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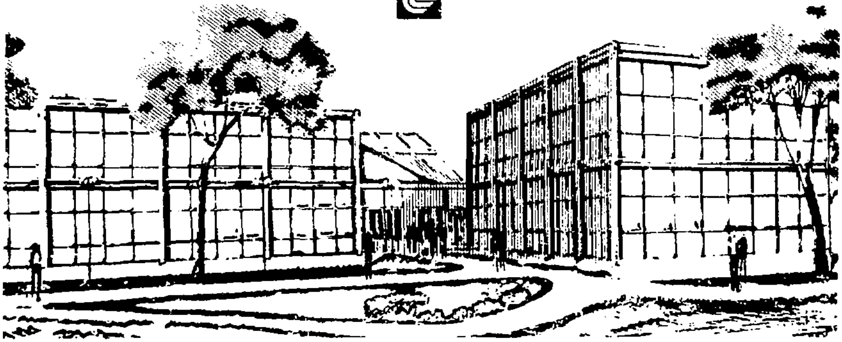

COMPOUND ELLIPSOIDAL FOCUSING SYSTEM FOR FUSION LASERS

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ABSTRACT

Isentropic compression of laser fusion targets requires highly uniform illumination over the entire target surface, and near normal incidence. For a two beam laser, this is best achieved using a fast catadioptric system. In designing such a system, the total thickness of refracting material must be minimized, to avoid loss of optical quality through small scale self focusing. Such a system is being fabricated for use with the ARGUS laser. It consists of a pair of nested ellipsoidal reflectors, coupled with an aspheric doublet refracting element which provides uniform illumination for the specified laser beam profile.

1. Introduction

In the design of an illumination system for laser fusion, it is essential that the target be illuminated uniformly and at as near normal incidence as possible. The simplest designs to improve uniformity involve multiple beam illumination. LLL's approach for 2-4 beams utilized in the ARGUS laser system is a unique combination of compound ellipsoidal mirrors and lenses to accomodate up to 6 TW.

The simplest increase in basic illumination may be accomplished by implementing two beams instead of one.[1,2] An ingenious two beam, 4π illumination system was designed by C. F. Thomas.[1] The design utilized fast lenses to fill two clamshell-like ellipsoidal mirrors. It provides an improvement in illumination over pure refracting systems by providing larger solid angle or higher angles of illumination on target. In order to reduce the amount of glass in the lenses, reduce the aspherization required, lower the numerical aperture of the lenses required, and to facilitate the anti-reflection coating of the lenses, an improved version of the Thomas system was designed at LLL. This system is presently operating in the JANUS II facility as shown in Figure 1.

The system uses a f/0.47 doublet designed with low internal reflections yet able to take a fifth power super gaussian beam profile

$$I = I_0 \exp -\left(\frac{r}{r_0}\right)^5 \qquad (1)$$

and provide a reasonable uniformity into the mirrors. The lens focus is placed at one of the two ellipsoidal mirror foci, the other ellipsoidal mirror focus is on the target. The ellipsoidal mirrors have been fabricated in Cervit at Perkin-Elmer and of beryllium at LLL. The beryllium mirrors were silver coated then accurately diamond turned and are now installed in JANUS II. The ellipsoidal mirrors must be decentered to focus slightly past the target center in order to fill the equatorial region required for diagnostics. This decentering can be seen in Figure 2A and increases the size of the shadow cone produced by the holes in the lenses. These holes were necessary for the prevention of potential internal damage due to internal reflection foci on axis. Figure 2B shows the illumination uniformity on target plotted as a function of input angle.

In order to increase power on target, the available aperture must be more uniformly filled if not also increased in order to keep the beam from breaking up. This break up is due to very high intensity causing non-linear index of refraction within the lenses. This non-linear undex leads to the break up of the transmitted beam into filaments. The measure of the break up is given in the following expression.[4,5]

$$B = \frac{2\pi}{\lambda} \frac{n_2}{n} \int \langle E^2 \rangle \, d\ell \qquad (2)$$

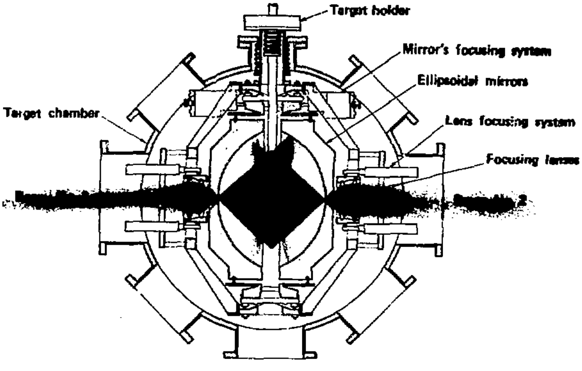

Fig. 1. Janus Spherical Illumination System

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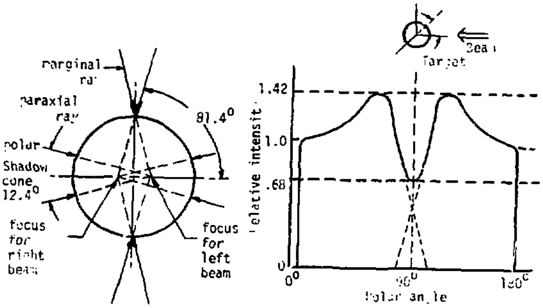


A. Focal configuration B. Intensity distribution

Fig. 2. Janus II Illumination Uniformity

The B or break up integral is a phase shift proportional to lens thickness ℓ and results in a loss of focusable power due to the formation of the filaments as described in the expression:

$$I_{filam't} = I_o e^{B} . \qquad (3)$$

When scaling up power in a single clamshell system like JANUS II, the aperture would also have to increase in order to keep B low. If JANUS II was increased up to 1 TW/beam, the aperture would have to increase up to 200 mm diameter in order to keep the B below 1.8 *radians which results* in a negligible focusable power loss. Table 1 shows the calculated B for the various existing LLL designs. If ARGUS II at 3 TW/beam utilized a single *clamshell system, in order* to keep B below 1.8 radians, the lens diameter would *have* to increase up to 600 mm. This lens was considered much too difficult to fabricate thus *compound elliposidal mirrors* were proposed as an alternative. The compound clamshell lower the necessary lens numerical aperture and thus the thickness of glass could be reduced resulting in a lower B shown in Table 1.

The resulting ARGUS spherical illumination system is shown in Figure 3.

The inside clamshell-like ellipsoidal mirrors operate as those in JANUS II but instead of lenses to fill the inner ellipsoidal *mirrors*, outer ellipsoidal *mirrors provide* the required large solid angle. This results in a lower required lens numerical aperture thus allowing thinner lenses and thus lower B.

We have designed an optical fuse[6] into the system in order to protect the relatively expensive ellipsoidal mirrors. The optical fuse is *evident in the optical* path presented in Figure 3 as the flat mirror in back of the inner ellipsoidal mirror. This flat, diamond turned copper plated, beryllium mirror will damage at power densities[7] over 35 GW/cm². Even though the flat is only loaded at 4 GW/cm², short pulses and filamentation *formation may* increase the flux. If *damaged*, this flat is easily replaceable thus protecting the *other mirrors*.

Decentering the foci of the inner clamshells for *better target uniformity is* not practical due to the complex optical coupling, thus the lenses were designed

SYSTEM (ALL TWO BEAM INPUT)	P POWER/BEAM (Terawatts)	R LENS RADIUS (mm)	A LENS AREA (mm²)	ℓ LENS THICKNESS (mm)	I PWR/LENS AREA (gigawatts/mm²)	B B = 0.546 Iℓ PHASE SHIFT RADIANS
JANUS II (LENS & CLAM)	0.2	42.5	5,674	45	0.0352	0.87
CYCLOPS (LENS & CLAM)	0.5	100.0	31,416	100	0.0159	0.87
ARGUS I (TWO BEAM)	1.5	140.0	61,575	66	0.0244	0.88
ARGUS II (FOUR BEAM INTO TWO)	3.0	140.0	61,575	66	0.0487	1.76

Table 1. Different Illumination System Design Parameters

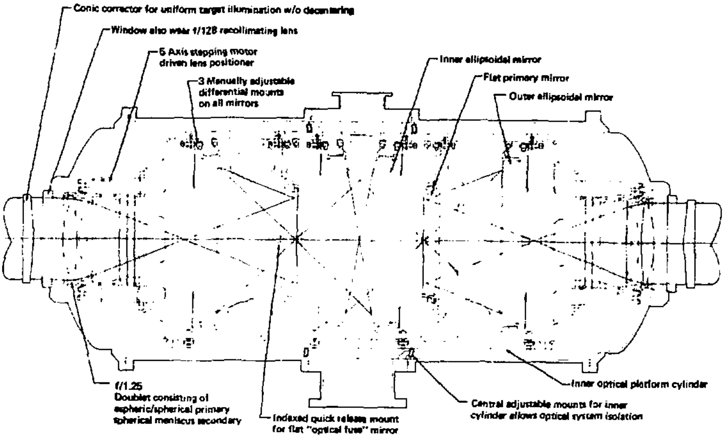


Fig. 3. Argus Spherical Illumination System

to provide the necessary overlap initially with a conic corrector evident in Figure 3, just in front of the window. This conic corrector bends the paraxial rays in to eliminate the shadow cone projected from the large holes in the mirrors. A spherical corrector must replace the conic in order to form a point focus required for alignment and necessary for the fabrication of the doublet.

The f/1.25 doublet was designed with the aid of the ACCOS 5 computer program[8] to provide perfect illumination while minimizing internal reflection foci which may be intense enough to cause damage. A LLL developed code,[9] GHOST 3, predicted such formations on axis as shown in Figure 4. In order to prevent damage from these predicted caustics, holes were designed into the lenses on axis.

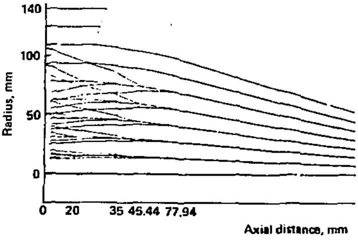


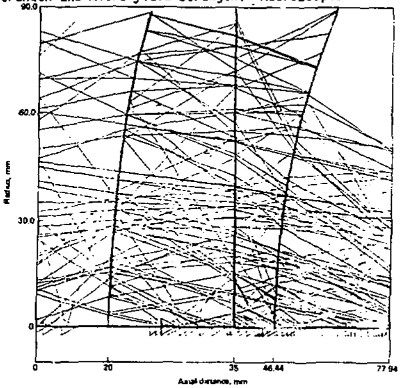
Fig. 4. Caustic formation due to ghost focusing from internal reflections.

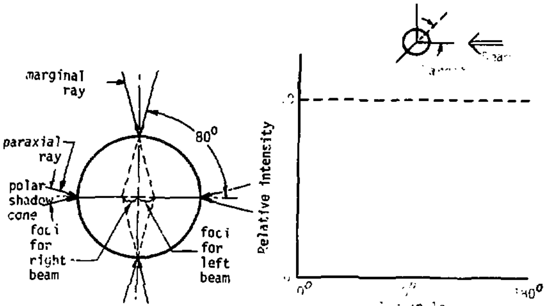
The vacuum window is also a weak f/128 lens necessary to recollimate the beam which was expanded from the 200 mm laser aperture to the 280 mm aperture of the chamber optics.

This system provides perfect uniformity on target with the conic in position which can be seen in Figure 5.

The mirror substrate material choices were BK-7, Cervit and beryllium. There are four primary properties which determine the final choice since each of the four affect the substrate design at different times during processing and final use.

The first property affecting substrate choice is strength and micro-yield strength. Macroscopic





A. Focal configuration

B. Intensity distribution

Fig. 5. *Argus Illumination Uniformity*

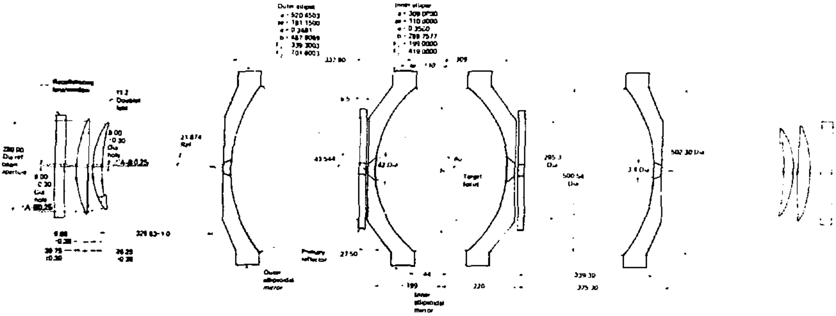


Fig. 6. Argus Optics Parameters

strength affects the shape of the substrate. Micro-yield strength describes local substrate strength. *Here beryllium substrates are seven times stronger* than those of BK-7 or Cervit thus giving superior rigidity for the same geometric dimensions as seen in Table 2. The second property of interest is the modulus of elasticity which is the magnitude of stiffness. Again from Table 2, beryllium is four times stiffer than BK-7 and three times stiffer than Cervit.

Due to the required high aspect ratio required in the geometry of the reflecting portion, both strength and stiffness necessitate thicker peripheral sections for BK-7 and Cervit than for beryllium substrates.

The third property affecting substrate choice is long term dimensional stability. Beryllium and Cervit substrates are both better than five times more stable than BK-7 substrates.

The fourth design property is thermal distortion which would be experienced in the final step of mirror processing, the dielectric overcoating. This overcoating subjects the substrate to temperatures of 200-300° C. BK-7 experiences nearly six times the distortion of Cervit while beryllium has only twice the distortion. The amount of distortion seen by beryllium substrates can be further reduced by coating both sides and by substrate stabilization where the substrate has been previously subjected to numerous cycles at these temperatures such that all creep has been accelerated prior to final lapping.

The logical choice based on the forementioned

MATERIAL	ρ (gm/cm^3)	E MODULES OF ELASTICITES (10^6 N/cm^2)	MYS MICRO YIELD STRENGTH (psi)	UTS ULTIMATE TENSILE STRENGTH (psi)	K THERM CONDUCT (Cal/gm C)	C SPECIFIC HEAT (Cal cm sec C)	COEF OF THERM EXPANSE (10^{-6} C)	DIMENSIONAL CHANGE K/… (x 10^3)	α_ρC/K (x 10^6)	T TRANS (C)
BK 7	2.200	7.00	1,500	–	0.0033	0.188	0.55	2 [illegible]	69.0	1,500
CERVIT	2.500	9.23	1,500	–	0.0040	0.217	0.10	16.0	14.0	800
BERYLLIUM (KBI HP 20)	1.852	28.00	3,000-10,000	55,200	0.3800	0.450	12.40	16.5	27.0	1,300

Table 2. Mirror Substrate Design Parameters

properties is beryllium but even this material is subject to further choices. The desired high strength and low creep with relatively low cost and delivery time was met using ultra pure beryllium particles further shattered by impact with a beryllium target in an inert gas atmosphere. This material is subjected to a number of proprietary elevated temperature pressing and sintering operations to give the highest density with a maximum isotropy. The amount of beryllium oxide in the chosen material directly determines the strength and indirectly the amount of long term creep, hence long term dimensional stability. A number of different vendors processes will meet the forementioned criteria but hot-isostatic pressed beryllium was the least expensive and was available in shorter delivery times than some of the more exotic but slightly superior processes.

The actual processing of the mirrors is detailed in Table 3. In order to insure that this processing would yield the required diffraction limited, high damage threshold mirrors, a test program was instituted to investigate variable parameters. Alternate plating material, bond strengths, alternate temperature anneal cycles, suppliers, different electroless nickel, timing variations on the substrate stabilization cycles, different vendors dielectric overcoatings damage thresholds and reflectivities and all these variations had profile tests performed at each step of their processing and finally interferometric tests in order to access dimensional stability. Table 4 shows the results of plating bond strength tests which lead to the main copper plating. Figure 6 shows the movement of the substrate during the sequential processes which lead to the decision to have the 900° C anneal cycle.

The optical mounting and positioning system is designed to provide stability with adjustment to properly illuminate the envisioned target sizes in their range of positional errors. The corrector lens mounts into a precision lapped clamp ring which can be quickly and accurately inserted into an indexed mount outside the chamber window. The chamber window generously overlaps the chamber and has a unique clamped edge design which lowers the vacuum deflection by a factor of five over ordinary edge clamping. The f/1.2 doublet is mounted in a lens positioner having five axis control.[10] There is a manual coarse adjustement on a differential screw that travels ± 6.35 mm and 0.711 mm/rev. The X and Y axis have differential screws driven by 200 step/revolution stepping motors in order to give 0.5 µm/step resolution. The Z, θ and ϕ axes have a differential screw which has a total range of eight revolutions at 89 µm/rev and attach to a 200 step/rev stepping motor which gives an ultimate resolution of 0.44 µm/step. The positioner also allows the inter lens distance to be adjusted manually. The five axis positioner is attached to a spider which, in turn mounts on the end of a cylindrical mounting platform which also supports

1. KBI CUTS ROUGH BLANKS 2mm OVER EACH DIMENSION EXCEPT 3mm OVER THE BEST FIT RADIUS ON THE ELLIPTICAL CONTOUR, OUT OF HP-20 MATERIAL.
2. VACUUM ANNEAL- HEAT AT LESS THAN 150°C/hr UNTIL 900 C IS REACHED, HOLD FOR 1 hr, COOL TO AMBIENT AT NOT MORE THAN 25°C/hr.
3. ROUGH MACHINE UNTIL SURFACE IS 0.46mm OVER FINISH CONTOUR.
4. REPEAT VACUUM ANNEAL.
5. MACHINE IN CUTS NOT EXCEEDING 0.254,0127 AND 0.051mm IN THAT SEQUENCE UNTIL SURFACE IS 0.025mm BELOW THE FINISH CONTOUR
6. REPEAT VACUUM ANNEAL
7. CHEM MILL UNTIL ALL SURFACES ARE 0.152mm BELOW THE FINISH CONTOUR AND RINSE.
8. BAKE FOR 6 HOURS AT 100 C IN A CHAMBER EVACUATED BELOW 10^{-4}mm Hg.
9. AFTER MASKING, IMMERSE IN TURCO 4215, RINSE, IMMERSE IN BOILING DIST. H_2O FOR 5–10 min, ACTIVATE IN COMBINED SOLUTION OF 97g/l AMMONIUM SULFATE AND 51 ml/l SULFURIC ACID AT ROOM TEMP FOR 60 secs, RINSE, IMMERSE IN A ZINCATE SOLUTION FOR 5 min, AT 80°C, RINSE, STRIP ZINCATE WITH NITRIC ACID AT ROOM TEMP, RINSE, REPEAT ACTIVATION THROUGH ZINCATE IMMERSION, APPLY SPECIAL COPPER STRIKE COATING AT 40.6 C FOR 5 min, RINSE, COPPER PLATE IN COPPER PYROPHOSPHATE TO A THICKNESS OF 0.300mm, RINSE, REMOVE MASKING
10. REMACHINE HOLES AND TURN DOWN NON-FUNCTIONAL SURFACES UNTIL REQUIRED DIMENSION.
11. Y-12 R/O MACHINE TO SINGLE POINT DIAMOND TURN CONCAVE SURFACES OR FLAT ON PRIMARY REFLECTOR UNTIL FINAL CONTOUR IS ACHIEVED.
12. STABILIZE: COOL AT 2.3 C/min TO –70 C AND HOLD FOR 15 min, HEAT AT SAME RATE UP TO ROOM TEMP, HEAT AT NOT MORE THAN 150°C/hr UP TO 200°C AND HOLD FOR 15 min, COOL AT 50°C/hr DOWN TO ROOM TEMP AND HOLD 15 min, REPEAT COMPLETE CYCLE ONCE MORE.
13. FINAL DIAMOND TURN SURFACES TO 0.013mm BELOW FINAL CONTOUR.
14. INSPECT FIGURE FOR ELLIPSOIDAL MIRRORS; FIGURE, REFLECTIVITY AND WAVEFRONT DISTORTION FOR FLATS.
15. MASK, IMMERSE IN 60g/l ENTHONE ENBOND S-61 AT 82°C FOR 1–5 min, RINSE, IMMERSE IN 60g/l ENPLATE AD-480 FOR UP TO 1 min AT ROOM TEMP, RINSE, ACTIVATE USING 30ml/l ENPLATE 440 AT ROOM TEMP FOR UP TO 30 secs, RINSE, PLATE WITH SHIPLEY'S NICULOY 22 AT 90.5 C AT A RATE OF 0.013 TO 0.018mm/hr UNTIL 0.025mm PLATED ON, RINSE.
16. REMACHINE HOLES.
17. REPEAT STABILIZATION CYCLE.
18. LAP ELECTROLESS NICKEL TO REQUIRED FIGURE AND WAVEFRONT DISTORTION.
19. INSPECT FIGURE, WAVEFRONT DISTORTION AND SPOT SIZE.
20. DIELECTRIC OVERCOAT CONCAVE SURFACE FOR 99% REFLECTIVITY AT 1.064 µm DAMAGE THRESHOLD GREATER THAN 25GW/cm^2 FOR 100–150psec PULSES.

Table 3. Be Substrate Processing

SAMPLE NO. LOC.	SINGLE ZINCATE Cu STRIKE Cu	DOUBLE ZINCATE Ni STRIKE Cu	DOUBLE ZINCATE Cu STRIKE Cu STABILIZED AT 100°	DOUBLE ZINCATE Cu STRIKE Cu STABILIZED AT 325°C
1 *RF	29,400 psi	4,400 psi	21,700 psi	25,900 psi
2 *RF	28,700	1,600	15,300	27,600
3 *RF	17,600	2,000	15,500	
4 *RF	16,600	1,700		
5 *RF	15,200	1,300		
6 *RF	15,100			
7 *RF	11,900			
8 *RF	11,300			
9 *RF	22,500			

	DOUBLE ZINCATE Cu STRIKE Cu	DOUBLE ZINCATE Ni STRIKE Cu (Ni 22)	DOUBLE ZINCATE Cu STRIKE Cu	DOUBLE ZINCATE Cu STRIKE Hcl DIP Cu
1 LLL		2,389 psi	18,875 psi	11,011 psi
2 LLL		1,502	27,694	12,991
3 LLL		1,805	33,518	11,161
4 LLL		2,004	28,557	10,654
		(Ni 22 + NiCl)		
5 LLL		1,863		
6 LLL		6,054		
7 LLL		4,040		
8 LLL		10,595		
		(415 Ni)		
9 LLL		8,564		
10 LLL		4,390		
11 LLL		6,839		
12 LLL		3,341		

*ROCKY FLATS PLANT OF NORTH AMERICAN ROCKWELL

Table 4. Plating Bond Strengths

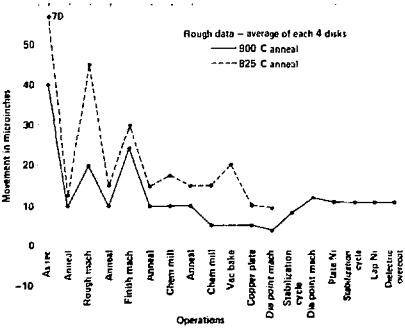


Fig. 6. Non-Contract Interometer Results on HP-20 Be 2" Disks

the elliptical mirrors and primary reflector. This cylindrical mounting platform has adjustable supports near the center such that it is nearly independent of chamber vibrations.

The ellipsoidal mirrors have numerous spring fingers which retain the mirrors without inputing excessive pressure which could cause long term dimensional change. The fingers, in turn, mount to a ring which has three independent and decoupled differential screws which have ± 3.175 mm of travel with 0.635 mm/revolution of course adjustment and motor drives with 3.8 μm/revolution for a total of 140 μm with the fine adjustment. There is a stepping motor option available which can provide 0.38 μm/step resolution.

The flat mirror mount is specially designed to offer the same adjustments available with the ellipsoidal mirrors and also provide an indexed mount for accurate insertion of the clamping fixture retaining the mirror.

The 10 mm thick, 360 mm diameter mirror presents problems in fabrication which may be resolved by resorting to a precision lapped clamp ring which offers five times lower deflection over a freely mounted configuration. The clamp ring may also be used to freely mount the mirror again as a sub-assembly.

The ARGUS illumination system presented an excellent solution to the problem of focusing power on targets with a minimum of glass to prevent loss of focusable power up to a maximum of 6 TW. Above this power, it becomes more economical to add more beams and additional beams require some alternate type of illumination as in LLL's SHIVA laser system which has 20 beams and can only accomodate a refractive illumination system.

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References

1. C. E. Thomas, "Laser Fusion Target Illumination System," Applied Optics, V14, p 1267-1273 (June 75)
2. C. Phipps, Reflective Optics System for Uniform Spherical Illumination, UCRL 75626 (1974).
3. H. G. Ahlstrom,"Target Experiments at LLL",Gordon 75
4. E. S. Bliss, D. R. Speck and W. W. Simmons, Appl. Phys. Lett. 25, 728 (1974).
5. B. R. Buydam, IEEE J. Quant. Electron.
6. T. Saito, private communications.
7. J. L. Emmett, private communications.
8. ACCOS5, a licensed computer code developed for ray tracing and system design.
9. GHOST, a ghost focusing computer code developed by E. Goodwin at LLL.
10. F. Rienecker, S. Glaros and M. Kobriercki, Lawrence Livermore Laboratory Internal Report UCRL 77248, "Argus Target Chamber," November, 1975.