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Optical Design of the National Ignition Facility Main Laser and Switchyard/Target Area Beam Transport Systems

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ABSTRACT

The optical design of the main laser and transport mirror sections of the National Ignition Facility are described. For the main laser the configuration, layout constraints, multiple beam arrangement, pinhole layout and beam paths, clear aperture budget, ray trace models, alignment constraints, lens designs, wavefront performance, and pupil aberrations are discussed. For the transport mirror system the layout, alignment controls and clear aperture budget are described.

Keywords: optical design, Nd:glass lasers, National Ignition Facility, large systems

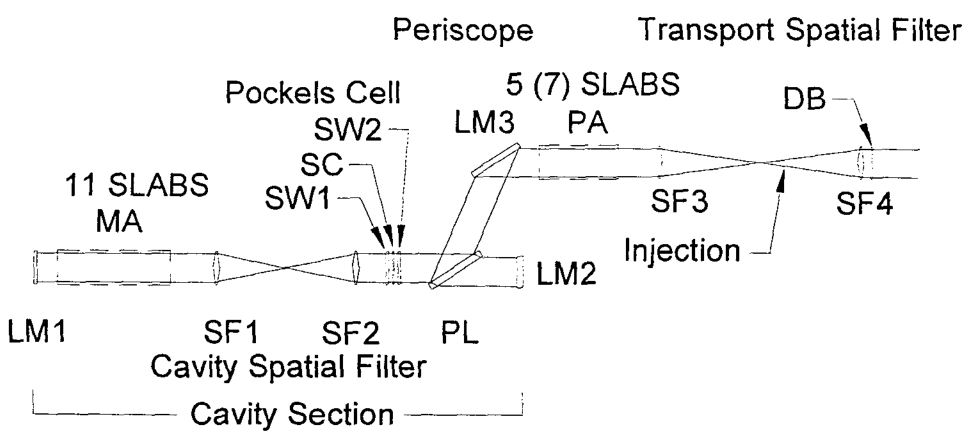
1. INTRODUCTION

The National Ignition Facility is a target irradiation facility for research in Inertial Confinement Fusion. The system includes 192 beamlines. For each beamline, the major optical subsystems are: the main laser, the transport mirrors, and the final optics. The main laser system is a four pass regenerative amplifier operating at 1053nm that includes Nd:glass Brewster's angle amplifier slabs. The maximum output energy is approximately 20kJ, in an effective pulse length of 3ns. The transport mirror system brings the beams from the output of the main laser to the target chamber. The final optics assembly includes frequency conversion crystals and the target focus lens, the light incident on target is at the third harmonic of the laser wavelength, 351nm. The incident energy on target for each beam is approximately 12kJ.

2. MAIN LASER SYSTEM

The main laser system for each beam comprises up to thirty large aperture optical elements. The optical components are shown schematically in figure 1.

Figure 1



The system is organized into cavity, transport, and periscope sections. The cavity section includes: two end mirrors (LM1 is the deformable mirror used for wavefront control), 11 Brewster's angle Nd:glass amplifier slabs, the cavity spatial filter (CSF), and the Pockels cell (PC, with two windows and a switch crystal). The transport section includes: either 5 or 7 amplifier slabs, the transport spatial filter (TSF), and a diagnostic beam sampling optic designated the diagnostic beamsplitter. These sections are connected by the periscope, which is made up of the polarizer and the elbow mirror.

Multiple beams are organized into several groups. Figure 2 shows one "cluster" of cavity spatial filter lenses. A "column" of beams is 1 wide by 4 high. The column is the typical optic mounting unit ("line replaceable unit"); the vertical beam center spacing within a column is 462mm. A "quad" is 2 wide by 2 high. This maps to the beam organization at the target chamber (the final optics assembly is organized by quads). A "bundle" is 2 wide by 4 high; thus it includes 2 columns and 2 quads. The bundle is the basic unit for main laser optical layout. It is also the smallest unit of the laser that can be operated independently (it is the spatial filter vessel vacuum isolation unit). The column beam center spacing within a bundle is approximately 571 mm at LM1 and 610 mm at SF1/2 (difference is due to beam walk in the odd number of amplifier slabs.) A "cluster" is 12 beams wide by 4 high, thus it is 6 bundles. This is the unit for the construction of the amplifier and spatial filter structures. The bundle centerline spacing within clusters is 1500mm. Each "laser bay" has 2 clusters. The full laser system has: 2 laser bays, 4 clusters, 24 bundles, 48 quads, and 192 beams.

Figure 2

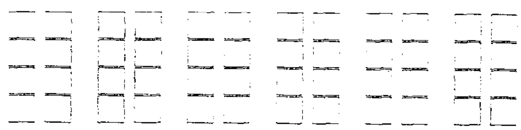
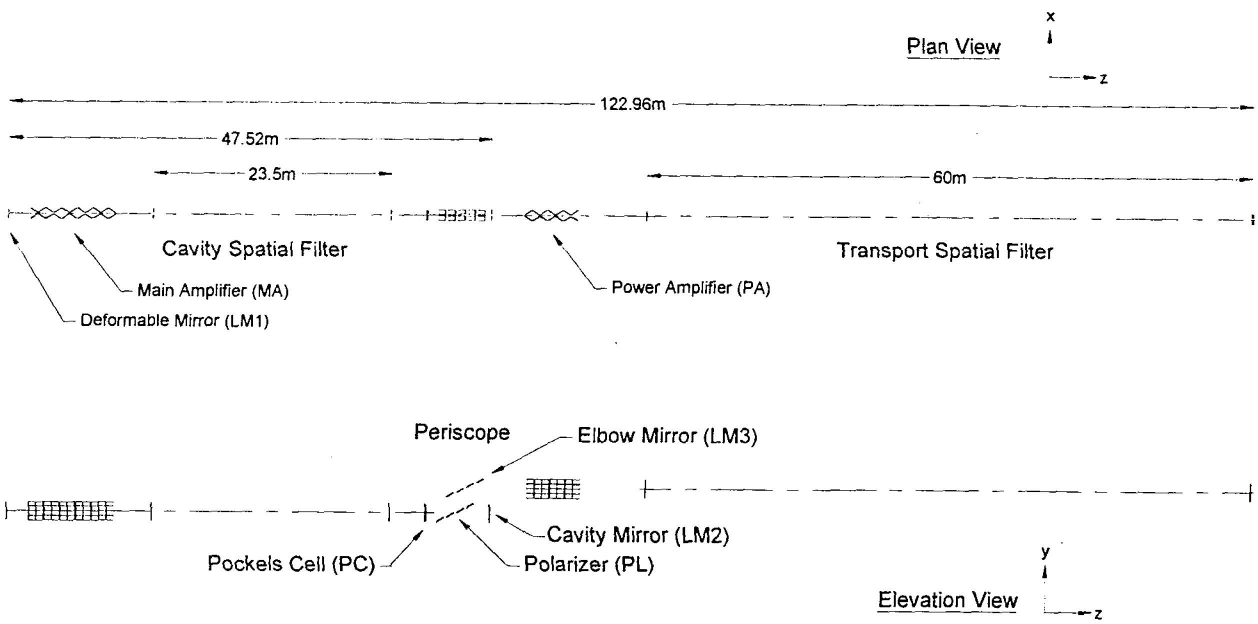


Figure 3 shows scaled plan and elevation drawings for one bundle:

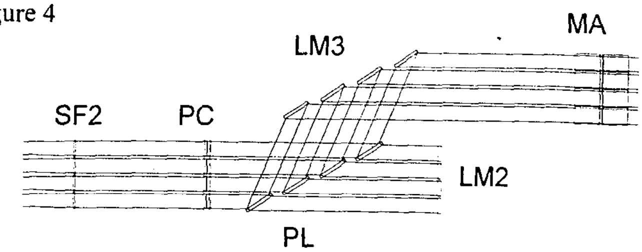
Figure 3



It is difficult to see individual optics at this scale because the system is very large: the overall length of the main laser system is approximately 123m. The cavity section is about 47m long and the transport spatial filter is 60m long. The axes that are shown conform to the NIF global directions.

The optical layout is determined by several factors. The first is relay imaging: LM2 is conjugate to LM1 via the cavity spatial filter. This imaging is complicated by pupil astigmatism due to the tipped plates. However LM1 is exactly conjugate to itself for the multipass beam center rays. An image of the last (toward +z) slab of the power amplifier is relayed approximately 50m from the transport spatial filter lens SF4 (this is from 12 to 24m from final optics assemblies at the target chamber.) The second factor is ghost stay-out zones: this sets the clearance of the MA from SF1 and the clearance between SF2 and the PC. SF3 is tilted by 2.8° in order to reduce the clearance between the PA and SF3 (SF4 is also tilted). The packaging constraints are also important: All large optics are mounted in line replaceable units (LRUs) and clearance between subassemblies is needed for transport and handling access. This is illustrated in figure 4, which shows a detail of the periscope region. Packaging constraints set the clearance between the PCs and the lowest polarizer, and the clearance between the top elbow mirror and the cavity end mirrors (LM2s). The beam spacings are set by the amplifier geometry. Beam walk in the amplifier slabs and polarizer also affects the layout.

Figure 4



The beam paths through the system are established by the geometry of the spatial filter pinholes. Each beam pass goes through a different pinhole. The pinhole layout is shown in figure 5. The pinhole angular separation is 1166μrad (in x and y). This converts to 35mm in the TSF and 13.72mm in the CSF. The system is designed to accommodate pinholes with a maximum acceptance of ±200μrad, or 12mm diameter in the TSF and 4.71mm in the CSF. The pinholes for the 4 passes are arranged in a square pattern, centered on the optical axis in the CSF. The optical axis in the TSF is centered between pinholes 1 and 4. The resulting beam paths are shown schematically in figure 6, which shows the system unfolded (without the offset in y at the periscope). The beam starts out inside the TSF from the injection system which is located to +z from the TSF pinhole plane. This is pass 1; it travels through TSF pinhole 1, into the cavity (via the periscope), through CSF pinhole 1, to LM1. The reflection is pass 2, which proceeds to LM2. The reflection from LM2 is pass 3; which travels back through the cavity. The second reflection from LM1 is pass 4, which travels out of the cavity, through the TSF, and on to the transport mirrors (to the target chamber). The switching is achieved by rotating the polarization using the PC; the PC is off (no rotation) for pass 1, on for passes 2 and 3, then off again for pass 4. Pass 5 in the CSF and passes 2 and 3' in the

Figure 5

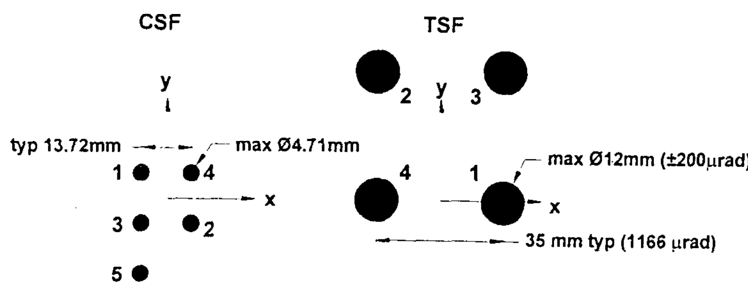
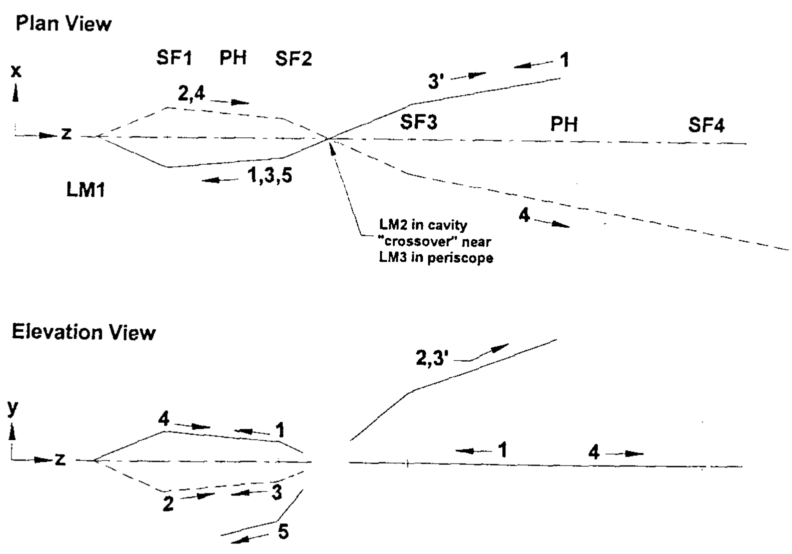


Figure 6



TSF are stray light passes. Pass 5 results from light left in the cavity after the pass 4 switch-out. Pass 2 in the TSF comes from PC leakage. And pass 3' in the TSF is from target back-reflections. The surface normals of end mirrors LM1 and LM2 lie in the y-z plane. Thus in the plan view the successive passes repeat a closed path, alternating sides of the z axis. In the elevation view, LM1 is normal to the axis but LM2 is tilted down, so pass 3 reverses the path of pass 2. This is done to avoid having pass 3 go back through the pass 1 pinhole. The axis rotation between the TSF and CSF is achieved by making LM3 and the polarizer not parallel.

As is apparent from figure 6, the CSF is closer to LM2 than LM1. As a result the greatest beam center separation occurs at SF1, where passes 1 and 2 are separated by about 16mm. The CSF lenses are centered on the line in the middle of the pass 1-4 centerlines. At SF3, passes 1 and 4 are separated by about 20mm. SF3 is centered midway between passes 1 and 4. SF4 is centered on pass 4 (SF4 is only required to transmit pass 4).

The main laser system includes several wedged, tilted, and decentered components. The PC optics are wedged and tilted for ghost control. The diagnostic beamsplitter is wedged by 4.7mrad to deflect the top quad up and the bottom quad down. This was done to relieve a packaging problem at the first transport mirror (LM4). The polarizer and elbow mirror each have small decenters to optimize the use of their apertures. The TSF lenses are tilted and decentered. SF4 is decentered by about 24mm.

The main laser configuration and lens design is maintained and optimized using ray trace models. The models include all 4 passes plus the injection system. Four models are needed: one for each height in a column. The models explicitly include the design on-line alignment constraints. The pointing constraints are beam alignment to the middles of the pass 1 and 4 pinholes in the TSF and the pass 3 and 4 pinholes in the CSF. The centering constraints are placing the pass 4 center on the axis at LM1 and at the "crossover" plane. (The crossover plane is approximately the image of LM2 that's in the periscope section.) An additional constraint is beam rotation ("clocking") at the crossover plane. The ray trace models make extensive use of global coordinates, pickups, and surface references via labels.

The optic sizes were established using a clear aperture budget. This budget has allocations for: the maximum beam size of 372mm square (at the 10^{-4} relative irradiance contour of the apodizer); beam walk due to the pinhole separation; diffraction (an image of the beam apodizer is put at LM1, diffraction is modeled as ray slopes in nominally-collimated space that would clear the maximum size pinholes); component and alignment reference locations errors of 1mm to 3mm; alignment system control errors of 2mm centering and 5mrad beam rotation; lens wedges of 20 arc sec maximum; and second order effects caused by component placement errors. The resulting specified dimensions for each optic are: the optical clear aperture (OCA), which includes all allocations except diffraction and is the optic test aperture; the mechanical hard aperture (MHA), which is the OCA plus the diffraction allocation and is the keep-out zone for all mechanical structure; and the optic size, which is the MHA plus mounting and fabrication "freeboard". The OCAs and optic sizes are given in table 1. The dimensions shown are in millimeters; the amplifier slab size shown includes the edge cladding. The design limiting aperture for the main laser system is the 400mm square aperture of the amplifier slabs.

Table 1

Component	OCA	Size
LM1	392 × 392	450 × 434 × 15
LM2	392 × 392	412 × 312 × 80
LM3	396 × 392	740 × 417 × 80
PL	396 × 396	740 × 417 × 90
MA, PA	400 × 400	805.5 × 458 × 41
SC	397 × 397	410 × 410 × 10
SW	397 × 397	430 × 430 × 35
SF1-4	410 × 406	438 × 434 × 46
DB	410 × 406	438 × 434 × 10

The material used for all of the spatial filter lenses is synthetic fused silica. The center thickness is 46mm. The lenses are vacuum barriers; the maximum tensile stress in the material is 500psi. The lens shape is nominally symmetric bi-convex. This was chosen to minimize stress birefringence. The inside (vacuum-facing) surface of each lens is spherical; the outside surface is aspheric. Each lens is corrected for spherical aberration individually. The back focal distance for the cavity spatial filter lenses is 11751.5mm (~F/21 referred to the aperture diagonal). The aspheric surfaces of these lenses are conics; the maximum aspheric departure is 1.4μm. The back focal distance of each transport spatial filter lens is 30m (~F/55 referred to the aperture diagonal). These lenses are more complicated because of the 2.8° tilt. The aspheric surface is bilaterally symmetric, containing surface terms in x^2, y^2, $x(x^2+y^2)$, and $(x^2+y^2)^2$. The maximum aspheric departure is 7.8μm.

Because of the multipass configuration, the lenses (except SF4) are used off axis. This contributes a small amount of internal wavefront error. In the cavity spatial filter: the wavefront error due to a single lens is ~0.06 waves peak-to-valley (P-V, at 1053nm), mainly coma. The coma is corrected each pass. The astigmatism is exactly corrected by the 4 pass symmetric use. The 4 pass field curvature is <0.02 waves. The wavefront error at pinhole 4 is 0.11 λ P-V (0.017 λ RMS). In the transport spatial filter the wavefront error due to 1 pass through SF3 is ~0.05 λ P-V, mainly astigmatism. The wavefront error at pinhole 4 is 0.015 λ P-V (0.004 λ RMS). The full system design wavefront error is 0.006 λ P-V (0.001 λ RMS) 4 pass, not including the effect of tolerances or fabrication errors.

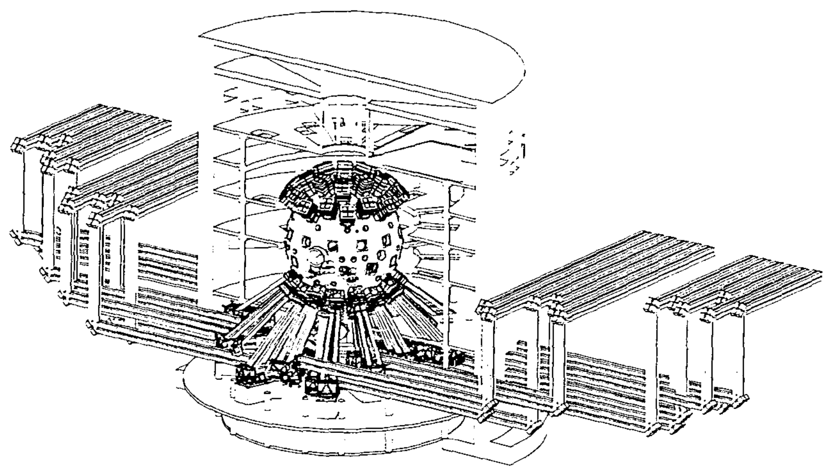
The specified maximum tilt error for the lenses is 0.1°. The multipass wavefront errors due to lens tilts are: for SF1 and SF2, 0.38 λ P-V (0.05 λ RMS); for SF3, 0.32 λ P-V (0.08 λ RMS); for SF4, 0.16 λ P-V (0.04 λ RMS).

The many Brewster's angle amplifier slabs (and polarizer) cause significant pupil astigmatism in the main laser. For a pupil located in the injection system, the longitudinal pupil astigmatism for the multipass is: 328mm at LM1 for pass 1; 488mm at LM2 for pass 2; 650mm at LM1 for pass 3; and 980mm at the output, at the LM1 conjugate that is approximately 43m (toward +z) from SF4. However, this is much less than the diffraction limited depth of focus for beam (pupil) imaging. The 90% contrast diffraction depth of focus at ±150μrad is 16.6m.

3. SWITCHYARD AND TARGET AREA TRANSPORT MIRROR SYSTEM

The switchyard and target area beam transport system is made up of 832 mirrors. This system maps the rectangular arrangement at the laser output to a spherical-geometry configuration at the target chamber. The system for one-half of the beam is shown in figure 7 (the top beams have been removed for clarity.) The path length from the transport spatial filter output lens (SF4) to the focus lens varies from 62m to 74m. Each path has either 4 or 5 mirrors. All reflections at the mirrors are in-plane (either S or P). The beam path through the transport system is constrained at both ends. The alignment references at the main laser output are pointing with respect to the center of the pass 4 TSF pinhole and beam centering at the crossover. The alignment references at the target chamber are centering at the focus lens and beam pointing with respect to target chamber center. On-line system alignment is achieved by tilting the second and last transport mirrors (LM5 and LM8).

Figure 7



A typical path from the laser to the target chamber is shown in three views in figure 8. LM4, 5, 6, and 7 are arranged with approximately rectilinear geometry. The beam is deflected to ±y by LM4, then to ±x by LM5, then to ±z by LM6. In beam lines with only 4 mirrors LM6 is omitted (LM7 is at the same z as LM5). LM7, LM8, the final optics (FOA), and target chamber center (TCC) are arranged in the spherical coordinates of the target chamber. The path from LM7 to LM8 is at constant y and φ where φ is the azimuthal angle. The path from LM8, through the FOA to TCC is (approximately) along a line of constant φ and θ where θ is the polar angle. (The line $\theta=0$ is parallel to the +y axis.)

To study the control of beam rotation and the setting of mirror apertures, ray trace models have been set up for all 192 beams. The mirror apertures were established using allocations for: the maximum 372mm square beam; a pupil location of 50m from SF4 and diffraction modeled using a 200μrad ray slope; beam focus offset of up to 30mm from TCC (achieved by offsetting the beam center at LM8, maintaining beam centering at FOA); the on-line alignment degrees of freedom; accommodation of a diagnostic beam that travels from the FOA to the TSF at an angle of 1.16mrad with respect to the main beam (this is used for alignment of the frequency conversion crystal angles and as a shot diagnostic beam sample); on-line alignment system errors at the laser and target chamber; mirror and final optics installation position and beam alignment errors; and fabrication freeboard. Parameters for the transport mirrors are given in table 2. The sub-types vary by mechanical details (for LM4) and coating design angles of incidence and substrate size (for LM7 and 8). The mirrors are all 80mm thick.

Figure 8

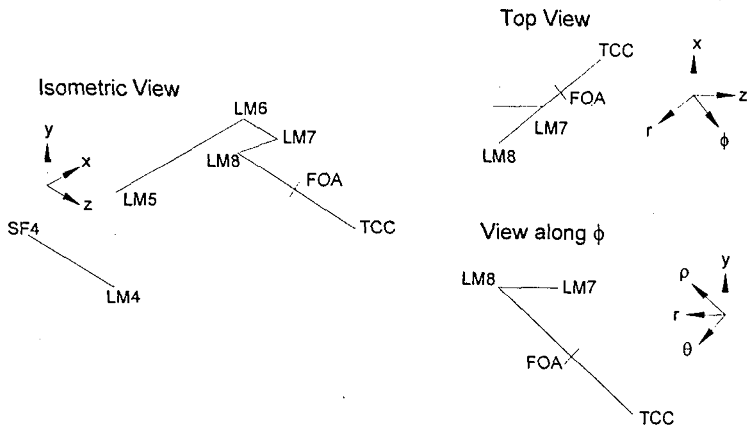


Table 2

Type	sub-types	pol	angle, deg	size
LM4	2	S	45	502 x 610
LM5	1	P	45	440 x 690
LM6	1	S	45	502 x 675
LM7	5	S	12.2-43.6	510 x 515 to 525 x 685
LM8	2	P	18.8-34.4	525 x 565 & 510 x 600

4. CONCLUSION: DESIGN DOCUMENTATION

The optical design of National Ignition Facility systems is documented primarily by optical configuration drawings and optical element drawings. The configuration drawings are linked to solid CAD models. These drawings document the positions and orientations of the optics, the ghost stay-out zones, nominal beam center paths, and path lengths. The element drawings are prepared using specification descriptions according to the ISO 10110 standard. Typically there are 3 drawings for each element: blank, finished, and coated. There are a total of about 84 large optics drawings. The element and configuration drawings are released under the configuration management system of the NIF project.

5. ACKNOWLEDGEMENTS

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