University of California, San Diego

UCSD-ENG-111

High Average Power Laser Program

Grazing Incidence Metal Mirror Mid-Scale Optics Research Plan

K. L. Sequoia, M. S. Tillack,
T. Albert, M. Wolford and J. D. Sethian

May 28, 2004

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Introduction

An experimental campaign is planned to be carried out at the Naval Research Laboratory during the summer of 2004 in order to demonstrate the laser damage resistance of grazing-incidence aluminum mirrors at a scale larger than previously studied in the UCSD laser damage testing facility. The goal of this campaign is to expose several candidate mirrors to at least 8 J/cm^2 laser fluence (measured normal to the beam) over an area greater than 10 cm^2 for shot counts exceeding 1000, and to compare the results with data previously obtained using a smaller beam (several mm^2).

Candidate mirrors are under development at UCSD (in conjunction with AlumiPlate Inc, II-VI Inc and General Atomics), MER Corporation and Schafer Corporation. UCSD will field at least two mirrors consisting of Alumiplated Al-6061. This mirror construction has been demonstrated at smaller scales (footprints several mm in linear dimension) up to 18 J/cm^2 and 10^5 shots. Under contract to UCSD, Schafer Corp. is developing two alternative mirror candidates: an evaporative Al coating of at least 5 microns on a polished Si-coated C-SiC substrate, and an alumiplated SiC substrate. Finally, MER has developed an innovative mirror consisting of a thin Al foil which is diffusion bonded to a Si-coated SiC substrate and subsequently diamond-turned. We will test whichever mirror candidates are available in sizes at least 4" across, and which have been previously demonstrated with at least 10^4 shots at UCSD.

As the first user experiment on Electra, a major aspect of the research plan is to establish a materials testing capability and solve issues which arise due to facility and procedural challenges. Materials testing requires a controlled environment for the test articles, radiation protection from the pulsed power system emissions, laser beam manipulation (the beam must be apertured, focussed, polarized and steered), beam diagnosis, and measurement of the materials interactions. This is particularly challenging due to the high pulse energy, high average power, short wavelength and radiation environment of Electra.

In this research plan we describe in detail the features of the experiments, including the required facilities, optics layout, diagnostics, test procedures, and a comprehensive listing of the optics and other equipment which will be needed in order to fulfill the research objectives.

Electra Facility Description

Electra is a 248-nm KrF laser currently operating as an oscillator [1] with a simple geometry consisting of a high reflector and an output coupler surrounding a gas cell pumped by a pulsed e-beam. The output laser energy is ~700 J over a single aperture of 30 x 30 cm with temporal pulse width of 120 ns. The maximum energy density at the output coupler is ~1 J/cm^2 and the maximum rep rate is 5 Hz. The beam emerges unpolarized. When operated in a repetitive mode, the output energy is stable after the initial 50 pulses.

The Electra laser bulding (see Figure 1) consists of an amplifier laser hall, front-end room, small shielded room and storage area. Experiments will be assembled in the amplifier hall where adequate space exists for a 4x8 table containing the beam manipulation optics and test chamber.

Figure 2 shows a blow-up of the area in front of Electra where our experiments will take place. The pulsed power systems in the amplifer hall produce copious amounts of x-rays, requiring us to provide localized Pb shielding. A simple solution was adopted in which a 45˚ steering mirrors will be located immediately outside of the lead-lined cell. At the location where the beam exits the cell, a lead aperture will be placed in order to block the majority of the beam and allow only the desired portion of the laser energy to propagate. In that way, only a small collimated beam of x-rays will leave the cell. Behind the 45˚ mirror we will place a local lead shield. Operation of the experiments will take place remotely from the region indicated in red on Figure 1.

Basic laser beam diagnostics are provided with the facility, including temporal pulse shape using photodiode detectors, a 33 cm x 33 cm calorimeter, and laser spatial profile measurement. Utility requirements include a supply of industrial argon for the mirror enclosure, 110 v power for general use, and x-ray shielding.

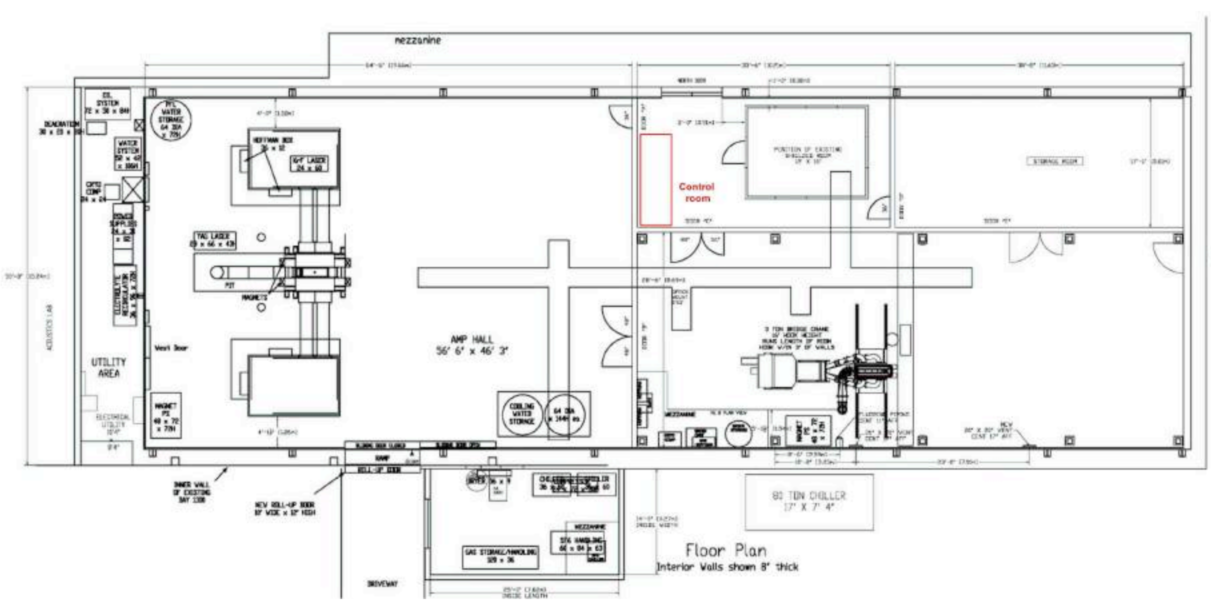


Figure 1. Electra building layout

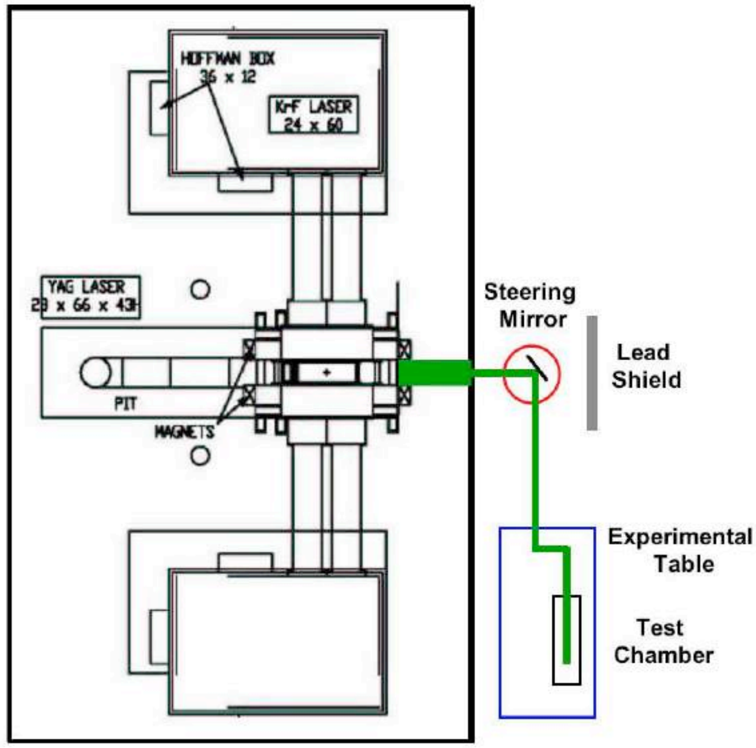


Figure 2. Experimental area around Electra

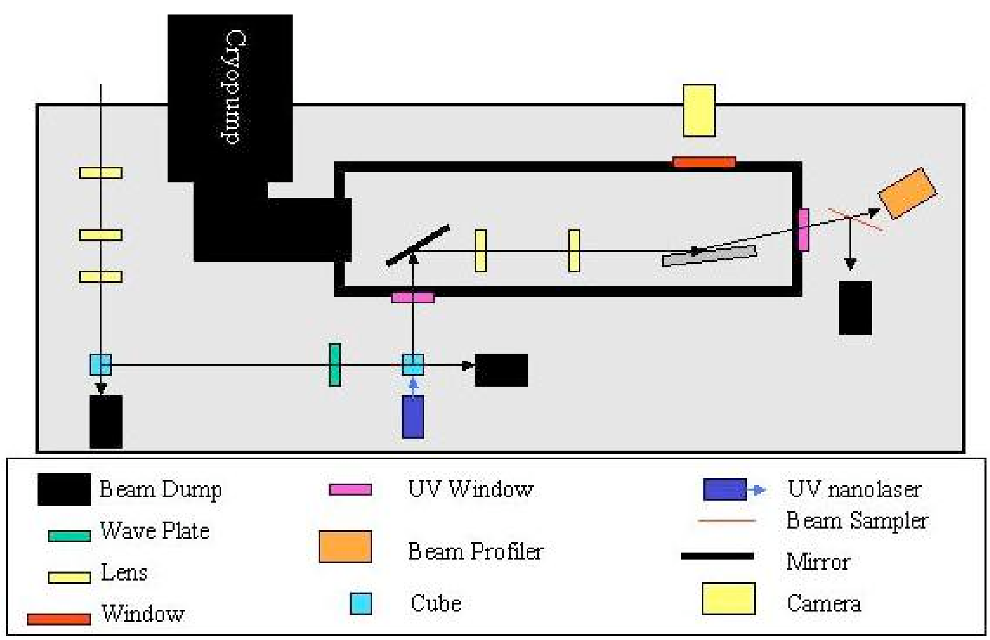


Figure 3. (optical path on the experimental table)

Optical Path for Mirror Irradiations

The output beam from Electra must be apertured, steered, focussed and polarized in order to irradiate our mid-scale mirrors at a grazing angle of 85˚ with minimal effects due to p-polarized light. Figure 2 shows the optical path leading to the experimental table and Figure 3 shows the optical path on the experimental table.

Aperture. The total amount of energy required is substantially less than the capability of Electra. Therefore, we will construct an aperture which intercepts the beam at the exit from the Electra cell. The fluence at the aperture will be less than 1 J/cm^2 (average power of <5 W/cm^2), but the total power will be as high as 3.5 kW. We anticipate test runs of approximately 1000 shots (200 seconds) at full power, such that the total absorbed energy will be 700 kJ.

Inertial cooling is not adequate. For example, a 1-inch solid piece of aluminum subjected to 1000 shots at 0.7 J/cm^2 would heat up by 100˚ K. Water cooling using facility chilled water will be utilized. For example, the flow rate of water required to remove 3.5 kW continuously with a 10˚ temperature rise is modest – about 100 g/s (6 liters/minute). An Al plate will be fabricated with integral coppper cooling channels for heat removal. The surface must be treated to provide efficient absorption of light at 248 nm. For this purpose, a graphite plate will be bonded onto the Al heat sink.

X-rays emitted from the Electra discharge will propagate through the aperture into the building. In order to minimize exposure to personnel, we will locate a steering mirror immediately outside of the cell. Directly behind this mirror we will place lead plates. Photons must scatter twice (once from the shield and once from the Electra enclosure) in order to leak out (see Figure 2).

Steering mirror and first telescope. Following the aperture we will place a 4" 45˚ steering mirror to divert the beam toward the test area.

Immediately following the mirror we will place a telescope to compress the beam from <1 J/cm^2 to >3 J/cm^2. The first optic in the telescope will be a 76.2 mm diameter plano-covex lens with a focal length of 507 mm. The beam diameter will be focused to 0.945" at a distance of 0.3 m down the beam path, were the second lens will be placed. This lens, plano-concave f = -491.6 mm, will change the focal geometry so that the effective focal length of the two lenses is 876 mm. A third lens, plano-concave f = -786.6mm, will be placed approximately 0.08 m down stream of the second lens, to provide fine tunning of the beam divergence without significantly changing the fluence. At this point, the fluence is 5 J/cm^2. (See Figure 4)

Polarization. The high cost of optics, especially high-energy UV polarization optics, has led us to examine in detail several options for the beam path following the main focusing lens. Our goal is to provide at least 100:1 polarization (s-polarized with respect to the test surfaces) with fluence of 8 J/cm^2 (normal to the beam) over an area of linear dimensions of the order of 3-5 cm on the test mirror surface. The absence of a specific quantitative goal for the area of the beam footprint leads to qualitative trade-offs between cost, complexity and footprint size.

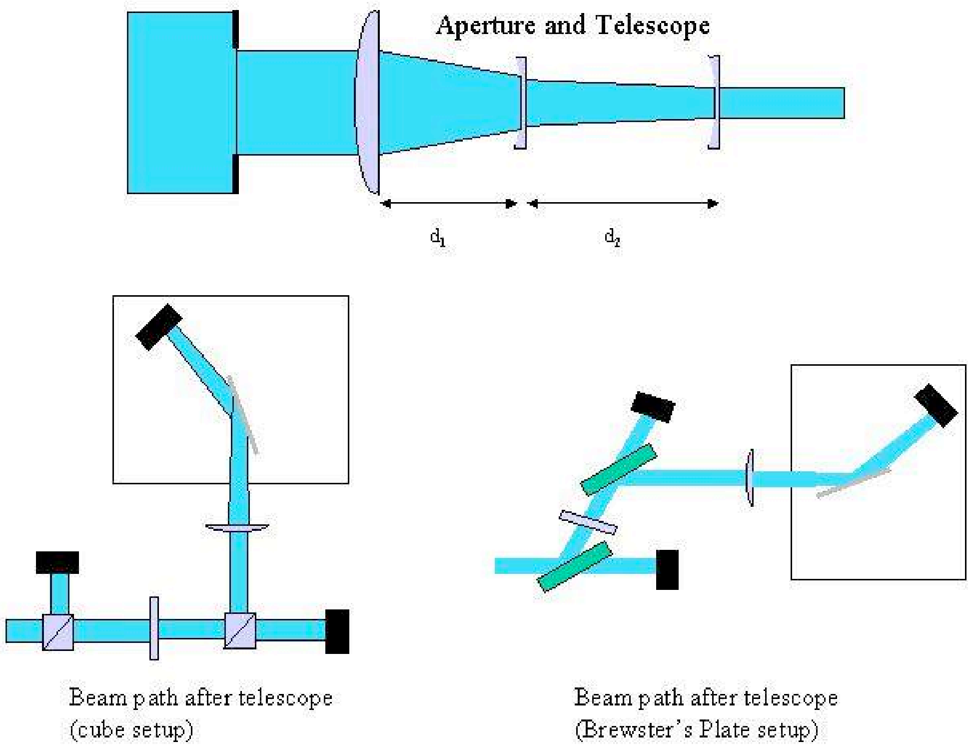


Figure 4. Beam path from the output coupler to the test piece using cubes or plate polarizers

Polarization of high-energy UV lasers can be accomplished with optically-contacted polarizing cubes or thin-film plate polarizers operated at Brewster's angle. In either case, the beam must be collimated at the polarizing optic and then focussed onto the test piece. In order to maintain a high total energy on target with affordable (*i.e.,* reasonably small) optics, we must compress the output of Electra from 1 J/cm^2 fluence to a value near the damage threshold – typically 3–5 J/cm^2 – using a telescope upstream of the polarizers.

Optical paths using both 1" cubes and 4" polarizing plates have been examined. (These optics cost approximately $1300 each and can be obtained in 4–8 weeks). The optical path changes only slightly between the two designs. Each setup will use a customized aperture to shape the beam to the needed dimensions, and to allow the correct amount of energy to pass into the optical train (total energy passed ~ 10-25 J).

Each polarizing method has advantages and disadvantages. The cube polarizer is easier to integrate into the system as compared to the Brewster plate. Brewster plates require careful alignment of the angle in order to get the maximum contrast in the polarization. Even with careful alignment the Brewster plates can only get a 100:1 ratio, were as a cube can get 200:1 without careful alignment. The Brewster plate system also requires the use of a 4" first lens, which must be custom made. A cube system would us a 3" lens, which is a stock item. In addition, the Brewster plate method requires using a large percentage of the clear aperture of all the lenses in the first telescope. A 1” cube would only require using a large percentage of the clear aperture of the first lens in the first telescope, limiting spherical abrasions. The advantage of the Brewster plate is that more energy can be utilized. A comparison of the energies and foot prints are shown in Figure 5. For the reasons described above, the use of 1” cubes has been selected as the polarization method. The test mirror will be aligned so that the beam is at an 85° incident angle. Figure 5 accounts for the fact that the footprint is ~10 times longer than if exposed at 0°.

After the first polarizing cube, a 1” half-wave plate in series with a second polarizing cube will be used as an attenuator. This allows for low energy cleaning shoots as well as precise control over the energy reaching the mirror. Each polarizing cube will require a beam dump to block the p-polarized light. These beam dumps will be fabricated at NRL, and be similar to the aperture described earlier.

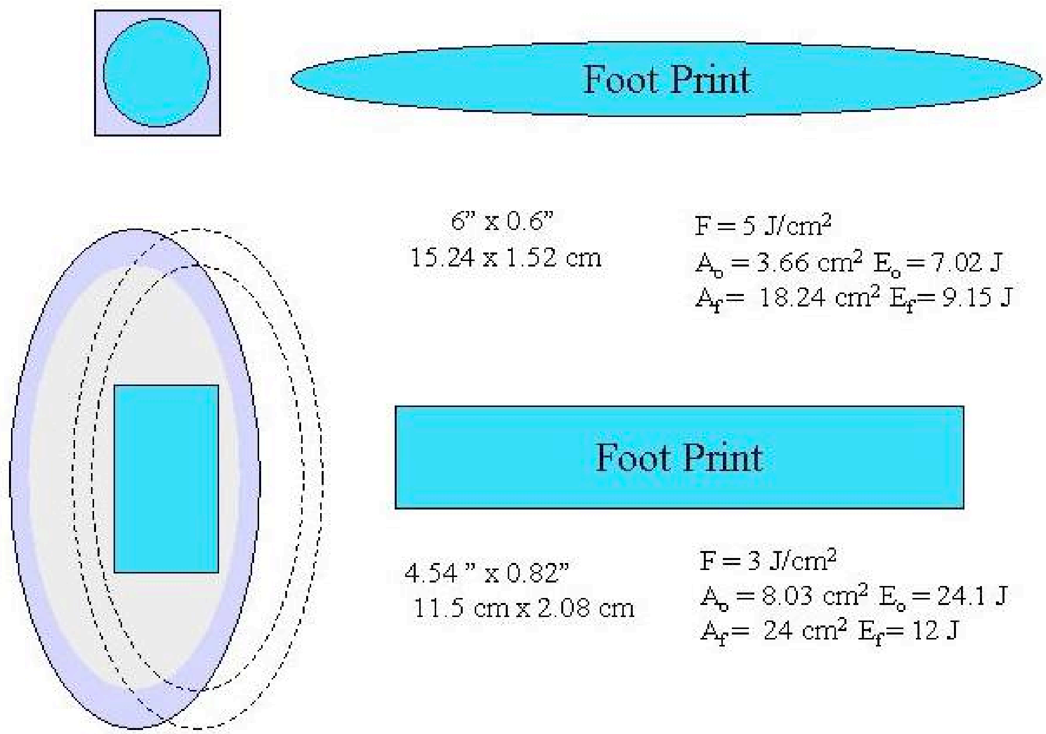


Figure 5. Comparison of footprint on the test article using cubes or plate polarizers. F = fluence at polarizer, A_o = beam area at polarizer, E_o = energy going into polarizer, A_f = area of footprint E_f = energy within the footprint

Second telescope. A second telescope will be made to focus and recollimate the beam after the polarizing optics. Only half of the laser energy entering the optical train will actually make it to the test mirror. There for it is necessary to focus the beam to the desired fluence (5-8 J/cm2). This telescope will consist of a 2”, f = 1 m, plano-convex lens and a 2”, f = -0.590 m, plano-concave lens, separated by a distance of 0.429 m. The effective focal length is ~ 29 m, and the fluence range at the mirror is around 8 J/cm2 with little variation over the length of the footprint. This allows for a less stringent alignment method than is currently used at UCSD.

Test mirror. The test mirror will be located in a vacuum chamber along with the second telescope. The mirror will be mounted on a standard post, which will be mounted on a translation and rotation stage. Each sample likely will have specific mounting requirements due to the difference in shape and substrate material. The sample will be placed approximately 0.5 m from the final lens in the second telescope at an incident angle of 85^o.

Optics protection. The high power laser optics from the first steering mirror up to the test chamber must be maintained in a clean condition. Dust and dirt can lead to distortions in the beam profile as well as possible laser-induced damage. Optics will be covered with plastic sheeting when they are not in use, and left open to the room during testing. All surfaces will be checked prior to testing and cleaned, if necessary, using compressed air and ethanol.

Test Specimen Enclosure

It is very important that the environment around the mirror be free of oxygen, hydrocarbons and other reactive molecules in order to prevent chemical reactions at the surface of the test mirror. This leads to the need for a chamber to enclose the test mirror during exposure. A steel vacuum chamber (the old "cell port adapter") will be used for this purpose (see Figure 6) It can be operated under vacuum or evacuated and backfilled with Ar.

A cryopump system will be attached to the NW200 port on the chamber. This may require the use of an 8" diameter elbow to prevent the cryopump from blocking the beam path. The laser beam will enter the chamber through a 2" UV window located near the pumping port. The beam will then be steered 90^o toward the second telescope and test mirror. Another UV window will allow the beam to exit the chamber after passing through the test mirror. A viewing port will be located directly across from the test mirror in a 4" flange (shown in Figure 3).

For experiments using an Ar backfill, a gas feed through valve will be attached to a NW50 port on the side of the chamber. This will require an Ar gas bottle with a regulator, as well as a gas line with all necessary fittings to connect to the regulator and feed through valve. The remaining ports should be covered with blanks.

The chamber as is will not serve as an adequate vacuum chamber. A lid and bottom must be made to complete the enclosure. The lid will need hooks that can support the weight of the lid. These hooks will be used to raise and lower the lid using the crane in the amplifier hall of Electra. The bottom of the chamber requires only that it be suitable for vacuum conditions and that it have an optical breadboard attached.

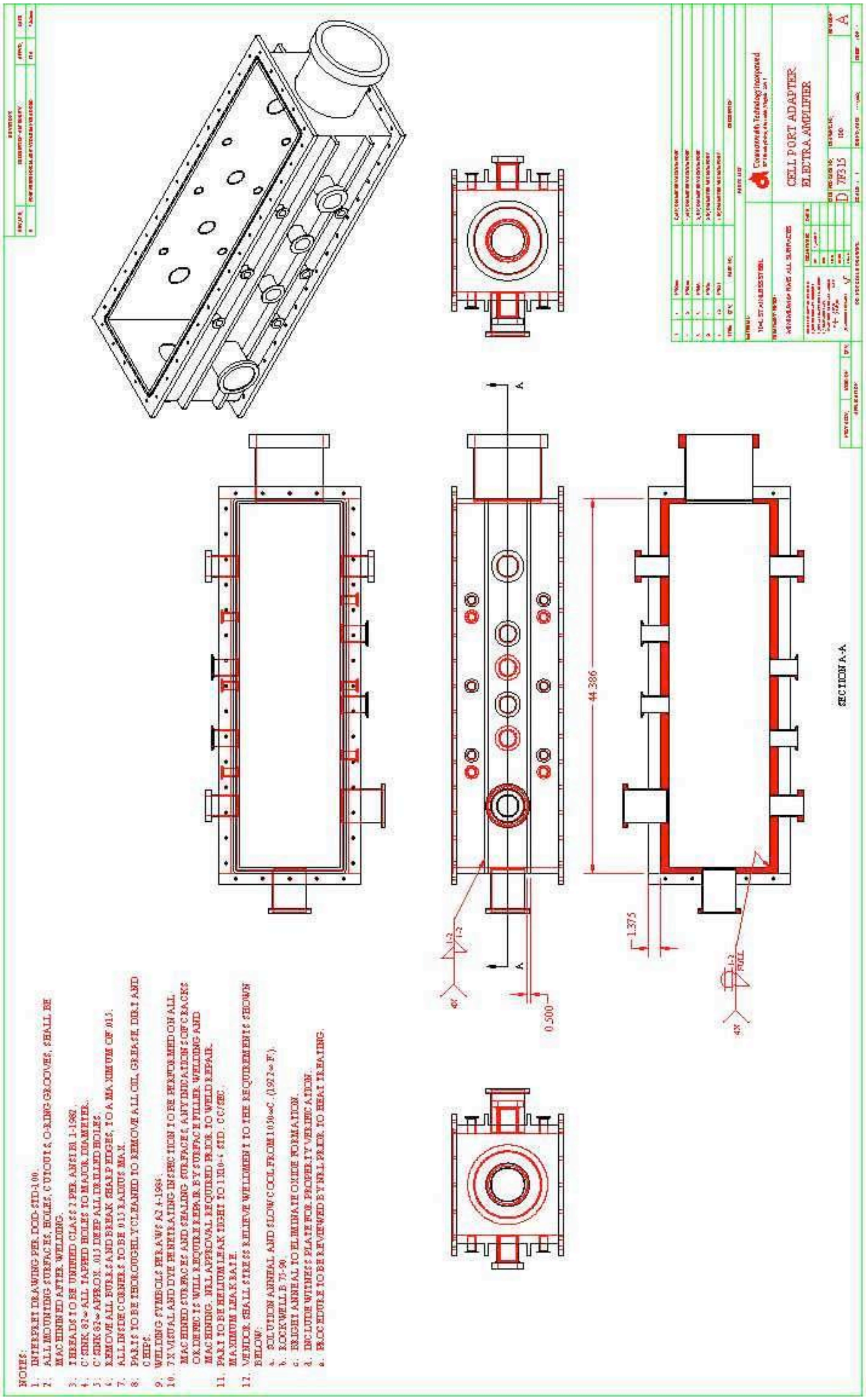


Figure 6. Test chamber drawing

Alignment Procedure

Optical path alignment procedure: We will pass the beam from a UV nanolaser (see Appendix C) through the optical system starting at the position of the test mirror and pointing up stream to the Electra beam path. All lenses and the half-wave plate will not be in place for this part of the procedure. The optics will then be aligned so that the beam will retrace its path back to the nanolaser using the rear reflector of Electra as a retroreflector. The lenses and half-wave plate can then be integrated into the system and aligned in the same way.

Test mirror alignment procedure: For rough alignment of the sample mirror, the nanolaser can be placed behind the second polarizing cube and aligned to follow the center of the beam path (see Figure 3). The sample mirror should be positioned at the correct distance (measured from the center of the sample) away from the final lens and rotated to the correct angle. The sample will then be positioned so that the nanolaser beam is centered on the mirror surface. Alignment does not have to as precise as the alignment at UCSD because of the long focal length of the second telescope. For example a change in the distance between the final lens and the sample mirror of 10 cm will only change the fluence by 0.06 J/cm^2. To ensure proper alignment, a seriget sample with burn paper glued to the surface will be used. Burn patterns will be taken to provide an accurate representation of the footprint on the sample mirror.

Test Procedure and Diagnostics

Prior to testing, the temporal and spatial profiles of the beam entering the enclosure will be measured. The full Electra energy will be measured inside the lead hut using a full-aperture sampler and a calorimeter. The temporal pulse shape can be obtained easily with a photodiode, provided an oscilloscope is available at NRL. The beam energy entering the vacuum chamber will be measured using a separate power meter. The spatial intensity profile will be obtained using a 2” StarTech UV imager connected to a 12-bit Dataray camera, which is operated through a PC running Windows XP. (Alternative methods for measuring spatial intensity profile should be sought using NRL equipment). For all beam diagnostics except energy measurements, beam sampling optics will be used. Pre-test beam characterization will be performed using single-shot operation so that personnel access is available to the optical path.

Each mirror that is tested will undergo an initial conditioning and cleaning procedure similar to the procedure currently used at UCSD. It consists of a series of single-shot or 1-Hz exposures starting at a low fluence, increasing to the final fluence of 8 J/cm^2. The fluence will be controlled by rotating a 1/2 waveplate manually. After the cleaning procedures, the mirror will then be exposed to a rep-rated (1–5 Hz) 8 J/cm^2 pulse for at least 1000 shots or until failure. The actual number of shots and rep rate will depend on the availability of the laser. Depending on the mirror geometry and availability of time, several locations may be tested on each mirror.

It is important that significant heating not occur during testing. For long-term exposures in vacuum, the temperature of test mirrors is monitored at UCSD using a thermocouple attached to the back of the mirror. However, the short exposure times and presence of Ar in the chamber will obviate the need for thermometry at Electra. Since the maximum total energy passing through the mirror is only 10 J per shot, 1% absorption will result in only 100 J total absorbed energy after 1000 shots. Assuming a 1-cm thick, 4” diameter mirror (~200 g), the adiabatic temperature rise would be only 1–2˚K.

The surface of the samples must be monitored in-situ in order to stop irradiation when damage first appears. This is accomplished by imaging the surface of the mirror during the laser pulse with a camera (see Figure 8). The camera detects a “hot spot” when damage occurs. It is important to be able to discontinue the experiment quickly when incipient damage occurs. Continued irradiation of a damaged optic can rapidly deteriorate the surface and prevent post-test inspection of the damage morphology.

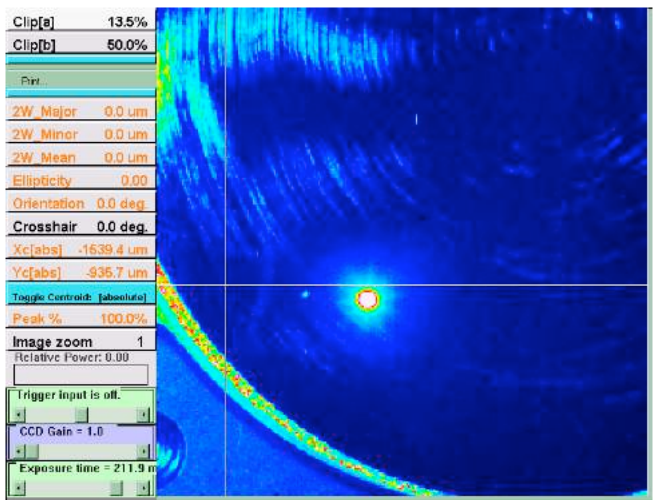


Figure 8. Example CCD camera image detecting surface damage during a laser pulse

Optical microscopy will be performed post-test to determine the mode and level of damage. This can be carried out at UCSD at the end of the testing campaign or by shipping the samples to UCSD during the testing campaign. It may also be possible, if facilities are available, to perform optical microscopy at NRL.

Optics and Equipment Inventory

Appendix A summarizes the optics and other equipment that will be needed to carry out these experiments.

References

1. M. Wolford *et al*. “Electra: A Repetitively Pulsed, 700 J, 120 ns, KrF Laser,” High Average Power Laser Program Workshop, 5-6 February 2004, Georgia Institute of Technology.

Appendix A: Parts List

Optics

Qty	Description	Provider	PN	Vender
2	1" High power UV polarizing cube beamsplitter	UCSD	HPB-25.4U	Lambda
1	1" UV 1/2 waveplate	UCSD	WPRM-38.1-30.0CQ-M2	Lambda
1	2" Plano-convex spherical UV lens f = 1 m	UCSD	PCX-50.8U-1000	Lambda
1	2" Plano-concave spherical UV lens f = -0.4916m	UCSD	PCC-50.8U-250	Lambda
1	2" Plano-concave spherical UV lens f = -0.7866m	UCSD	PCC-50.8U-400	Lambda
1	2" Plano-concave spherical UV lens f = -0.590 m	UCSD	PCC-50.8U-300	Lambda
1	3" Plano-convex spherical UV lens f = 0.507 m	UCSD	PLCX-76.2-257.5-UV-248	CVI
2	Aperture (custom)	NRL	-	-
3	Beam dump	NRL	-	-
1	4" 45 deg UV mirror	NRL	-	-
1	Beam sampler	UCSD	BS1-248-10-1525-45-S	CVI
1	1.5" 45 deg UV mirror (3 J/cm2)	UCSD	KRF-1537-45-S	CVI
2	2" periscope mirrors	UCSD	-	-

Mounts

Qty	Description	Provider	PN	Vender
1	Periscope post and kinematic mirror mounts	UCSD		
20	Post base	UCSD	BA2	Thorlabs
3	Magnetic base	UCSD	MB175	Thorlabs
15	Post 3"	UCSD	TR4	Thorlabs
15	Post holder 3"	UCSD	PH3-ST	Thorlabs
4	Post 2"	UCSD	TR2	Thorlabs
4	Post holder 2"	UCSD	PH2-ST	Thorlabs
1	Post 1.5"	UCSD	TR1.5	Thorlabs
1	Post holder 1.5"	UCSD	PH1.5-ST	Thorlabs
5	Lens mounts	UCSD	VLH-3A	Newport
2	1" Cube mount	UCSD	KM100P	Thor
?	Mount for non-standard test optics (vendor)	UCSD	-	vendors
2	X translation stage	UCSD	PT1	Thorlabs
1	Rotation stage	UCSD	CR1	Thorlabs
1	Rotation Stage For 1" Optics	UCSD	RSP1	Thorlabs
1	4' x 8' optical table (approximate)	NRL	-	-
1	"Steering mirror" table (including telescope?)	NRL	-	-
1	mag base for steering mirror	UCSD	-	-
1	Box of 1/4-20 screws 1"	UCSD	NT55-176	Edmund
1	Box of 1/4-20 screws 3/4"	UCSD	NT55-177	Edmund
1	Box of 1/4-20 screws 1/2"	UCSD	NT55-175	Edmund

Diagnostics

Qty	Description	Provider
1	2" Beam profiler (WinCam, StarTech, board)	UCSD
1	PC for running WinCam software	NRL??
1	248 nm filtered Photodiode and other photodiodes	NRL
1	Imaging camera	NRL
1	10x Optical microscope	UCSD
1	Surface analysis lab	NRL??
1	Power meter	NRL
1	50 MHz oscilloscope and cable	NRL

Chamber

Qty	Description	Provider		
1	Gas feed thru valve	NRL		
1	Ar gas w/ regulator	NRL		
1	Gas tubing w/ connectors	NRL		
1	Vacuum Chamber	NRL		
1	Roughing pump	NRL		
1	Cryopump and Compressor	NRL		
1	Gate valve	NRL		
?	Flanges and O-rings / Gaskets	NRL		
2	UV window 2"	NRL	450028	MDC
1	4" view port	NRL	450013	MDC
1	10 x 12 Al bread board	NRL	MB1012	Thorlabs
1	Kinematic Breadboard Seats	NRL	KBS98	Thorlabs

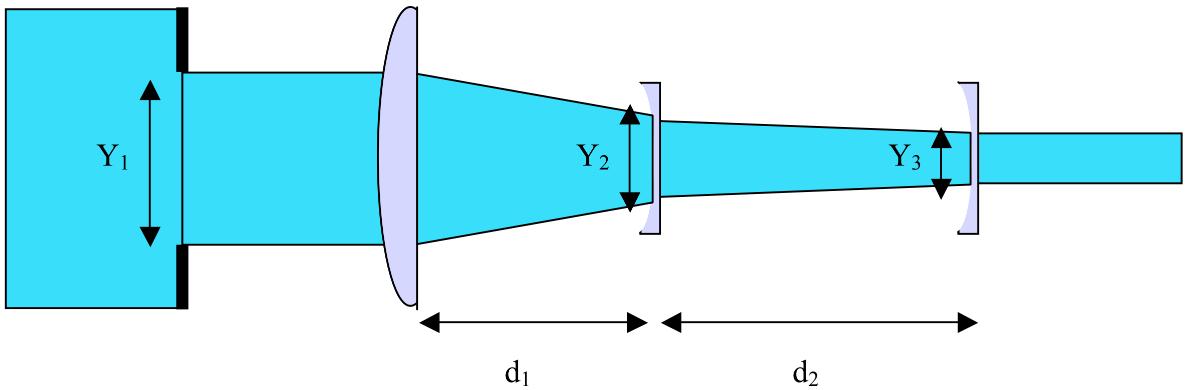
Test Specimens

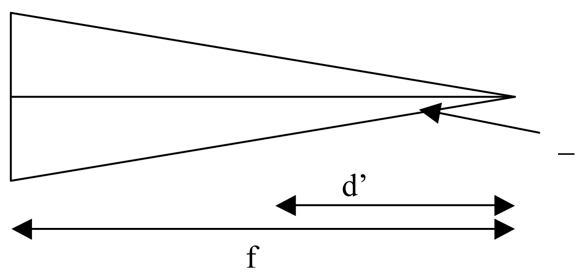
Qty	Description	Provider
2	"Al on Al6061" test specimens (4-6")	UCSD
?	2" round diamond-turned alumiplated optics	UCSD
?	Schafer test specimens, MER test specimens	UCSD
1	Blank (for burns)	UCSD

Supplies

Qty	Description	Provider
1	Ethanol	NRL
1	Package of lens paper	NRL
1	Box of large latex gloves	NRL
2	Canned air	NRL
1	Box of plastic bags (to cover optics)	NRL
1	Meter stick (ruler)	NRL
1	Roll of burn paper	UCSD
1	Glue stick	UCSD

Appendix B: Telescope Calculations





$$\frac{Y_1}{2f} = \tan\theta \qquad \frac{Y_2}{2d'} = \tan\theta \qquad d_1 = f - d' \qquad d_1 = f\left(1 - \frac{Y_2}{Y_1}\right)$$

d_1 is calculated such that Y_2 is 1.1 times Y_3. Likewise d_2 is calculated so that Y_3 is the desired dimension of the beam at the polarizing optic. The focal length of two concave lenses are chosen so that d_1 and d_2 are resonable distances using the equation below.

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

f is the effective focal length, f_1 and f_2 are the focal lengths of the two lenses in question, a d is the seperation of the two lenses.

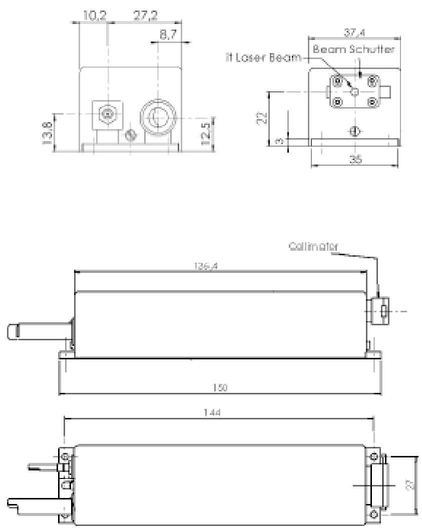
Appendix C: UV nanolaser (see spec sheet)

MicroChip NanoUV™ 266 lasers

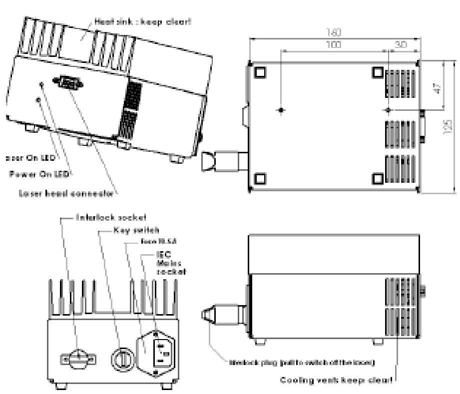
CDRH Package

Ultraviolet passively Q-switched Microchip lasers, λ = 266 nm

Laser Head NU-10210-100



Power Supply PS-0140x-400



System model: NU-0021x-100

	Specifications
Output Performance	
Power	2 mw
Pulsewidth	< 600 psec.
	0.5 ns typical
Repetition rate	6KHz - 10KHz
Wavelength rejection	$<10^{-4}$ @ 808, 532 nm
	$<10^{-3}$ @ 1064 nm
Beam Quality	
Beam profile	Near Gaussian
Beam size	< 0.5 x 0.5 mm
Beam divergence full angle	<3 mrad
Horizontal	< 1 mrad
Vertical	> 100:1, Vertical
Polarization	
Beam position	
Beam height	22 mm
Static alignment	± 0.5 mm
Angular tolerance	± 5 mrad
Pointing Stability (1 hr)*	
Peak to peak Horizontal	< ±300 µrad
Vertical	< ±75 µrad
At σ Horizontal	< ± 75 µrad
Vertical	< ± 20 µrad
Power stability*	
Short term (10 min)	< ± 1% , <±0.2 % at σ
Long term (1 hrs)	< ± 5% , <± 1% at σ
Temperature	
Operating	Laser head base-plate must be kept between 15 C and 35 C
Storage w/o humidity	+10 C, + 50 C
Dimensions (LxWxH)	
Head	153 x 36 x 31 mm
Power supply	160 x 125 x 97 mm
Weight	
Head	350 g
Power supply	2.2 kg
Class	IV

*For ambient ΔT< ± 3 C and < 3 C/hour, detector band [DC, 5Hz]

NanoUV lasers exist in various voltage, select your voltage to define the appropriate complete reference :
100 V AC or 115 V AC : select x = 1 , 230 V AC : select x= 2

Note: The power supply drawing is actually the model PS-012X-100, the model PS-012X-400 for the NU laser is slightly different.

JDS Uniphase