UCRL-JC-134786
PREPRINT

Overview of Small Optics for the National Ignition Facility

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This paper was prepared for submittal to the
44th Annual Meeting of the International Symposium on
Optical Science, Engineering, and Instrumentation
Denver, Colorado
July 18-23, 1999

July 1999

Overview of Small Optics for the National Ignition Facility

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ABSTRACT

LLNL's project to construct the National Ignition Facility (NIF), a 192 beam laser system capable of generating enough light energy necessary to achieve fusion ignition, will require 26,641 small optics, many of which will be supplied in the form of cleaned, tested and aligned assemblies. These assemblies will be built to print, cleaned to specifications, and tested to performance specifications, ready to be installed in the laser system. A wide range of potential suppliers will participate in the manufacture of these sophisticated opto-mechanical systems.

The injection laser system requires 7,440 precision optical components manufactured to state of the art performance specifications. In addition to 550 aspheric lenses, almost 2,000 precision spherical elements are required. Wave-fronts are specified in terms of P-V, RMS and RMS Gradient wave-front error, with strict requirements on the filtering and resolution which is required. Precision polarizers, high reflectors, leaking mirrors, high damage threshold coatings and cleanliness levels of 50 to 100 are also specified for this section of the NIF laser.

The alignment and diagnostics systems for the NIF require 19,201 optics, many of which have requirements that exceed those of the injection laser system. All of these optics will be purchased using the ISO 10110 drawing notations. Other sections of the laser system will utilize commercial, off the shelf components to control cost.

This paper will give an overview of the project and its objectives, with specific attention to the small optics required for the NIF.

Keywords:NIF, small optics, overview, components.

Work performed under auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

1. THE NIF PROJECT

In October of 1994, with the signing of key decision 1 (KD1) and the approval of the mission need, the Department of Energy began the process of planning, defining, designing and constructing the worlds largest laser system. In December of 1995, the preliminary or Title 1 design of the facility was commenced, and line item funding of the $1.2B project began. On June 11th, 1999, Secretary of Energy Bill Richardson christened the 120 ton target chamber, and declared the project, now in it's fourth year, was continuing on schedule and on budget. The conventional facility, shown in Figure 1, is now well on its way to completion. When completed, the facility will house 192 beam-lines that run the length of the facility and deliver huge amounts of energy upon a fusion fuel capsule the size of a BB. Because fusion ignition will create temperatures and densities that occur only in the sun and in nuclear weapons, the NIF is a key element in science-based stockpile stewardship, which aims to maintain confidence in the safety and reliability of the U.S. weapons stockpile under a Comprehensive Test Ban Treaty. Stockpile stewardship will depend heavily on the use of NIF experimental data in complex computer simulations. The NIF will also be used for research in basic science and fusion energy.

Figure 1 The NIF conventional facility

The NIF has passed through the public National Environmental Policy Act process. Construction of the facility is scheduled to proceed through 2003, when NIF operation will begin. Over 75% of the project's $1.2 billion cost will be spent on construction and manufacturing. This intense effort will create over 6,000 jobs around the country, including 2,800 in the San Francisco Bay area. The NIF will push many of its industrial partners' technology capabilities to new levels, raising their international economic competitiveness. In optics manufacturing, it has already done so.[1] In addition, the spin-off technologies generated by the NIF are predicted to be worth hundreds of millions of dollars for U.S. industry. When completed, the National Ignition Facility will be the world's largest and most powerful laser, and the most complex optical instrument ever constructed. The success of this ambitious project is dependent on the 34,193 optical elements that will make up its optical system.

2. NIF MAIN LASER OPTICS

The NIF main laser system comprises 192 independent laser beams. They are stacked four high, and two columns are grouped so that they can be operated as a “bundle” (4x2 laser beams); there are 24 bundles. Because of this arrangement, the laser beam footprint is square and adjacent beams are relatively close together to optimize the extraction of energy from the amplifier. The optical system design[2] has proceeded by considering the NIF to comprise six main subsystems: the pulse generation system and injection system (here referred to together as the Injection Laser System, or ILS), main laser, switchyard and target area, final optics assembly, and alignment and diagnostics. These six sub-systems are shown in block format in Figure 2. A summary of large aperture optical components is presented in Table 1.

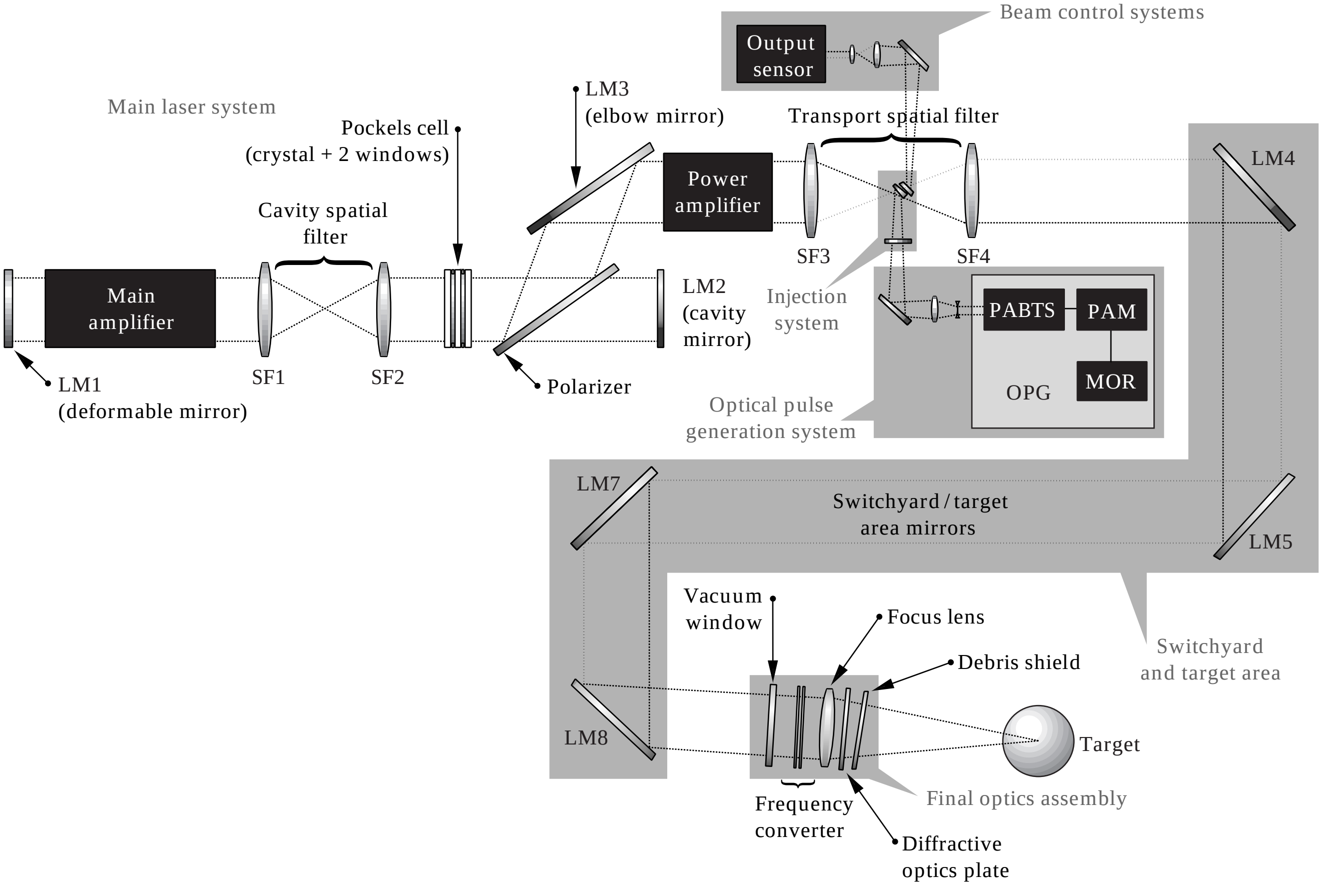

Figure 2. The NIF laser system is comprised of six main subsections; the pulse generation system and injection system, discussed together here as the injection laser system, the main laser, the switchyard and target area, the final optics, and the alignment and diagnostics subsystem.

Two mirrors and a 1:1 afocal telescope (cavity spatial filter) whose length is 23.5m, one-half the cavity length of 47m, form the NIF main laser cavity. Pinholes at the focal plane “scrape off” unwanted, high-angle diffracted and scattered light to prevent nonlinear growth of scattered waves that would produce intensity modulation and damage optical components. In the NIF main laser system, these lenses are fused silica, equi-convex, aspheric with a clear aperture slightly larger than 40cm square. The cavity or main amplifier is four-passed; the booster or power amplifier is two-passed. The amplifier slabs are oriented at Brewster’s angle to minimize loss. When each beam has made its second (and final) pass through the power amplifier, it is brought up to energies in the area of 18kJ. One end mirror, LM1, is a 39-actuator deformable mirror; its primary purpose is correction of pump-induced, cladding-absorbed ASE that causes thermal aberrations in the phosphate laser glass amplifier slabs. Additionally, the mirror corrects passive optical fabrication and installation errors.

The transport spatial filter projects the beam-defining aperture toward the final optics assembly and does final clean up of the laser beam. This beam clean-up is especially important here because of the high peak irradiance. Nonlinear (i.e., irradiance-dependent) index of refraction phase gradients build-up substantially in the last two slabs and input lens to the transport spatial filter lens. The final pinholes have an angular extent of +/- 100µrad to filter out unwanted high spatial frequencies and reduce the modulation that would arise from these phase gradients.

After the transport spatial filter, the beams are routed to the target chamber through a pair of 45 degree folds in the switchyard and a second pair of transport mirrors in the target area surrounding the target chamber itself. In addition, some of the beam-lines require an additional mirror between these two pairs of mirrors to properly map the laser beams into the correct polar coordinates while avoiding the target area structures. The reflections are nominally s- or p-polarization. There are variations in path length (beam-to-beam) from the main laser system to the final optics system. In the final design, this path length ranges from 62m to 74m.

Once the beams have been routed to the correct polar angles at the target chamber, the four beam quads then pass into the final optics assemblies. The primary functions of the final optics assembly are to convert the laser light to 3ω and focus it on target. Four beams come into one assembly that contains four separate sets of optics. Each beam passes through a vacuum window (the target chamber is at vacuum), a pair of frequency conversion crystals (KDP/KD*P), a focus lens (focal length 7.7m), two diffractive optics plates, and a debris shield.

Table 1. Large aperture optical components for NIF

Component	Quantity	Material	Size (mm)
Amplifier slabs	3072	phosphate glass	808x458x41
Spatial filter lenses	768	fused silica	438x434x46
Focus lenses	192	fused silica	430x430x25
Cavity mirrors	384	BK-7	412x412x80
Elbow mirrors	192	BK-7	417x740x80
Transport mirrors	832	BK-7	various sizes minimum dim. 440 maximum dim. 690 all 80 thick
Polarizers	192	BK-7	417x807x90
Crystals	576	KDP/KD*P	410x410x10*
Switch windows	384	fused silica	430x430x35
Target chamber windows	192	fused silica	450x440x43
Diffractive optics plates	384	fused silica	430x430x10
Debris shields	192	fused silica	430x430x10
Diagnostic beamsplitter	192	fused silica	438x434x10

*Doubler/tripler are 11/9

3. NIF SMALL OPTICS

Figure 3 shows schematically the NIF optical architecture, focusing on the small optics sub-systems. These sub-systems make up the injection laser system and the alignment and diagnostics, or beam control systems.

The injection laser system, containing 7,440 optical components, consists of 4 sub-systems. The Preamplifier Module, or PAM, which amplifies the master oscillator signal from the nanoJoule (nJ) range to more than 10 J, is a line replaceable unit (LRU) with 64 optical components. The PAM is followed by a 4 element telephoto relay telescope contained within the Input Sensor Package (ISP), which expands the beam from 30 mm square to 45 mm square. The third subsystem of the ILS is the Preamplifier Beam Transport System (PABTS). The PABTS transports the beam into the structure beneath the main laser Transport Spatial Filter (TSF), and has the ability to adjust path lengths for timing and mild beam expansion for power balance, while maintaining proper near field imaging conditions. There are 48 of each of these sub-systems. The beam is then inserted into the main laser by the fourth sub-system, a 2 element injection telescope within the TSF vacuum vessel. There are 192 injection systems, or 1 per beam-line. The ILS is described in detail elsewhere[3]. The optics for the ILS are described in more detail in section 4.

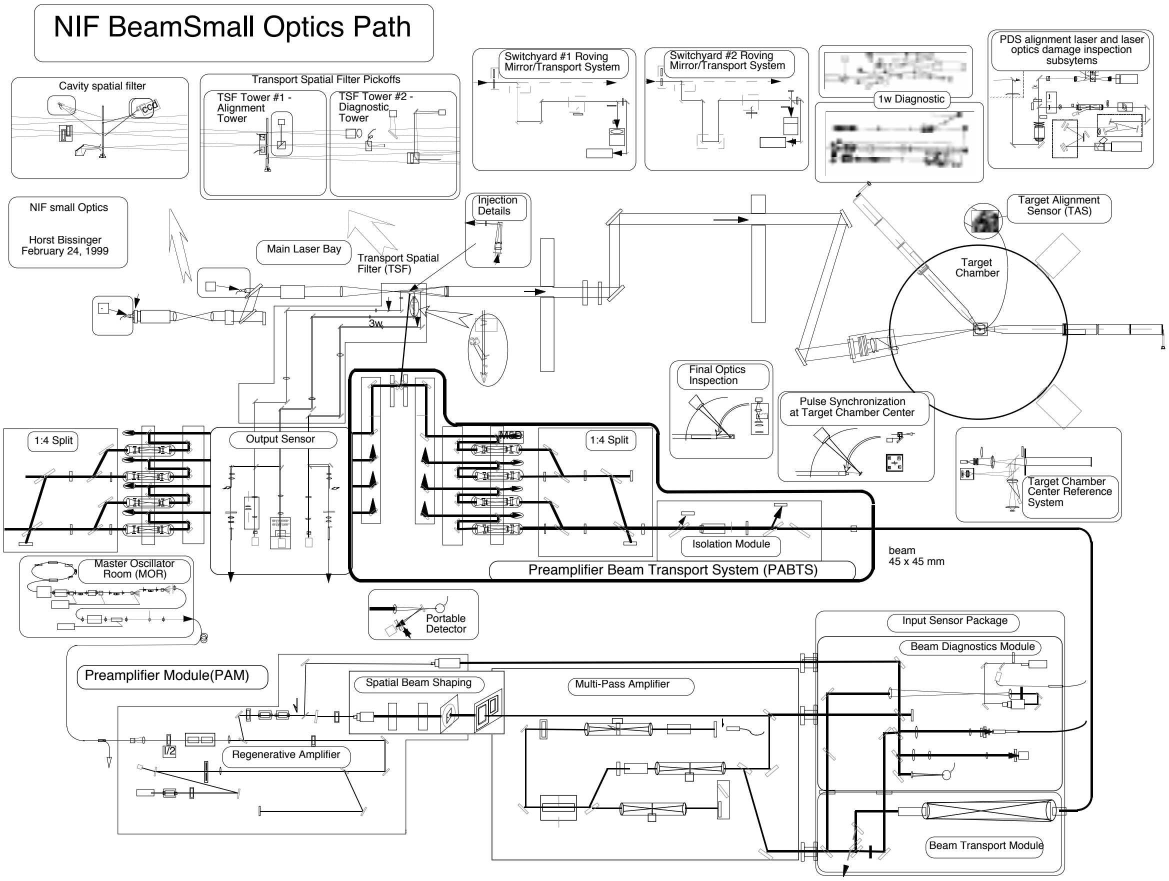

Figure 3. The NIF small optics subsystems in relation to the main laser.

The alignment and diagnostics systems are comprised of 19,201 optics, deployed in a series of systems and packages. Most of these elements are in the input sensor package and output sensor package and its associated transport systems. These systems are needed to both align the laser system in near field and far field, as well as to diagnose the laser beam quality at the input and output of the main laser system. There are 48 Input Sensor Packages and 96 Output Sensor Packages for the NIF systems. Alignment light sources exist at critical locations in both the near field and the far field of the main laser (192 each) and the injection laser (48 each) systems. These include the LM1 and LM3 near field light source packages, the 1w and 3w pinhole light sources, and the MPA near field and far field sources in the ILS. In addition to these alignment and diagnostics packages in the ILS and Main Laser, there are several target area diagnostics systems. They include the chamber center reference system (CCRS), the target alignment system (TAS), the final optics damage inspection system (FODI), and the pulse synchronization system. There are only 1 or 2 of each of these systems in the NIF. Also shown in Figure 3 are the precision diagnostics systems (PDS) which are resident in the switchyards. These systems allow a more complete and precise diagnosis of the condition of any one laser beam. The light from the appropriate beam is relayed to the PDS through the roving pickoff mirror system. There are two PDS systems, one in each switchyard. Only the PDS in switchyard 2 has a 3w diagnostics system, however. The alignment and diagnostics systems are described in detail elsewhere[4]. The optics for the alignment and diagnostics systems are described in more detail in section 5.

4. THE INJECTION LASER SYSTEM

Preamplifier module optics and ISP relay telescope optics

The Preamplifier Module (PAM) is shown in block diagram form in Figure 4. The light is coupled into the PAM from the Master Oscillator Room (MOR) via a fiber launch assembly. The light is then delivered into a Regenerative Amplifier System (Regen), where the beam is increased in energy by 10^6. The light is then coupled out of the Regen, and sent through the Beam Shaping Module (BSM), which sets the size of the beam to 30 mm square as well as the intensity profile through a series of apertures. Within the BSM, the first relay plane, RP0 is defined as the location where the edges of the beam are defined using a serrated aperture. The beam is then sent to the other side of the PAM, to the Multipass Amplifier (MPA), which increases the beam energy by an additional 10^4. In doing so, the beam is re-imaged eight times, as it passes through a 50 mm diameter rod amplifier four times. At that point, the beam leaves the PAM and enters the Input Sensor Package (ISP). The relay telescopes within the MPA create an external relay plane, RP8, a short distance outside of the PAM, between two fold mirrors in the ISP transport section. In addition to its alignment and diagnostics functions, the ISP also houses the ISP Relay Telescope, which expands the beam 1.5x to 45 mm square, and relays the pupil to RP9, several meters beyond the ISP, in the PABTS sub-system.

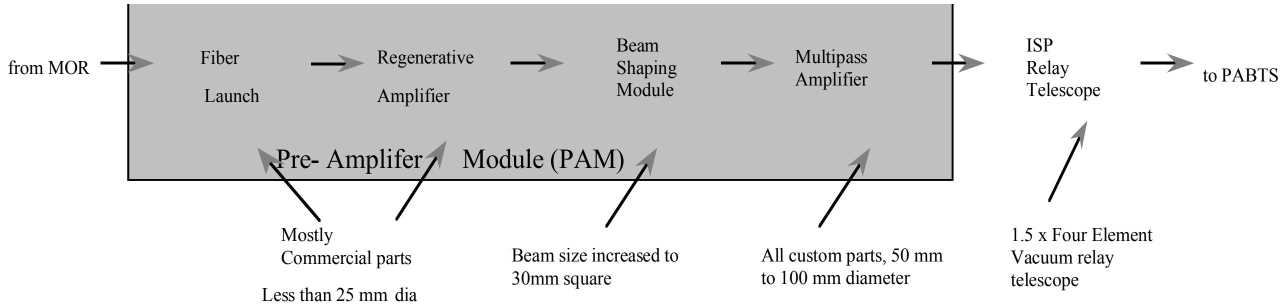

Figure 4. Block Diagram of the PAM and ISP Relay. There are two PAM and ISP's per bundle, or 48 total, in the NIF.

The optics types and quantities for the PAM and ISP Telescope are shown in Table 2. The table differentiates between Regenerative amplifier optics (RA), beam shaping optics (BSM) and multi-pass amplifier (MPA) optics in the PAM, as well as the ISP relay telescope optics (Input sensor laser optics). Elements are grouped into types (window, lens) per package, and then multiplied by the number of packages. Finally, the number of spares expected to be purchased as manufacturing spares is added.

	Regenerative Amplifier	Beam Shaping Module	Multi-Pass Amplifier	Input Sensor, Laser Optics	**Total Elements**
Bst & partial refl.				1	
Mirror	10	1	6	1	
Lens	5	2	6	4	
Diffractive Optics			1		
Waveplate	8		2		
Faraday Rotator	2		2		
Laser Rod	1		1		
Polarizer	6		3		
Special prism	1				
Aperture		3			
Attenuator			4		
subtotal/Package	33	6	25	5	
# of Packages	48	48	48	48	
Total of NIF optics	1584	288	1200	240	3312
Total NIF Optics + Spares	**1664**	**303**	**1260**	**252**	**3479**

Table 2. Optics in the PAM and ISP Relay

Preamplifier beam transport system (PABTS) optics and Injection System

A block diagram of the PABTS sub-systems is shown in Figure 5, and an Isometric view of the system is shown in Figure 6. Light is delivered from the PAM to the PABTS through the ISP relay telescope. On entering the PABTS, the 10-12 J pulse passes through an isolation module, which consists of a wave-plate, a set of polarizers, and a faraday rotator assembly. By rotating the polarization the faraday causes backward propagating beams to reflect off of the polarizers in the assembly, thereby preventing them from re-entering the PAM and causing damage. After the isolation module, the pulse is then split into four equal parts, each 2.5-3 J, using a series wave-plates and polarizers. By rotating the wave-plates, the amount of reflection and transmission of each polarizer can be varied, balancing the four beams. The light then passes through a series of four, 45 degree mirrors, in a pattern like a trombone. By moving the first two mirrors with respect to the other two, the optical path length can be increased, much like a trombone. This is done to allow very precise adjustments to each optical path length with respect to the other three beams in any given quad, for “beam to beam timing”. These timing adjustments are needed to compensate for the differing path lengths found in the main laser transport section in the switchyard and target areas.

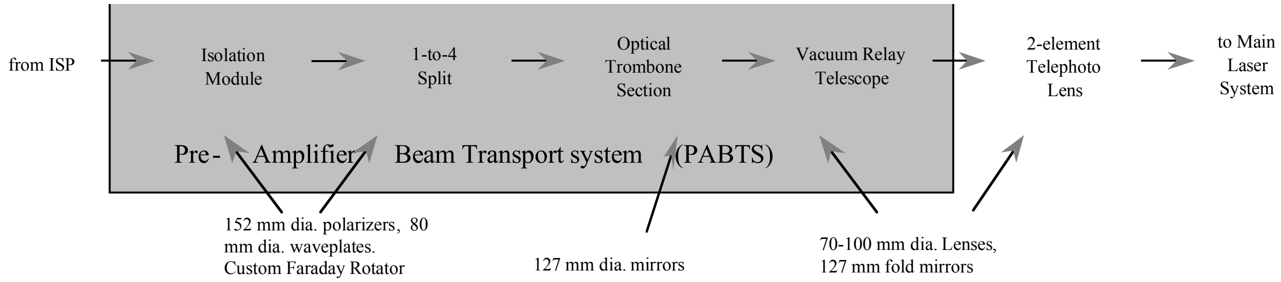

Figure 5. Block diagram of the PABTS.

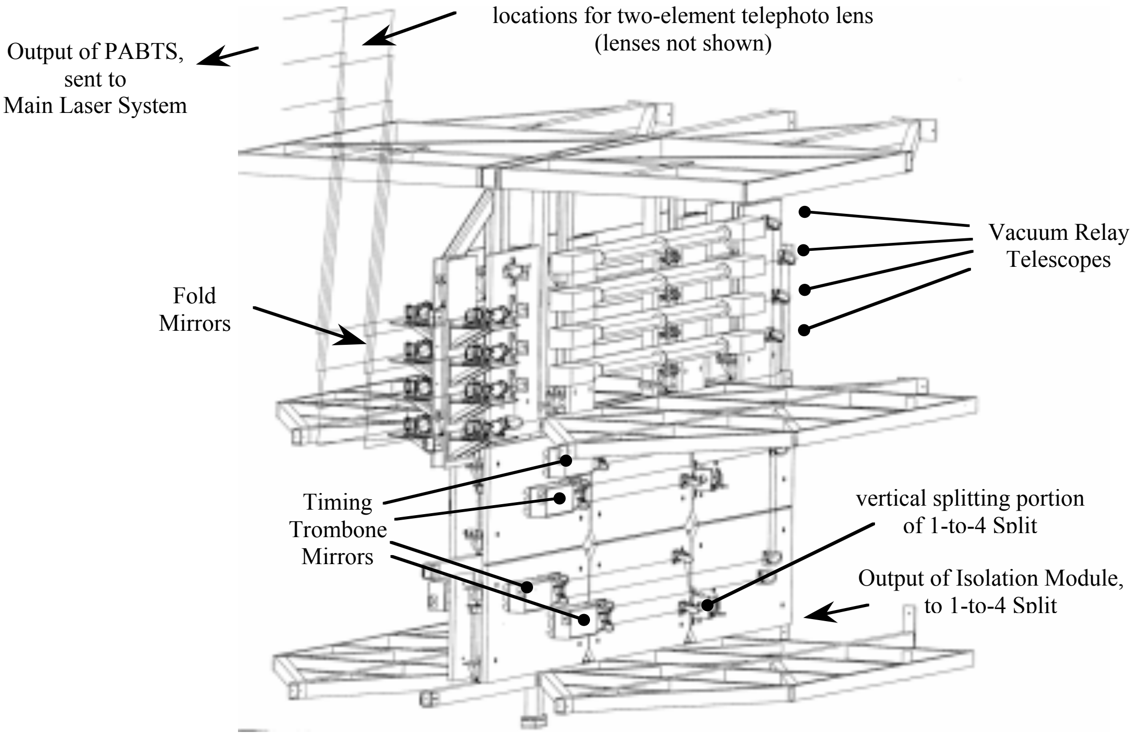

Figure 6. Isometric view of PABTS opto-mechanical layout

Once the path length is set exactly so that all four beams will arrive at chamber center at the same time, the light passes through a multi-element telescope. This system re-images the relay plane from the ISP telescope (RP9) to the entrance pupil of the injection telescope. To do this, the vacuum relay telescope compensates for the variations in path length in the timing trombone. Seven different types of telescopes can be used, each of which can relay a range of +/- 500 mm of path length. Once set for path length and collimation, the telescope can then be zoomed in magnification by +2.5% to -5%, to allow optimum fill of the main laser amplifiers. A series of fold mirrors direct the beam into the injection telescope through the injection window in the transport spatial filter center vessel. This last two element telephoto lens system formats the beam to the acceptance f/number of the main laser system, and relays the entrance pupil onto the appropriate location in the main laser to allow it to be imaged onto the deformable mirror LM1, at RP12.

The optics sizes, types and quantities for the PABTS and Injection system are shown in Table 3. The table lists all of the optics in the isolation modules, the 1:4 split, the trombone and the vacuum relay telescopes together, and those of the injection system. On NIF there will be 48 each of the isolation module and 1:4 split, and 192 each of the trombone section, vacuum relay telescopes, and the injection systems.

	PABTS	Injection System	**Total Elements**
Mirror	26		
Special mirror		8	
Large window		1	
Lens	24	8	
Waveplate	6		
Faraday Rotator	1		
Polarizer	7		
Attenuator	4		
subtotal/Package	68	17	
# of Packages	48	48	
Total of NIF optics	3264	816	4080
Total NIF Optics + Spares	**3428**	**857**	**4285**

Table 3 Optics in the PABTS and Injection System

5. ALIGNMENT AND DIAGNOSTICS OPTICS

Input Sensor Optics and ILS alignment optics.

The input sensor package resides at the end of the PAM and houses the ISP relay telescope described above. The primary purpose of the ISP, however, is to serve as a feedback for the laser alignment system of the MPA and to diagnose the beam quality coming out of the PAM. In addition it serves as a surrogate front end laser during alignment, by providing a CW laser source coaxial with the PAM laser. The system is shown in block diagram form in Figure 7. The main ILS laser beam enters the ISP from the multi-pass amplifier (MPA). A leaking mirror transmits a small amount of this light through a near field reference and into the ISP itself. The rest of the light is reflected into the ISP relay telescope, described in section 4, and then passes on to the PABTS system. In addition to the leak from the MPA output beam, a small leak is also taken from the output of the regen and the output of the beam shaping module (BSM). These three beams are combined in a series of splitters, and then divided again in another series of splitters into an energy detector, a fiber input to a timing detection system, and a camera. The camera can operate either in near field (pupil) or far field (focus) diagnostics mode.

In addition to the ISP, there are a near field alignment source in the MPA behind M5 and a reticle and illuminator in the MPA, in the first vacuum relay telescope in the PAM (T1).

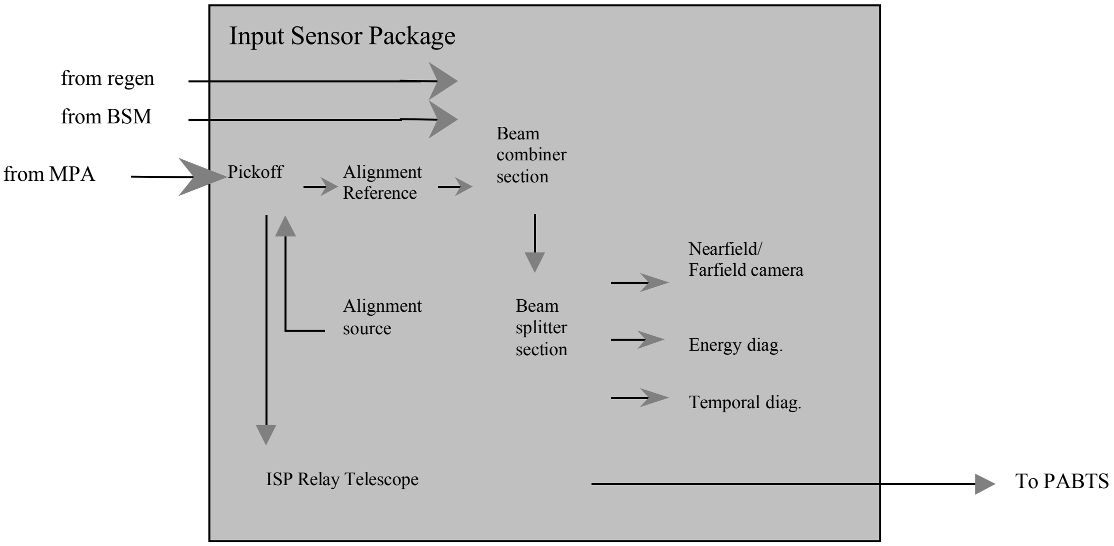

Figure 7. Block diagram of the Input Sensor package

The optics types and quantities for the ISP system, not including the ISP relay telescope and its associated mirrors, are shown in Table 4. Also listed are the ILS light source optics.

	MPA illuminator, Reticle, ALS	Input Sensor, diagnostics	**Total Elements**
Bst & partial refl.		3	
Mirror		12	
Small window		3	
Lens	2	12	
Diffractive Optics		1	
Integrator		1	
Waveplate		1	
Laser Rod		1	
Polarizer		1	
Special prism		1	
Reticles	1		
Aperture		3	
Attenuator		3	
Filter, circular		1	
Filter, wedged		1	
subtotal/Package	3	44	
# of Packages	48	48	
Total of NIF optics	144	2112	2256
Total NIF Optics + Spares	**152**	**2218**	**2370**

Table 4. List of Input Sensor Optics

Output Sensor optics and their associated relays and main laser light sources

The output sensor package is also located beneath the Transport Spatial Filter center vessel. This package receives light from the main laser after the beam has made four passes in the large optics amplifier cavity and two passes through the power amplifier. Light is picked off with a reflection from one of the optics in the final optics assembly (FOA), and a wedged beam-splitter in the main beam line, just after the transport spatial filter output lens, before the transport section of the main laser. In either case, the light returns to the TSF center vessel, where it is picked off and routed, through a series of relay telescopes, to the output sensor package (OSP). In addition to providing images of the main laser output beam in the near field and far field, the OSP provides feedback to the wave-front control system using a Shack-Hartmann wave-front sensor.[5] The system also provides energy measurements and has another channel to couple light into a fiber for delivery to a time-resolved energy detector for pulse shape diagnosis and timing. A block diagram of this system is shown in Figure 8.

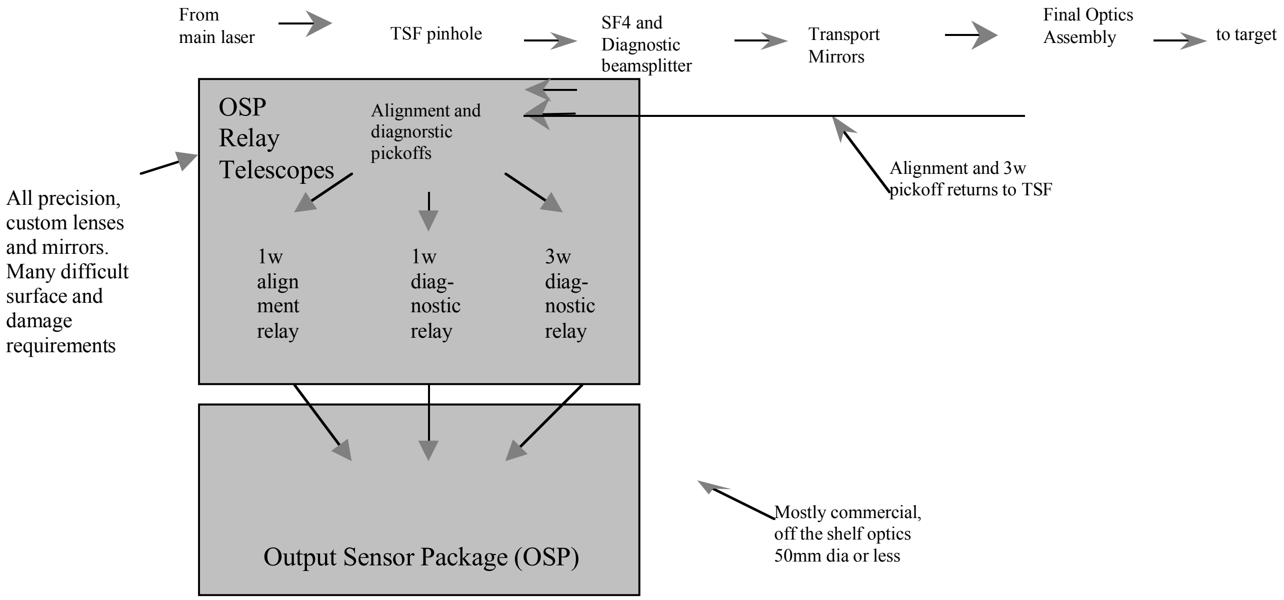

Figure 8. Block diagram of the OSP and its associated relay telescopes.

In addition to the optics required for the output sensor package, there are various illuminators, reticles, and light sources located at the pupil and pinhole planes of the main laser.[6] In the cavity this includes the LM1 near field light source assembly, the CSF pinhole viewer, an illuminator and a reticle. In the transport section this includes the LM3 near field light source assembly (very similar to the LM1 assembly), a reticle and illuminator, a 1w and a 3w pinhole plane light source assemblies, and a couple of other optics required for the alignment system. Generally, there are 192 of each of these alignment packages and components.

The optics types and quantities for the OSP, the OSP relays, and the main laser light sources, illuminators, reticles and viewers, are shown Table 5. The table lists all of the optics by sub-system.

	Output Sensor	1w Alignment Relay	1w Diagnostic Relay	3w Relay	Main Laser Alignment Light Source	Illuminator - Reticle - Viewers	**Total Elements**
Cube beamsplitter		12					
Bst & partial refl.	3		8			1	
Mirror	2	16	28	28	3	1	
Special mirror				8			
Small window					4	1	
Large window		1	1	1			
Lens	26	46	32	44	4	5	
Diffractive Optics	2						
Integrator	2						
Waveplate						1	
Prism	2				4		
Special prism			4		1	2	
Aperture	3						
Attenuator			16				
Filter, circular	12						
Filter, wedged	4						
subtotal/Package	56	75	89	81	16	11	
# of Packages	96	24	24	24	192	192	
Total of NIF optics	5376	1800	2136	1944	3072	2112	16440
Total NIF Optics + Spares	**5645**	**1890**	**2243**	**2042**	**3226**	**2218**	**17264**

5. Optics for the OSP, OSP relays, and other main laser alignment optics.

Target Area Systems and Precision Diagnostics

Other systems reside in the target area or switchyards in the NIF system. The target alignment sensor, or TAS, is positioned at the center of the target chamber and is used to align any of the 192 beams to the target by allowing simultaneous viewing of both.[7] The chamber center reference system is a high-resolution camera system that resides just outside the target vessel, and views through a vacuum window to the center of the target chamber. The CCRS provides an absolute centering reference for the positioning of the TAS.

In addition to these critical alignment functions, there is a final optics damage inspection system (FODI) which can also be inserted into the target chamber, and which can view the final optics and record changes in the beam obscuration profile, thereby cataloging damage to the laser optics. Finally, the pulse synchronization detector (PSD) can be inserted to the target chamber, to diagnose the timing of a given beam-line with more accuracy than can be provided by the OSP.

When a beam-line is to be examined with even greater precision, it can be routed, using the roving mirror assembly in the appropriate switchyard, to the precision diagnostics system (PDS). The PDS provides a 1w near field and far field diagnostic, a Schlieren diagnostic table,[8] and a large optics damage inspection system (LODI). This last allows the user to examine the optics in the main laser for damage without actually opening the beam tubes. The LODI and FODI together form the online damage inspection approach for the NIF[9]. In addition to the damage inspection, the PDS system provides an alignment laser for the alignment of the transport mirrors and the FOA. In switchyard 2, there will also be a 3w diagnostic capability. The beam to be diagnosed can be routed into a surrogate final optics assembly (FOA), which will allow frequency doubling and tripling, and will even allow analysis or observation of the laser performance at the 3w focal spot.

The optics for these target area and precision diagnostics systems are listed in Table 6.

	Target Alignment Sensor	Chamber Centering Ref. System	PDS	LODI/ALS	FODI / Pulse Synch.	**Total Elements**
Bst & partial refl.		3	34			
Mirror		1	75	16	1	
Special mirror	2					
Small window			6	4		
Large window		1	2	1		
Lens	2	6	42	14	14	
Waveplate			1			
Prism				1	1	
Reticles		3				
Aperture					3	
Attenuator			7		2	
Filter, circular		1	33	12	2	
subtotal/Package	4	15	200	48	23	
# of Packages	1	2	2	1	1	
Total of NIF optics	4	30	400	48	23	505
Total NIF Optics + Spares	**8**	**45**	**420**	**51**	**46**	**570**

Table 6 List of alignment and diagnostics NIF optics

6. CONCLUSION

While there are 7552 large optics in the NIF laser system, there are more than three times as many small optics required for the NIF, many of which have demanding tolerances and specifications. In the ILS this comes in the form of stringent wave-front, surface quality and cleanliness requirements. In the alignment and diagnostics systems, there is a wide variety of part types and quality of optics required. In some cases, most notably the OSP relay telescopes, there are wave-front, quality and damage threshold requirements that exceed those of the ILS and the main laser. All of these optics will need to be fabricated, coated, assembled, tested, and then integrated into a series of opto-mechanical packages and systems during the next few years.

7. ACKNOWLEDGMENTS

The authors would like to acknowledge the work of Jenny Rustmann, Lynn Kot, Dave Wang, Ed English, Curt Laumann, and Cal Thompson. Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48

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