Grazing incidence liquid metal mirrors (GILMM) for radiation hardened final optics for laser inertial fusion energy power plants*

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Abstract

A thin film of liquid metal is suggested as a grazing incident mirror for robust final optics in a laser inertial fusion energy (IFE) power plant. The amount of laser light the GILMM (grazing incidence liquid metal mirror) can withstand, called the damage limit is limited by the surface disturbances initiated by rapid laser heating. For 0.35 µm light, the damage limit for a sodium film 85° from normal is calculated to be 57 J/cm^2 normal to the beam for a 20 ns pulse and 1.3 J/cm^2 for a 10 ps pulse (2 m^2 and 90 m^2 of mirror area per 100 kJ of laser energy at 20 ns and 10 ps, respectively). Feasibility relies on keeping the liquid surface flat to the required accuracy by a combination of polished substrate, adaptive (deformable) optics, surface tension and low Reynolds number, laminar flow in the film. The film's substrate must be polished to ±0.015 µm. Then surface tension keeps the surface smooth over short distances (<10 mm) and low Reynolds number laminar flow keeps the surface smooth (disturbances less than ± 0.01 µm) over long distance >10 mm. Adaptive optics techniques keep the

substrate flat to within ± 0.06 μm over 100 mm distance and ±0.6 μm over 1000 mm distances, even after 30 years of cumulative damage via neutron irradiation. The mirror can stand the x-ray pulse when located 30 m away from the microexplosions of nominal yield of 400 MJ (50 MJ of X rays) when Li is used, but for higher atomic number liquids like Na there may be a significant temperature rise, forcing use of other x-ray attenuation methods such as attenuation by xenon gas. The GILMM should be applicable to both direct and indirect drive and pulse lengths appropriate to slow compression (~20 ns) or fast ignition (~10 ps). For direct drive laser beams near the poles (70°, where 90° is vertical), stable thin films become more challenging. Proof of concept experiments are needed to verify the predicted damage limit and required smoothness.

1.0 Introduction

Metal mirrors have long been used in optics but for wavelengths of interest for laser IFE of 0.25 to 0.35 μm, grazing incidence (≈85° to normal) is needed to reduce energy absorption. Bieri[1] analyzed a grazing incidence metal mirror (GIMM) and found aluminum could handle 18 J/cm^2 normal to the beam, which is 1.5 J/cm^2 on the plane of the mirror. His design was used for the Prometheus[2] (Fig. 1) and Sombrero[3], laser IFE power plants studies. Sombrero had mirrors at 6° grazing at 30 m distance. The normal cross section of

1 m x 0.43 m required a mirror 1 m wide and 4.1 m along the slope direction. There were 60 beams totaling 3.6 MJ or 60 kJ/beam. The 60 kJ over 4.1 m^2 gave an intensity of 1.5 J/cm^2 on the film (14 J/cm^2 normal to the beam). At 50 m, the distance to the first conventional optics, the 14 J/cm^2 drops to 5 J/cm^2 —the damage limit of conventional optics such as dielectric layers. A problem, however, with the designs is that mirror surface flaws as small as ~1 μm "looks" locally like normal incidence (~14 J/cm^2) which far exceeds the damage threshold of 1.5 J/cm^2. That is, local absorption of heat would cause a small flaw to grow from shot to shot quickly leading to failure. If the surface were composed of a thin liquid metal film (grazing incidence liquid metal mirror or GILMM), surface imperfections would heal due to surface tension and replenishment by fresh flowing liquid. The surface must flow slowly enough so that no shear flow instabilities cause surface ripples. Liquid metals (mercury) have already found application in telescopes based on a thin (~1 mm thick), 2.7-m diameter slowly rotating pool supported on an air bearing to form a parabolic mirror[4]. More detailed discussion of GILMM can be found in Moir[5].

The second optical element which is out of the line of sight of the microexplosion can be of conventional optics design, e.g. dielectric coatings or refractive or diffractive SiO_2. An alternative concept for final optics is use of SiO_2 operated so hot (~400° C) that damage is annealed continually, Marshal, Speth and Payne[6] and can withstand up to 30 J/cm^2. It is not known how long such materials can continue to serve as quality optics. GILMM appear to be a complete solution to the final optics, being radiation hard to both neutrons and x rays, having long service life of >30 years and probably acceptable cost while being able to deliver high quality laser light to the target. Another application of GILMM might be final optics in laser fusion propulsion of space craft, Orth[7]. In space a slowly rotating set of GILMMs can function as discussed in this paper.

2.0 Optical System layout

Typical final optics (in the Prometheus, [2] design) are shown in Fig. 1. The angle of the beam lines (where 0° is horizontal and 90° is vertical) is up 67° in [3]. In the upper half of the chamber the mirrors are 5° steeper so are sloped up to 72°, in the lower half, the mirrors are sloped 5° less steep so are sloped up to only 62°. The distance to the final optics is 20 m in Fig. 1 [2] and 30 m in [3]. For our examples we will use 30 m as well.

A schematic of GILMM is shown in Fig. 2. The surface shape is controlled by methods of adaptive optics where servos turn a screw connected to a spring in order to vary a force pushing or pulling at as many places as necessary on the back of the mirror. The adaptive optics are intended to correct for changes in shape over minutes, hours or longer; however, with piezo-electric transducers, beam pointing from shot to shot can be accomplished if needed in times of <0.1 s. The liquid is fed in at the top of the inclined plane with care so that the feed rate is constant across the mirror and disturbances are minimal. The liquid must wet the surface at all times. If dry out occurs for some reason, vapor deposition methods could be used to recoat, however, this would require a short plant shut down which should be avoided if at all possible and therefore is a serious concern that will need research. The servos and robotics for the GILMM can be out of line of sight of neutrons and x rays. The first and only structures to “see” uncollided neutrons will be the GILMM at 30 m distance from the shot point.

3.0 Damage limit theory and choice of liquid metal

The light pulse on the surface causes a temperature rise until some effect sets a limit, which we will call, the damage limit light flux, in J/cm^2. The reflectivity, R, is calculated (Moir[5]) and examples are shown in Fig. 3. At grazing incidence (10° or less) the value can range from 93% to 98% depending on the liquid metal. The remaining light will be absorbed and heat the liquid metal surface. The temperature rise at the surface, •T is given in Eq. 1 and is the solution to the transient conduction heat transfer equation.

$$\Delta T = \frac{2(1-R)q_{beam}}{k}\left(\frac{\alpha_T t}{\pi}\right)^{1/2} \qquad (1)$$

Where α_T is $k/\rho c$, q_{beam} is the power density of the optical beam on the metal surface, t is the time duration of the pulse, ρ is the density of the metal, α_T is the thermal diffusivity, k is the thermal conductivity and c is the heat capacity of the liquid metal.

The choice of material for GILMM should be based on the damage limited light flux and ease of handling. The mechanism that sets the damage limited flux is avoidance of excess liquid ablation or liquid spall caused by the sudden (isochoric) heating and subsequent rapid expansion. The surface temperature rises monatonically until the end of the pulse, set arbitrarily at 200 °C as a measure of the damage limited heat flux. Liquid ablation calculations need to be performed with hydro codes (ABLATOR, Anderson[8], for example). For comparison Bieri[1] found a temperature rise limit of about 100 °C set by surface distortion for Al at room temperature. The damage limit at a wavelength of 0.35 μm for 200 °C temperature rise is given in Table 1 for a number of candidate liquids. The peak pressure, P, given in Table 1 is the Gruneisen pressure neglecting hydro motion, that is $p = \Gamma E/V$ where Γ is the Gruneisen parameter (usually near unity). The energy is deposited at the surface in a volume V. As the surface heats up, expansion occurs at the speed of sound so the pressure falls short of the values given in Table 2, hence the need for a hydro code calculation.

The reflectivity varies with the angle of incidence as shown in Fig. 3 and varies with wavelength as well. Commonly in inertial fusion the intense portion of the laser pulse is 8 to 10 ns long. However, it might be as long as 20 ns if a slow compression is used to make a dense cold core for fast ignition or in the case of fast ignitor 10 ps (Tabak et al., [9]). The highest intensity allowed is for liquid Al, however, its high melting point of 660 °C suggest use of liquid Na or Li may be more practical with their melting points of 98 and 179 °C, however, the required mirror size for Li would be 7 times larger than for Na.

The damage limit scales as $(\text{pulse length})^{0.5}$, so that a 10 ps pulse could only handle a factor of 45 times less energy for the same surface temperature rise. If the ignitor pulse at the mirror had not fully compressed but rather were 200 ps long there, then the damage limit would be reduced by a factor of 10 from those in Table 1.

The performance of GILMM might be strongly effected by wavelength of possible lasers. For Li the damage limit for 1/4 and 1/3 µm light is about the same but is about 2.8 times higher for 1/2 µm light and 7.3 times higher for 1 µm light compared to 1/3 µm light.

4.0 Theoretical basis for smooth film flow

The film must be sufficiently thin so that viscous forces overcome shear effects that lead to wave buildup. According to theoretical analysis, if the Reynolds number is below the critical value, disturbances will damp rather than grow. Short wave length disturbances damp quicker than long wave disturbances and when surface tension (which is unimportant at long wavelengths >100 mm) is included, short wave disturbances damp even more quickly. All this suggests that impulses delivered at 5 to 10 Hz or higher may not be a problem because laser-induced disturbances might damp out by the next pulse. The film flow Reynolds number from Howard[10] is given in Eq. 2, where ρ is density, h_0 is the film thickness, η is viscosity and θ is the angle of the film flow plane.

$$Re = \frac{\rho^2 g h_0{}^3 \sin\theta}{2\eta^2} \qquad (2)$$

The surface flow speed based on a balance between viscous drag and gravitational acceleration is U_o and the average flow speed is $2U_o/3$.

$$U_0 = \frac{\rho g h_0^2 \sin\theta}{2\eta} \qquad (3)$$

The critical Reynolds number for stability of long wave length disturbances is:

$$Re_{crit} = \tfrac{5}{4}\cot\theta$$

The Weber number is useful to show when surface tension effects might be important.

$$We = \frac{\sigma}{\rho g h_0^2 \sin\theta} \qquad (4)$$

For lithium the Weber number, We, is 4000 for θ= 10° and 100 µm film thickness. Surface tension effects are extremely strong over dimensions comparable to the film thickness of interest. A more complete analysis needs to take into consideration more effects such as inertial forces compared to gravitational forces and temperature variation driven surface tension effects.

The film thickness required for stable flow ($Re<Re_{crit}$) is plotted in Fig. 4 for liquid Na with the geometry and variables defined in Fig. 5 (Howard[10]). We can see that if the film is <100 μm, then the surface should be smooth for a 10° slope for Na. What determines the minimum possible thickness is not known, but maintaining wetting in very thin films when Van der Waals forces become important might be a limitation.

For inclination to 72° we see from Fig. 4 that $h_0< 25$ μm for Na to avoid waves. Experiments will be needed to see if stable thin flowing films can be made especially for steep slopes.

4.1 Stability of the flowing film

We can imagine even with perfectly smooth steady flow, disturbances can be initiated by events such as laser heating of the surface at 5 to 10 Hz rate, including uneven heating, acoustic motion due to gas (target debris) striking the surface, heating by neutrons, and so forth. The metal backing is assumed to be fastened with damped actuators at multiple places behind the flowing surface to help adjust for these effects but the damping in the liquid itself will be the critical mechanism for suppressing surface waves. From the analysis of Howard[10] we find the growth rate of a disturbance of wavelength λ is given by γ:

$$\gamma = \frac{2\alpha^2}{3\sin\theta}\left[\left(\frac{6}{5}R\sin\theta - \cos\theta\right) - \frac{\Gamma}{\rho g h^2}\alpha^2\right] \quad (5)$$

where Γ is the surface tension and α is 2πh / λ. For the sake of the discussion to follow, we assume there is a disturbance produced by external factors such as the acoustical response of the laser heating or the gas shock that hits the surface of the mirror. The growth exponent, G, is defined as growth of the disturbance, e^G, where for a 1 m distance down the flow path G is given as:

$$G = \frac{U_0}{h}\gamma\left(\frac{100}{2U_0}\right) = 50\frac{\gamma}{h} \quad (6)$$

Eq. 5 & 6 use units that have been normalized, see [10]. Fig. 6 shows the case for Na for a 5 degree slope. Disturbances of wavelength below about 10 cm for 5 degrees (and below 5 cm for 70 degree slope not shown) are strongly damped due to the effects of surface tension. The damping rate becomes small for wavelengths longer than 10 cm for a 5 degree (and longer than 5 cm for a 70 degree slope). Isochoric heating will set up sound waves that will travel from the mirror front to the back in times of 5 μs and from one end to the other in about 1 ms. Since there is no net momentum in isochoric heating expansion, these sound waves should damp out after some number of transits. For a 5 degree slope from Fig. 4 we see a film <0.17 mm will be stable and flow at a surface speed of 20 mm / s for Na. However the waves travel at twice the surface speed giving 40 mm/s. In an interpulse time of 0.17 s for 6 Hz the distance a wave travels is <7 mm. As can be seen in Fig. 6, a 15 cm wavelength disturbance will damp (1/e) in 1 m or 25 s (1 m/40 mm/s). If there is a driving force for surface displacement disturbances over distances greater than 10 cm, there may be a problem because these disturbances may damp too slowly. Thinner films than 0.3 mm will damp disturbances more quickly. For the 70° slope, the damping rates are much smaller. Preliminary data from Morley [11] for a 500 μm thick stagnant Hg film shows disturbances formed by 1 μm wave length laser pulses up to 14 J/cm^2 at normal incidence damp in < 100 ms. More analysis and experimentation will be needed to prove surfaces can be kept sufficiently smooth for the application to IFE, especially for steep slopes.

4.2 Required smoothness of the liquid film and metal substrate

A simple analysis is done to show how smooth the liquid surface must be. Suppose there is a sinusoidal surface ripple of $\pm\Delta h/h$, over a wavelength, λ, then the angle of reflection will be spread by $\pm 4\pi\Delta h/\lambda$ as shown in Fig. 7. For a 30 m distance and a displacement of ± 0.25 mm at the target, which is about 10% of a typical capsule radius, we can tolerate a value of ±0.066 μm (±660 Å) for a wavelength of 100 mm. This is a pointing accuracy of ±8.3 μradians. The surface tension will be helpful in keeping surface disturbances small over short distances <10 mm. Over long distances (>10 mm) the backing plate must be kept flat to the parameters in Table 2.

The “polish” will have to be <±0.0066 μm over distance of < 10 mm which is brought about by surface tension. Over distances of 10 mm or more the substrate polish must be ± 0.007 μm. Surface tension may relax this somewhat and should be the object of more analysis. We will assume the figure is twice this or ±0.015 μm when surface tension is fully included. We can use adaptive optics to hold the substrate to ±0.66 μm over 1 m distances. A substrate polish of ±0.015 μm (±150 Å or $\lambda/20$) with adaptive optics should meet the requirements to hit targets to within ±0.25 mm (about 10% of the capsule radius) at 30 m. The diffraction limited spot size is about 9 μm. These conditions impose strict requirements on the stability of the liquid flow itself.

4.3 Experimental test apparatus

An experiment is needed to verify liquid surface smoothness. It could be done with any liquid metal and any laser wavelength by looking at its reflected focal spot using the Reynolds number to extrapolate to other liquids. Another experiment is needed to verify the reflectivity at the high intensity shown in Table 1. This experiment would be preferably done with Na and the correct optical wavelength so that no extrapolation by theory would be required assuming Na turns out to be preferred. The GILMM concept can be tested in relatively simple low cost apparatus that is then brought to an appropriate laser for testing. A high power density ($57\ \mathrm{J/cm^2}$ over 20 ns or $2.9\times10^9\ \mathrm{W/cm^2}$ based on sodium from Table 2 at 0.35 μm) laser can test deliverability of high power into a reflected focal spot. For a focal spot size of >0.1 mm, the laser should have >4.9 mJ, > 2.2×10^5 W for 20 ns. Larger spot sizes would provide a better test of a realistic application of the GILMM but at a cost of higher energy in the laser. Care will be needed to obtain smooth flow. Both inlet and outlet flow conditioning are important and sufficiently large area of flow to test against the more dangerous long wave length disturbances will be important.

5.0 Conclusion

A thin liquid metal film of ~100 μm thickness flowing down an inclined plane is suggested as the final optical element for laser fusion. This reflective mirror should be robust and have long service life and can stand bursts of neutrons, debris and x rays from fusion microexplosions. The allowed intensity on the mirror at 85° from normal incidence is predicted to be 9.3, 5, and $0.7\ \mathrm{J/cm^2}$ for aluminum, sodium and lithium, which is 106, 57, and $7.7\ \mathrm{J/cm^2}$ normal to the beam for aluminum, sodium and lithium. Environmental acoustic vibrations may present some problem because they can couple to standing waves on the film. Non uniform laser heating is not predicted to lead to ripples. More analysis and experiments will be needed to determine feasibility of the concept and to chose which liquid metal best meets the IFE requirements.

Acknowledgments

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Figure captions

Fig. 1. Final optical elements in the Prometheus reactor design

Fig. 2. Grazing incidence liquid metal mirror (GILMM)

Figure 3. Reflectivity versus angle of incidence for mercury. The curve labeled R_s has the electric field parallel to the surface and R_p has a component of the electric field perpendicular to the surface. For comparison the reflectivities for other liquid metals are shown.

Fig. 4. Liquid film thickness and speed for laminar flow of sodium.

Fig. 5. The variables describing film flow down an inclined plane are shown above.

Fig. 6. Growth exponent versus wavelength for 5 degree slope film flow with liquid sodium plotted for 1 m flow path.

Fig. 7. A surface ripple on the liquid will cause a smear in the focal spot at the target by $\pm 4\pi\Delta h/\lambda$ in radians.

Table 1

Damage limit for 20 ns pulses for a 200 °C surface temperature rise

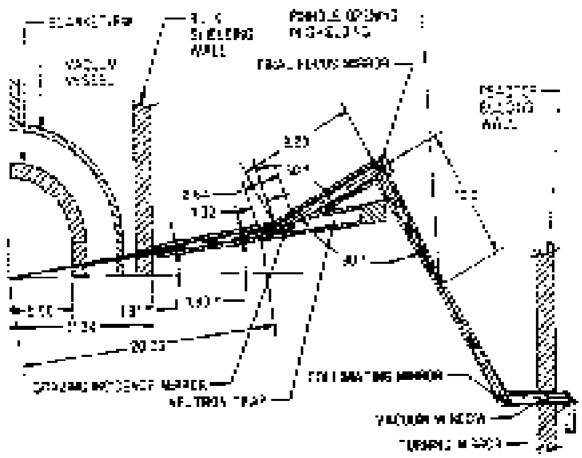
	T_{melt} °C	Laser fluence on mirror (85°), J/cm^2 (absorbed)		Laser fluence transverse to beam, J/cm^2	Peak pressure, GPa	Mirror area for 60 kJ per beam, m^2
Al	660	9.2	(0.064)	106	2.1	0.65
Na	98	5.0	(0.025)	57	0.16	1.2
Ga	30	2.4	(0.022)	28	0.4	2.5
Li	179	0.67	(0.025)	7.7	0.8	9.0
Hg	-39	0.53	(0.010)	6.0	0.3	11
Pb	328	0.33	(0.013)	3.8	0.7	18
Al(solid)[3]		1.5		14		4.1

Table 2

Surface disturbance allowed over the liquid metal mirror

Distance along mirror, λ, mm	Allowed perturbation, ± •h_0, µm
1	±0.00066
10	±0.0066 = 6.6 nm = 66 Å
100	±0.066 = 66 nm ~ $\lambda_{laser}/4$

1000=1 m	±0.66
5,000=5 m	±3.6



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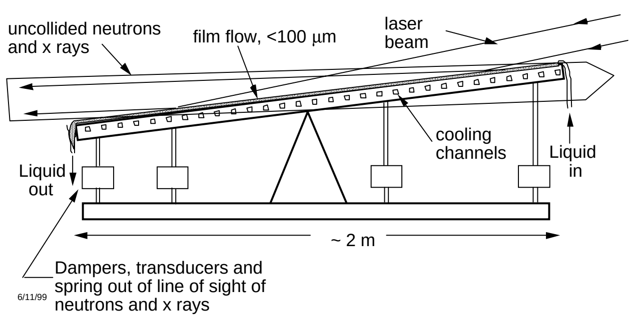

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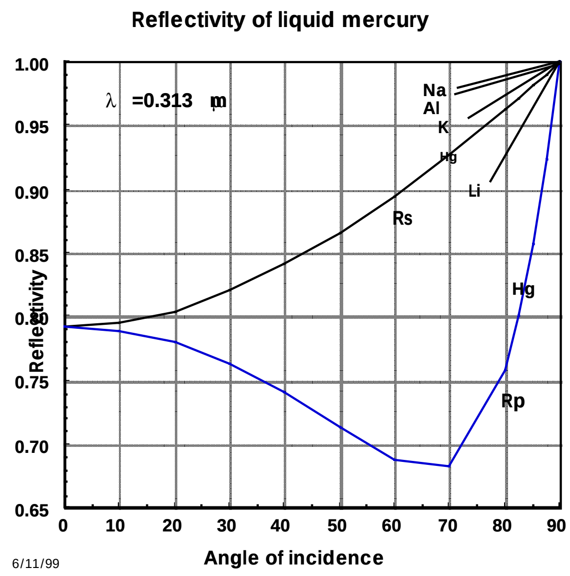

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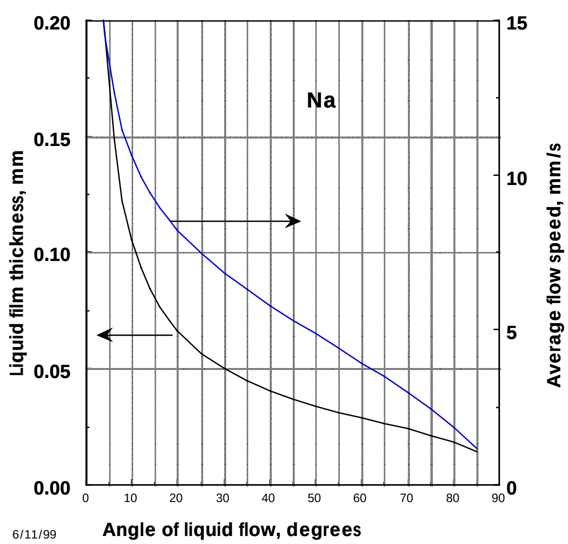

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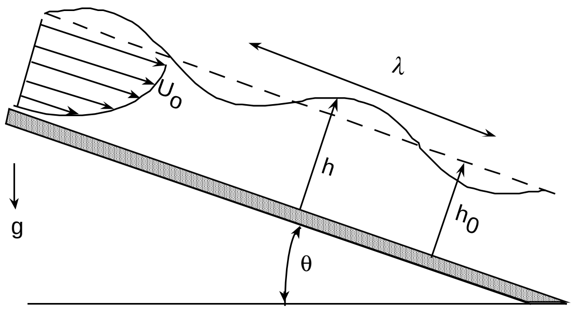

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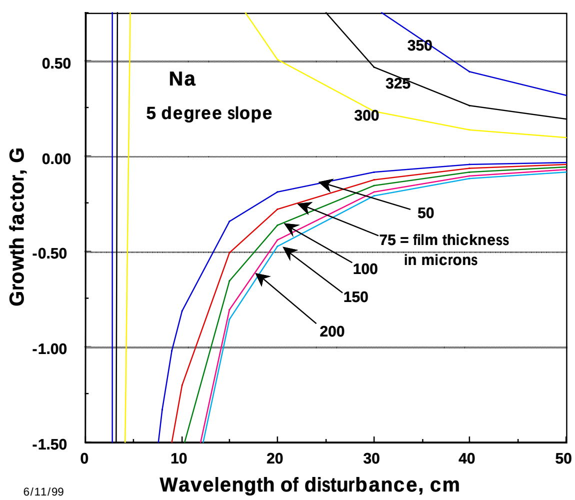

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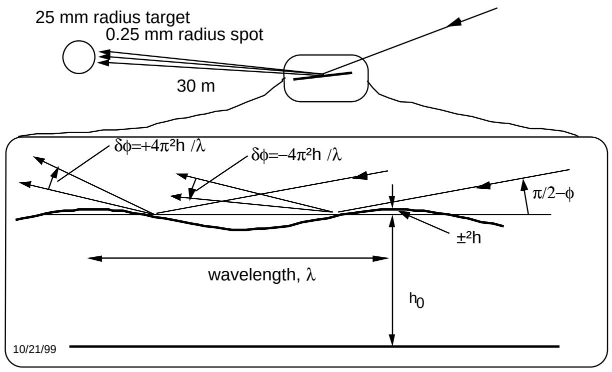

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