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Grazing Incidence Metal Mirrors as the Final Elements in a Laser Driver for Inertial Confinement Fusion

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Abstract

Grazing incidence metal mirrors (GIMMs) have been examined to replace dielectric mirrors for the final elements in a laser beam line for an inertial confinement fusion reactor. For a laser driver with a wavelength from 250 to 500 nm in a 10-ns pulse, irradiated mirrors made of Al, Al alloys, or Mg were found to have calculated laser damage limits of 0.3-2.3 J/cm^2 of beam energy and neutron lifetime fluence limits of over 5×10^{20} 14 MeV n/cm^2 (or 2.4 full power years when used in a 1,000-MW reactor) when used at grazing incidence (an angle of incidence of 85 degrees) and operated at room temperature or at 77 K. A final focusing system including mirrors made of Al alloy 7475 at room temperature or at liquid nitrogen temperatures used with a driver which delivers 5 MJ of beam energy in 32 beams would require 32 mirrors of roughly 10 m^2 each. This paper briefly reviews the methods used in calculating the damage limits for GIMMs and discusses critical issues relevant to the integrity and lifetime of such mirrors in a reactor environment.

1 Introduction

A 5-MJ laser producing a 1000-MJ thermonuclear yield will result in approximately 3.6×10^{20} 14 MeV neutrons per shot; at a distance of 50 m from the target this corresponds to a fluence of 1.1×10^{12}n/cm^2 for each shot. Since the last focusing or turning element of each beam cannot be shielded from these neutrons, it must be made of a material which can withstand the lifetime fluence associated with these radiation levels. Figures 1 and 2 diagram an inertial confinement fusion (ICF) laser driver whose use of metal mirrors[1] allows the more sensitive optical elements to be located out of direct line-of-sight of the neutrons. In this geometry, the metal mirror is located 30 m from the target, and the dielectric mirror is 20 m behind the GIMM and 10 degrees removed from the direction of line-of-sight neutrons. Neutron transport calculations indicate that this geometry provides the more sensitive optical components with a sufficiently reduced neutron exposure to ensure an affordable component lifetime.

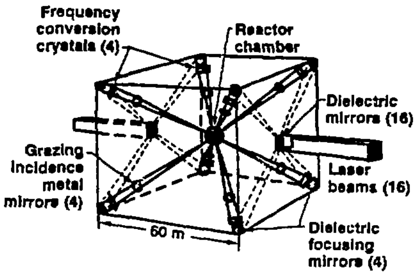

Figure 1. Spaceframe for an ICF reactor with a laser driver.

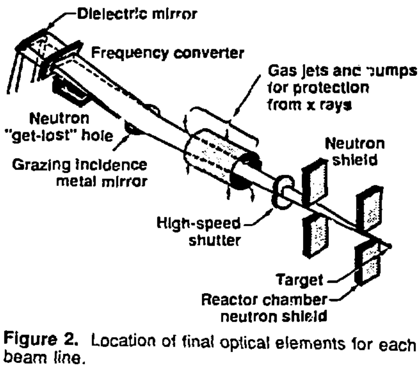

Figure 2. Location of final optical elements for each beam line.

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2 Protection of Sensitive Optics

Neutron transport calculations have been done to address several issues concerning how effectively the GIMMs shield the remaining optical elements of the driver[2]. The calculations include the neutron flux, spectrum, and energy deposition for the GIMM, the dielectric turning mirror, a KDP nonlinear optic crystal (if required for frequency conversion), liquid nitrogen to cool the mirror (if low temperature operation is required), and 1 Torr-meter of argon used to attenuate soft x-rays. The implications for the activation of beam-line components were also examined.

2.1 Effect of Neutrons on Multilayer Dielectric Mirrors

Neutron radiation can destroy dielectric multilayer mirrors by degrading the optical transmission of the dielectric layers, by chemical decomposition of the dielectrics, or by destroying the boundaries between layers. Transmission degradation data is sparse, but measurements[3] for MgF_2 and ZnS show an order-of-magnitude degradation in absorption or transmission after 10^{16}n/cm^2 (or about 1 hour of operation for an unshielded dielectric 50 m from a 1,000-MWe reactor) for wavelengths of interest (250–500 nm). This damage may be removable through continuous annealing, and dielectrics may exist which have color centers far removed from wavelengths of interest. Unfortunately, even if there is no loss of transmissive properties, the multilayer mirror can still be compromised by neutron damage. All ionic dielectrics will undergo significant radiolysis[4], radiation-induced chemical decomposition, after energy depositions of about 1 eV/atom, or 5×10^{17}n/cm^2 for MgF_2; a few eV/atom energy depostion is also enough to cause significant amorphization in SiO_2. For dielectric materials which are more resistant to damage, chemical mixing at the interfaces will still be a problem. Any collisional cascade at an interface will cause mixing of the two dielectrics and create a thin, possibly amorphous, third phase region with unknown optical properties. Collisional mixing at the boundaries will occur over a thickness of roughly 3 nm/(DPA)$^{1/2}$ (1 DPA $\simeq 5\times10^{20}$ 14MeV n/cm^2 for most dielectrics, which corresponds to about 1 full power year for a 1,000-MWe plant), and enhanced diffusion will cause mixing over a thickness of roughly 30 nm/(DPA)$^{1/2}$[5]. If the very existence of a third phase does not destroy the optical properties of a multilayer mirror, a change of thickness of only $\lambda/16$ in a $\lambda/4$ layer will destroy the constructive interference required for high reflectivities. Under the most optimistic assumptions the best conceivable unshielded multilayer mirror would probably only last a fraction of a full power year.

2.2 Results of Neutron Transport Calculations

Neutron flux
The results of the TART 3-D neutron transport code indicate that the neutron flux at the final optics is almost entirely from neutrons that shine directly on the GIMM. There will be significant contributions to the flux at the final turning mirror (and frequency converter if present) from scattered 14-MeV neutrons and from lower energy backscattered neutrons; less than 10% of the neutrons arriving at the sensitive optics will have energies $\geq$ 1 MeV. There is little or no data on neutron damage to dielectric mirrors, but if we make the conservative assumption that a multilayer mirror with no color centers will have a lifetime fluence limit of $10^{17} - -10^{18}$ neutrons/cm^2 for neutrons with energies above 1 MeV, we can estimate the lifetime of a dielectric mirror. The total neutron flux at the turning mirror and the frequency converter, if present, is $1 - 2 \times 10^{10}$ neutrons/(cm^{2}s). Since only 10% of these have energies above 1 MeV, the lifetime of the sensitive optics will be from 2–20 years. If there were no GIMM, the flux at a turning mirror 50 m from the target would be 10^{12} n/cm^2 and consist almost entirely of high energy neutrons; this flux would give a lifetime of only 1 day under our damage assumptions.

Activation
Because of the activation of Al and Mg, the mirrors will have to be within a shielded area. A Mg mirror would require 17 days of cool-down before it could be worked on; an Al mirror would require remote or limited maintenance because of the long lived Al^{26} that is formed after 10 days of operation. Waste disposal and accidental release are not a problem if the metal mirrors are replaced every 1–2 years.

3 Laser Damage Thresholds for GIMMs

3.1 Reflectivities and Absorptances of Grazing Incidence Metal Mirrors

The reflectivity of a conducting metal is a function of the wavelength and polarization of the incident light and the angle at which the light strikes the surface of the metal. Since laser drivers include polarization, we can

Table 1. Calculated resistivities, laser damage thresholds, and mirror sizes for grazing incidence metal mirrors.

Metal	Mg	Mg	Al 1100	Al1100	Al 6061	Al 6061	Al 7475	Al 7475
Operating temp. (K)	293	77	293	77	293	77	293	77
Fatigue stress (MPa)	34	80	43	140	180	310	290	395
Surface temp. rise (K)	23	75	19	90	75	158	110	185
R (G.I.)	0.9934	0.9941	0.9933	0.9940	0.9930	0.9937	0.9929	0.9936
R (G.I.) after irradiation	0.9899	0.9900	0.9898	0.9899	0.9895	0.9896	0.9894	0.9895
Max. beam energy (J/cm)	0.34	0.65	0.39	1.01	1.29	1.65	1.88	2.26
Min. mirror area (m)	47	24	40	15	12	9.4	8.3	6.9

orient the mirrors so that the incident light has the polarization (transverse electric) which produces the highest reflectivity. The reflection coefficient for a transverse electric (TE) polarized wave is given by [6]:

$$r_{12} = (n_1 \cos\theta_1 - n_2 \cos\theta_2)/(n_1 \cos\theta_1 + n_2 \cos\theta_2)$$

where θ_i is the angle of incidence of the light in medium i. For a conductor, $n_2 \cos\theta_2 = u + iv$,and the reflectivity is given by

$$R = |r_{12}|^2 = \frac{u^2 + v^2 - 2u\cos\theta_i + \cos^2\theta_i}{u^2 + v^2 + 2u\cos\theta_i + \cos^2\theta_i}$$

for

$$2u^2 = (n^2 - k^2 - \sin^2\theta_1) + [(n^2 - k^2 - \sin^2\theta_1)^2 + 4n^2k^2]^{1/2},$$

$$2v^2 = -(n^2 - k^2 - \sin^2\theta_1) + [(n^2 - k^2 - \sin^2\theta_1)^2 + 4n^2k^2]^{1/2}$$

where n and k are the frequency dependent refractive index and extinction coefficient of the metal.

The undamaged grazing incidence reflectivities for Al and Mg calculated from experimental values for n and k for 250 nm light are shown in Table 1. The dependence of the grazing incidence reflectivities on photon energy is shown in Figure 3.

3.2 Radiation Damage to Metal Mirrors

Successful operation of a magnesium or aluminum mirror located 30 m from a 1000-MJ, 3-Hz pellet is theoretically possible. The mirror must be shielded from α particles, other charged particles, short-ranged neutral particles, macroscopic pellet debris, and x-rays. For high ρR targets, less than one torr-meter of argon provides sufficient shielding for everything except the slow-moving pellet debris, which must be stopped by a high-speed shutter. Neutron damage will increase the optical absorptance by a factor of at most two, thus lowering the laser-damage threshold by a factor of approximately two. Overall swelling, melting, vaporization, surface erosion, creep, and dimensional and mechanical instability, as well as increased absorptance from transmutation products and neutron-induced defects, are expected to be tolerable.

Neutron radiation can compromise the first mirror in three ways:

1) The laser damage threshold may be lowered by increased resistivity of the metal due to defects, transmutations, and surface roughening on an atomic scale.

2) The laser damage threshold may be lowered by increased absorptance of the mirror due to microscopic surface roughening.

3) The focusing of the mirror can deteriorate due to macroscopic distortions from swelling or creep of the mirror and support structure.

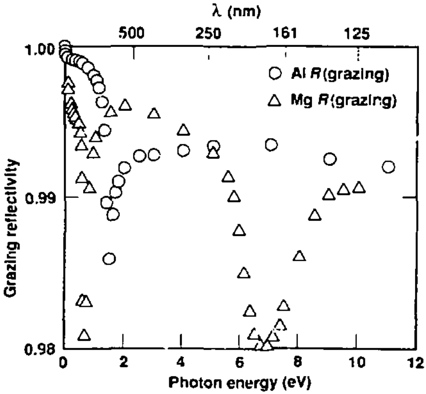

Figure 3. Grazing incidence reflectivity versus photon energy.

The first effect raises the normal incidence absorptance by 1% and the grazing incidence absorptance by 0.5%; in both cases a contribution to the absorptance of 0.35% is due to the anomolous skin effect resulting from roughening of the surface on an atomic scale.

Damage from the second effect is negligible. The total sputtering from neutrons[7] and scattered argon[8] will be only 30 nm/year, with the variance in the surface due to sputtering considerably smaller.

The third effect will be lifetime limiting for a room-temperature mirror, but will not be a concern for a cryogenic mirror made of Al or Mg. There will be negligible saturation swelling or creep in an Al or Mg mirror at cryogenic temperatures since the vacancies are immobile and saturation occurs. If the 7 m × 1.8 m final mirror is conservatively limited to nonuniform swelling differences of $\lambda/4$, the allowed volumetric swelling is 1.5% and the resulting lifetime fluence limits for 14-MeV neutrons for room-temperature mirrors made of pure Al, pure Mg, and Al 7475 are 2.5×10^{20}, 8×10^{19}, and 5×10^{20} n/cm^2 respectively. The corresponding mirror lifetimes in a 1,000-MWe plant are 1.2, 0.4, and 2.4 full power years.

3.3 Laser Damage Limits for Irradiated Metal Mirrors

The reflectivities for the damaged mirrors are used with thermal stress limits for a cyclic load to give the maximum allowable beam energy density and corresponding minimum mirror size for each of 32 beams delivering a total of 5 MJ of beam energy in 10 ns. The resulting damage thresholds and mirror sizes are shown in Table 1.

4 Critical Issues and Areas for Further Work

From considerations of neutron damage, reflectivity, heat removal, and surface temperature rise, grazing incidence metal mirrors appear to be very attractive. The most crucial future work needed to verify the integrity of these mirrors includes:

- Experimental verification of laser damage thresholds

  A small-scale experiment could be done with small undamaged mirrors to verify the calculated normal and grazing incidence reflectivities and to measure the effect of oxide coatings on reflectivity for each of the candidate metals. The effect of an oxidation layer on the normal incidence 353 nm reflectivity of Al or Mg is small (a fraction of a percent) or nonexistant, but the effect may be larger for grazing incidence. A Los Alamos study of Al grazing incidence mirrors[9] showed significant degradation of the relectivity for light with wavelengths below 100 nm.

- Experiments with irradiated mirrors:

  The laser damage experiments could be repeated with small irradiated samples to verify the effects of neutron irradiation on the laser damage threshold. Although it may be difficult to get a sufficient source of 14 MeV neutrons, fission reactor irradiations could be used and the results scaled with total damage energy.

- Protection of the final mirror from debris and x-rays

  Even if the heat loads on a perfectly smooth and clean mirror are low enough to avoid surface vaporization, a particle or surface defect on the mirror surface would be exposed to the full normal incidence beam energy and could cause explosive "pitting" of the mirror surface. Accumulation of material (target debris, Flibe, or other coolant/breeder materials) from the reaction chamber on the mirror surface must be prevented. Gas jets used for protection from x-rays will not provide sufficient protection from high-velocity debris. There is a need for a high-speed mechanical shutter[10] to protect the mirror. Both the gas and shutter systems require significant design work before their effectiveness can be judged.

- Development of techniques for cleaning the final mirrors

  If a combination of high-speed shutters and gas jets can protect the mirror surface from damage but cannot keep it clean, it may be possible to remove accumulated material from the mirror surface between shots. A possible technique would be to vaporize the contaminants with a lower energy beam between shots.

- Manufacturing studies for large high-quality mirrors

  Large-scale high-quality mirrors can be manufactured, but the cost of producing 10-m^2 mirrors with surfaces finished to 10's of nm's may be prohibitive.

  Other concerns that are independent of future mirror work are:

- The effect of large mirror cooling requirements on system efficiency

  The energy required to cool a room-temperature mirror is not large, but cooling a cryogenic mirror could require enough energy to significantly affect the plant power balance. Removing 1% of the total beam power from the final mirrors at 77 K could require 10's to 100's of MWs of recirculating power. Since low laser-driver efficiencies are a critical problem, the cost of additional recirculating power may be unacceptable.

- Nonuniform beam intensity

  Nonuniform beam intensity could force the use of larger mirrors. Multiplexed beams from KrF lasers will not only have nonuniformities, they will also be coming from different angles of incidence. The best achievable peak-to-average power ratios at the final amplifier of Nova are typically 1.4–1.6. Streak camera profiles of a Nova beam immediately after polarization and frequency conversion show a lower peak-to-average power ratio, with spike widths on the order of a millimeter. Transverse heat flow and stress release during a 10-ns shot in the mirror can only average out nonuniformities over distances of a micron or less, so peaks wider than a micron will lead to local failure unless a larger mirror is used. Beam nonuniformity grows as the beam converges, so nonuniformities at the mirror will be worse than those after the final focusing or conversion element.

- Brightness requirements for KrF lasers may require a minimum solid angle illumination which would correspond to mirrors much larger than those which are damage limited. A required total illumination solid angle of 0.04π steradians would require a grazing incidence mirror size of $40 m^2$ for each mirror in a 32-mirror system.

5 Conclusions

Preliminary calculations indicate that grazing incidence metal mirrors appear to offer a solution to the critical problem of neutron damage to beam line components. A final mirror made of Al alloy could be used for 2.4 years at room temperature before replacement and for much longer times at 77 K. Larger mirrors made of pure Al or Mg could also be used at 77 K. Although there are important concerns which have yet to be investigated, metal mirrors may provide a solution to the crucial problem of how to interface a laser driver with an ICF reactor. Solving this problem is essential if lasers are to be credible driver candidates for ICF power plants.

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References

[1] R. L. BIERI and M. W. GUINAN, "An Analysis of Grazing Incidence Metal Mirrors in a Laser ICF Reactor Driver,"UCRL-JC-106094,Lawrence Livermore National Laboratory preprint (1990).

[2] M. TOBIN and R. BIERI. "Analysis of the Grazing Incidence Metal Mirror (GIMM) Concept for HYLIFE-II," internal LLNL HYLIFE-II memo (1990).

[3] M. J. WEBER. *Handbook of Laser Science and Technology*, Vol. III, Optical Materials: Part 1, 336 and 366, CRC Press, Inc. (1986).

[4] F.W. CLINARD, JR., and L. W. HOBBS, "Radiation Effects in Non-Metals," in *Physics of Radiation Effects in Crystals*, 225-280, Eds. R.A. Johnson and A.N. Orlov, North Holland, Amsterdam (1986).

[5] H. WIDERSICH, "Phase Stability and Solute Segregation during Irradiation," ibid, 387-471.

[6] R. KINGSLAKE, Ed., *Applied Optics and Optical Engineering*, Vol. III, Optical Components, 317, Academic Press, N.Y. and London (1965).

[7] O. K. HARLING and M.T. THOMAS in *Proceedings of the 2nd Topical Meeting on Technology of Controlled Nuclear Fusion* (USERDA Report CONF-760935-P1) Vol. 1, 149-167, (1976).

[8] H. H. ANDERSEN and H. L. BAY, in *Sputtering by Particle Bombardment I, Topics in Applied Physics, 47*, ed. R. Behrisch, 167-168, Springer-Verlag, Berlin (1981).

[9] B.E. NEWNAM, "Multifacet Metal Mirror Design for Soft X-Ray and Extreme-Ultraviolet Free-Electron Laser Resonators," in *Laser Induced Damage in Optical Materials: 1985*, H.E. Bennett, A.H. Guenther, D. Milam, and B.E. Newnam, Eds., (Natl. Bur. Stand., Washington D.C.), NBS Spec. Publ. 746, 261-269, 1988.

[10] D. G. NILSON and J. G. WOODWORTH, "Final Optic Protection Designs for ICF Containment Chambers," in *Proceedings of the Eigth Topical Meeting on The Technology of Fusion Energy*, Salt Lake City, Utah (1988).