge of the typical size distribution of dust particles, we can relate the fraction of the beam obscured by damage sites to the concentration of damage sites exceeding a given size. We have collected data of this sort by carefully examining all damaged

optics removed during routine maintenance. Figure 2 shows the number of damage sites larger than 100 μm observed on damaged Shiva disk surfaces as a function of the number of amplifier firings. The average value of damage sites greater than 100 μm appears to be 770/m^2, which corresponds to only a 0.2% loss (attenuation) for the system.

As the number of firings increases, we note a slow increase in the amount of damage. This additional damage results from the slow infiltration of additional contaminants into the sealed amplifier and is a measure of the effectiveness of our contamination-control measures. These data imply that we can expect very long component lifetimes. Many Shiva components are still in good condition after two years of continuous service.

Design for cleanliness

The Shiva disk amplifiers are designed, fabricated, assembled, and operated with minimum contamination as a goal. For instance, the original mechanical design eliminated screw fasteners in the disk cavity. Gas filters on the inlet and exhaust of the amplifier reduce contamination from the nitrogen cooling gas to a minimum.

Furthermore, we selected the structural materials for their high corrosion resistance and optical reflectivity and then specially processed them to ensure particle-free surfaces. The stainless steel components were machined to fine surface finishes with a minimum of burrs. They were then electropolished and chemically etched to further smooth and passivate the surface and remove surface inclusions. Figure 3 shows the main frame of a disk amplifier and disk holder during assembly.

Plastic and elastomer materials tend to become sources of contamination under the intense ultraviolet and infrared radiation encountered in a laser amplifier. We therefore included such materials only when absolutely necessary, selecting them for low outgassing and high resistance to ultraviolet and infrared light and shielding them from all direct radiation to prevent their volatile constituents from condensing onto the optical surfaces.

All sliding surfaces generate wear particles in sizes and numbers that depend on surface hardness, surface loading, sliding distance, and the materials involved. One measure to keep the optical surfaces clean and particulate-free during assembly and operation is to eliminate sliding surfaces wherever possible.

Conventional threaded fasteners are the worst offenders, since the

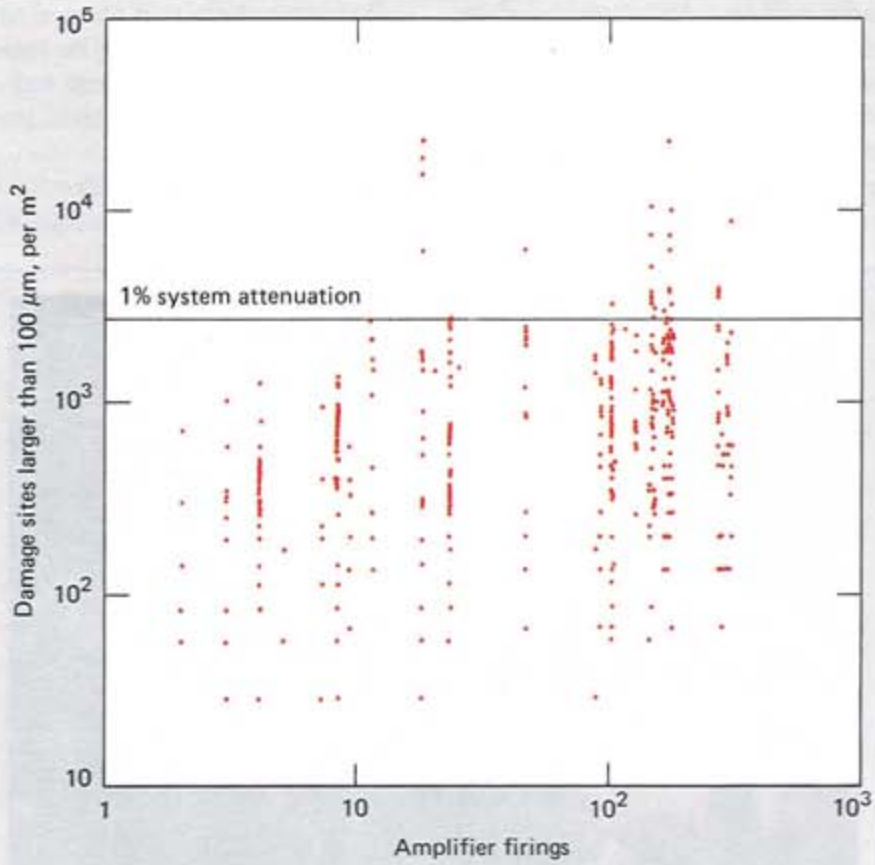

Fig. 2 *Concentration of damage sites as a function of the number of amplifier firings for the Shiva laser system. The data were collected during routine maintenance of the system over the past two years. They represent only those amplifiers damaged enough to warrant rebuilding. The 1% line represents the damage level that would cause a 1% loss in power if all 1000 disk surfaces were damaged to the same extent.*

threads slide for considerable distances with high contact stresses. Inserting a single No. 10 machine screw can generate more than 10 000 metallic particles 5 μm in diameter and larger. Hence we use no threaded fasteners inside our laser disk amplifiers, substituting instead spring-loaded clips that, although perhaps harder to attach than conventional fasteners, generate far fewer microscopic particles during assembly.

The intense light from the xenon flashlamps would ionize any oxygen present inside the amplifiers and might generate enough heat (and therefore thermal stresses) to deform laser disks slightly, with resulting laser beam distortion. In addition, ionized oxygen is very corrosive. To minimize distortion and potential corrosion, we pass clean nitrogen gas through the amplifier to cool the disks and reduce the oxygen concentration.

This nitrogen flow could itself be a source of damage-causing dust particles. To avoid this possibility, we filter the nitrogen through a membrane pierced with millions of holes 1 μm in diameter.

Clean-room facilities and assembly procedures

During the past several years, while the Janus and Argus laser systems were being developed, the laser program has also steadily improved its clean-room facilities. In the Shiva system we have three vertical-flow clean rooms, a Class 1000 laser bay, a Class 1000 target bay, and the Class 100 clean assembly room shown in Fig. 4. (The class of a clean room refers to the maximum concentration per cubic foot of airborne particles 0.5 μm in diameter and larger. Conventionally air-conditioned rooms are usually in the million-particle class.)

Vertical-flow clean rooms are the most costly to construct but are by far the most effective in which to get surfaces really clean and keep them that way. Air enters the clean room through high-efficiency filters in the ceiling that remove at least 99.97% of all particles 0.5 μm in diameter or larger. The air moves rapidly downward (0.5 m/s), sweeping out any particles generated by the personnel working in the room.

The filters are so efficient that practically the only contaminants entering the room come in on the clothing of the occupants. Additional particles are generated in the room by the rubbing of the special garments worn in the clean room or by dandruff, skin flakes, hair, and other such debris.

Another factor in maintaining absolute cleanliness is the exclusion of all soft metals, paper, and machines with exposed electric motors and belt drives. We have also found it necessary to eliminate all assembly procedures, such as soldering, cutting, and filing, that could generate particles. The room is completely cleaned every night, and all tools and work areas are cleaned before use.

Although the Class 100 assembly room is not biologically

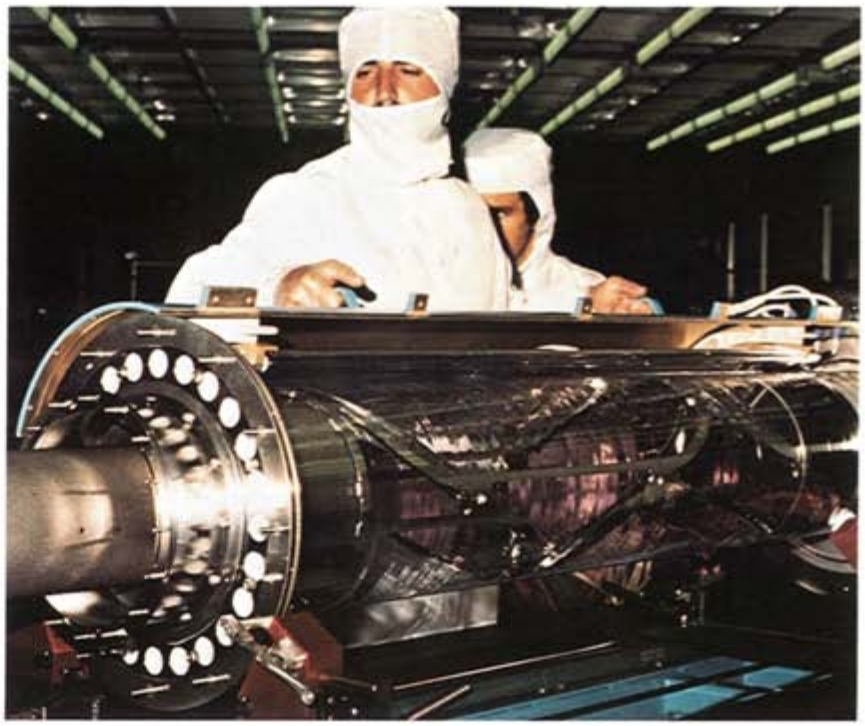

Fig. 3 *A 20-cm-aperture disk amplifier being assembled on an assembly fixture by a specially trained clean-room technician.*

sterile, it is probably cleaner than most surgical operating rooms. Figure 5 shows a typical airborne particle count over a 24-h period in this room.

Three or four years ago it became apparent that surfaces cleaned by conventional and well established methods, such as vapor degreasing and ultrasonic cleaning, were not clean enough for use in our lasers. Some disk amplifiers assembled under these cleaning procedures were being rebuilt monthly as a result of optical damage, an intolerable drain on our financial and manpower resources. Part of the problem was the lack of a reliable means of measuring cleanliness, and part of it was inadequate awareness of the degree of cleanliness required.

A research program quickly determined that, although vapor degreasing could potentially remove organic contaminants (such as fingerprints), it was totally ineffective at removing small insoluble particles. Ultrasonic agitation, then the main cleaning procedure for removing particles, was found to be effective mainly above the 100-μm-diam size range. Its removal efficiency for 5-μm-diam particles is only about 30%.

We then tried a large number of cleaning methods using a variety of solvents and cleaning mechanisms to find a way of removing quickly and reliably particles as small as 1 μm. One of the most efficient methods we found was a high-velocity jet of liquid directed at the surface. The liquid could be either water or an organic solvent; we chose the latter because it removes organic residues better and because it evaporates rapidly, leaving the clean surfaces dry and ready for assembly.

Fig. 4 *The vertical-flow Class 100 clean room used for cleaning and assembling all Shiva laser amplifiers.*

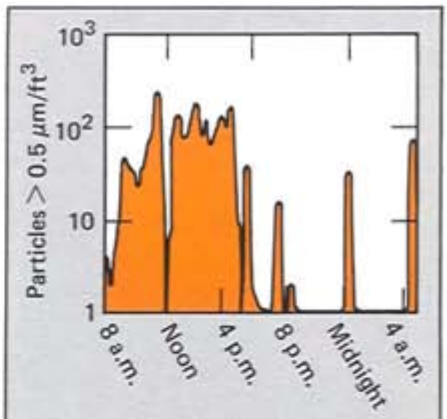

Fig. 5 *Typical airborne particle concentration in the vertical-flow clean assembly room for the Shiva laser.*

Table 1 shows the relative effectiveness of many of the methods tested. The liquid spray at 7 MPa typically removes about 99.9% of particles 5 μm in diameter and larger in only a few seconds. High-pressure solvent spraying removes particles with very high efficiency because it can apply a high shear force to an attached particle only 5 to 10 μm from the surface being cleaned and because it flushes away the particles that have been dislodged by the shearing action.

Figure 6 shows the liquid-solvent spray box being used to clean an amplifier weldment. The spray box protects the operator from the high-pressure spray and confines the vapor for efficient recovery and recycling. The recycled solvent passes through a distillation

recovery system and a series of membrane filters to maintain the highest possible level of cleanliness.

To verify surface cleanliness, we collect solvent effluent from the box and pass it through a membrane filter. We then examine the filter microscopically and count a statistical sample of the particles. From this we can estimate the total number of particles removed and the number remaining. Currently, a nonoptical component is clean enough when the contaminant level is less than two particles greater than 5 μm in diameter per square centimetre.

Since optical surfaces must be even cleaner than the supporting hardware, we manually scrub these surfaces with an extremely clean lens tissue soaked in extremely pure acetone and ethanol. Scrubbing applies a great deal of mechanical force to a particle, and a wet tissue wiped across a surface exerts high drag forces. This method is somewhat archaic and time-consuming, but it is as efficient as the high-pressure spraying and it allows the technician to inspect the optical surfaces simultaneously.

We are now developing a high-pressure optical cleaning unit to reduce the need for cleaning optical surfaces by hand. (Our present high-pressure cleaning unit is unsuitable for this purpose because evaporation cools the optical surface enough to make moisture condense on it. This problem does not arise with metal components; their high conductivity prevents the surfaces from getting cold enough to form much condensation, and they are not as subject to attack by moisture as the optical glasses.) Our new unit will operate at higher temperatures, with an atmosphere of dry organic vapor to exclude moisture.

After cleaning the optical parts, we assemble them on a fixture (Fig. 3) specially designed to let clean-room air flow through unobstructed. After their assembly into the previously spray-cleaned

Table 1 *Comparison of cleaning methods used for removing particulate aluminum oxide from polished metal and glass surfaces.*

	Pressure	Particle-removal efficiency, %		Cleanliness achieved
	MPa	>5-μm	>1-μm	>5-μm particles/cm^2
Scrubbing and dragging with lens tissue soaked in ethanol and acetone	—	99.6–99.98	—	2–40
Spraying with liquid solvent for 5 to 30 s				
Fluorocarbon	0.35	97	3	1 500
Fluorocarbon	7	99.7–99.9	81	10–35
Water	17	98–99.5	—	2–60
Adhesive strippable coating	—	95–98	—	500
Ultrasonic agitation in solvent for 1 to 2 min	—	24–92	1	9 000–70 000
Sequential cleaning				
Ultrasonic agitation in solvent				
Solvent low-pressure spray				
Vapor degrease				
Immersion in boiling solvent				
Ultrasonic rinse	—	92	—	4 000
Compressed gas jet for 10 s	0.7	50–61	—	5 000–5 800
Vapor degrease in organic solvent	—	11–28	—	65 000–80 000

mechanical hardware, we give the disks a final inspection using a high-intensity light and remove the few remaining particles with a vacuum probe, as shown in Fig. 7.

Finally, we transport the amplifier to the laser space frame, mount it into a cradle, and align it optically. Because the alignment must take place with the amplifier open, we made the laser room itself a vertical-flow clean room with a Class 1000 rating. After alignment, we interconnect the amplifiers with beam tubes that prevent airborne contamination from reaching the inside of the amplifier. The beam tubes and the amplifiers are continuously flushed with membrane-filtered gaseous nitrogen (derived from liquid-nitrogen boiloff) to exclude oxygen, cool the optical components, and keep them clean and dry.

Summary

All facets of the design, manufacture, assembly, and operation of the Shiva laser system are intended to give a disk-amplifier service life of 500 shots before rebuilding. It is now clear that most of the amplifiers will reach that goal. There have already been about 300 system shots, and only a very few amplifiers have been removed, most for reasons unrelated to contamination-initiated damage to the optics (failure of a flashlamp, for instance).

We are using the knowledge gained on Shiva in designing the Nova laser components. We expect to manufacture, assemble, install, and operate the Nova components without ever having to rebuild them during their operational lifetimes.

Fig. 6 *A spray box used for cleaning all laser mechanical components sensitive to particulate contamination with liquid solvent delivered at 7 MPa.*

Fig. 7 *Final inspection (after assembly) using a high-intensity light and a vacuum probe to locate and remove any small particles. After inspection, the disks are enclosed in a protective shield of fused quartz. An external cover supports the xenon flashlamps that pump the optical cavity and protects the quartz shield from contamination.*

Key words: cleaning; clean rooms; contamination control; laser damage; Nova laser; particulate removal; Shiva laser.