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The National Ignition Facility: Laser System, Beam Line Design and Construction

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The National Ignition Facility: Laser System, Beam Line Design and Construction

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ABSTRACT

The construction of the National Ignition Facility (NIF) building and laser beampaths at the Lawrence Livermore National Laboratory has been completed. This 8-year design/construction effort has successfully erected a 450,000 sq ft building and filled its interior with a complex of large-scale optical benches. These benches support all of the large-aperture optic elements of the NIF and the environmentally controlled enclosures that protect each of the 192 laser beamlines as they propagate from the injection laser system, through large aperture amplification stages, and into the target chamber. Even though this facility is very large, nearly 200 m long, 100 m wide, and 30 m tall, stringent mechanical performance requirements have been achieved throughout including temperature control <0.3 °C, laser-beam pointing stability on target <50 μrms, and level 100 surface cleanliness on internal components. This presentation will provide an historical perspective explaining the basis of the design, technical details describing the techniques of construction and a chronological progression of the construction activities from ground breaking to beampath completion.

1. INTRODUCTION

In September of 2003, the construction of the laser beampaths of the National Ignition Facility was completed. This was the culmination of a five-year effort that required the coordination of a general construction contractor with a staff of up to 300 people, more than 30 subcontractors and a dedicated staff of 200 NIF engineers, designers, procurement staff and support personnel. Recently, the optical glass and other laser hardware have been installed into the beampaths of 4 of the 192 beamlines, which have been operated at full performance levels, confirming the success in meeting many of the challenging construction requirements.

Each of NIF's 192 beamlines must be enclosed in a stringently controlled environment. Alignment, thermal, humidity, vibration and cleanliness requirements were defined early in the project during the Conceptual Design Review in 1995. These requirements were of paramount importance in determining the fundamental design features of the facility. As the design progressed through the Preliminary Design Review, and Final Design Review in 1997 and 1998 respectively, these requirements were flowed down to all lower-level subsystems and optimized to produce the minimum cost facility. During construction, LLNL staff carefully monitored field activities to assure full compliance with all specifications that were established during the design phase. This paper will follow the construction of the facility from ground breaking through to completion and show how these requirements were successfully implemented.

2. FACILITY DESCRIPTION

An aerial photograph of the NIF facility and layout of the NIF floor plan are shown in Figures 1 and 2. The Laser and Target Area Building (LTAB) is segmented into five major areas: Laser bays (LB), Capacitor Bays (CB), Switchyard (SY), Target Bay (TB), and core area where the Main Control Room, Master Oscillator Room (MOR) and Preamplifier Maintenance Area (PAMMA) reside. The main experimental area is approximately 100 meters wide and 200 meters long with more than 40,000 m^2 of total floor space available at all floor levels. All areas are one level except for the TB and SY, which have seven floors and in the central core where elevated floors provide space for facility utility equipment.

Figure 1. NIF Facility

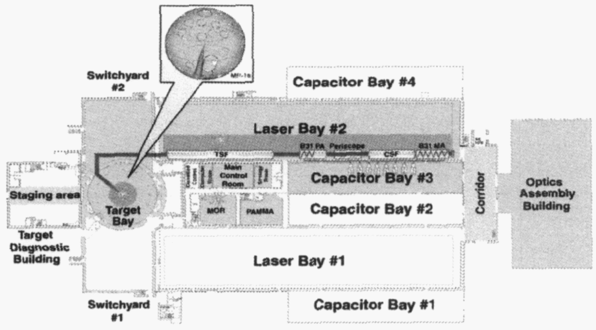

Figure 2. NIF floor plan

Within the facility, approximately 4000 line replaceable units (LRUs) will be installed into the laser beampath. The LRUs propagate, amplify, maintain laser beam quality, and frequency convert the laser light wavelength from 1 micron to 0.35 micron. Each LRU shown in Figure 3 is about the size of a large phone booth and is designed to be portable and easily inserted and extracted into the beampath. These components are installed into a sequence of interconnected enclosures that are collectively called a laser bundle. Each bundle propagates eight laser beams. For NIF, there are 24 bundles arranged in the facility to deliver 192 lasers beams. The function of the laser beampath is to provide the controlled environment for each bundle and to stably support each of the LRUs during experiments.

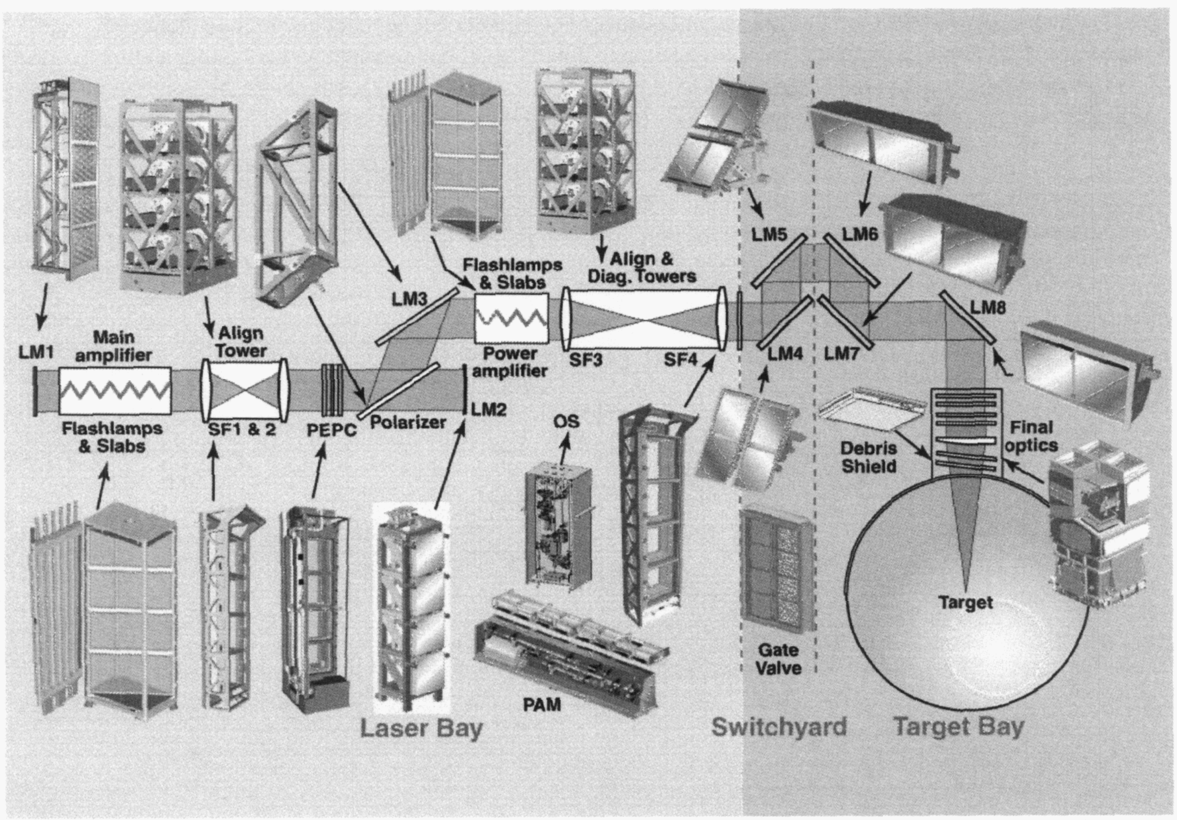

Figure 3. Array of NIF Line Replaceable Units

3. SCHEDULE AND REQUIREMENTS

Figure 4 shows NIF's construction schedule. Construction activities commenced in 1997 at a flat parcel of land in the northeast corner of LLNL's 1-square-mile site. Over the next four years, the LTAB was constructed. During the final two years of building construction, additional work was executed in parallel to install the support structures internal to the building and the laser beam enclosures. These structures were completed in September 2003. During the last year of this effort, laser equipment was installed in parallel with the construction effort. This permitted the successful activation of the first four beamlines approximately one year ahead of schedule. This required intense coordination between the LLNL and construction management team.

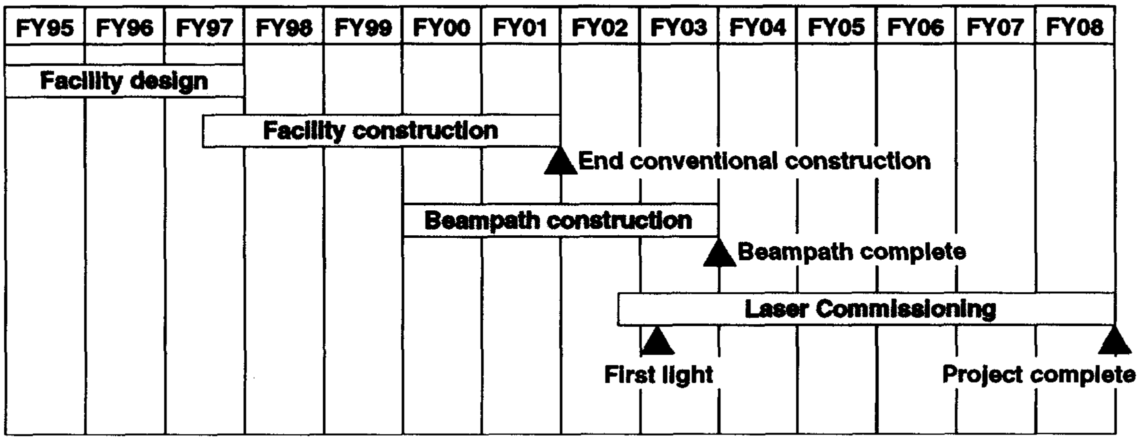

Figure 4. NIF construction schedule

There are seven main requirements, shown in Table 1, which drove the design and cost of the facility and beampath. Stability requirements demanded that the support structures be designed with high stiffness and high structural damping to minimize the effects of nearby rotating machinery. The positional alignment requirement of approximately 1 mm was a challenge for the large size of the structures involved (the SY support structure is 30 meters high) and weight (some vacuum vessels weigh >10 metric tons) and required carefully formulated design features and stringent procedures to

Table1. Top level construction requirements

Requirement	Value
Positional alignment	1–3 mm
Laser pointing stability on target	50 microns
Temperature control	± 0.3°C
Humidity control	50% ± 5%
Facility Cleanliness	Class 10,000
Beampath cleanliness	Class 100
Beampath internal surface cleanliness	Level 100

be developed and strictly followed. Cleanliness, temperature, and humidity control requirements necessitated the construction of central plant facilities and distribution facilities capable of delivering large volumes of HEPA-filtered air into each of the laser bays, switchyards and target bay to achieve Class 10,000 cleanliness conditions external to the laser beampath. Acoustic and mechanical damping was designed into the hardware to minimize vibrations caused by its operation.

Internal to the laser, even more stringent cleanliness condition are maintained. To be successful in achieving Level 100 cleanliness conditions of the installed equipment, strict controls were imposed during fabrication, assembly, transportation and installation of every hardware element exposed to the internal cavity of the laser. A stand-alone clean dry air (CDA) system was constructed to provide the air to the internal components to maintain Class 100 cleanliness conditions and in the area of the amplifier to provide high-velocity air flow to sweep out residual heat from the amplifier components after every laser shot. This was necessary to minimize thermally induced distortions in the laser beam.

4. BUILDING CONSTRUCTION

A 1998 construction photo of the LTAB building is shown in Figure 5. At this point in time the construction team had completed major excavating activities. The conventional steel girder construction of the laser and capacitors bays is shown. Approximately 15 meters tall and 150 meters long, this structure, with its insulated siding, shelter the LB

Figure 5. Early LB construction photo

Figure 6. LB Support pedestals

components from the weather and contains the temperature- and humidity-controlled air that circulates within the facility. Vibrations in this structure caused by the wind and HVAC rotating equipment were isolated from the optical equipment. This was achieved by the constructing a 2-meter-thick concrete slab that covered the full width and length of each laser bay. This inertial slab was vibration isolated from the building structure with physical gaps that were filled with damping material. The slab was made in a single pour and heavily reinforced to provide maximum stiffness and strength. All of the LB optical support structures are mounted on this isolation slab.

In Figure 6 the laser slab and some of the LB support structures are shown prior to the installation of the beampath enclosures. Each structure is rigidly attached to the slab with imbedded rebar and formed from very thick concrete sections that develop high stiffness and relatively high resonant frequencies. Extensive finite element analyses were performed for all of the NIF structures. In general, the lowest resonant frequencies of the structures in the laser bay were calculated to be greater than 8 Hz.

To establish vibration requirements for the NIF facility, extensive vibration measurements and analyses were conducted. Prior to any construction, free-field accelerometer measurements were made at the site. Based on these measurements and calculations, it was concluded that it would be reasonable to maintain the power spectral density (PSD) levels at the base of any optical support structure less than about 1×10^{-10} g^2/Hz. Detailed calculations indicated that if this were maintained, then the optics resting upon these structures would have translation and rotational displacements consistent with the overall requirement of maintaining laser pointing on target less than 50 microns rms. As the NIF design progressed, this simple requirement was modified to decrease the PSD levels by a decade in the frequency range less than about 70 Hz. Throughout all of the design and construction activities, this requirement played an important role in controlling the amount of vibration permitted into the facility and determining whether the installed equipment was adequate to meet the stability needs of the project.

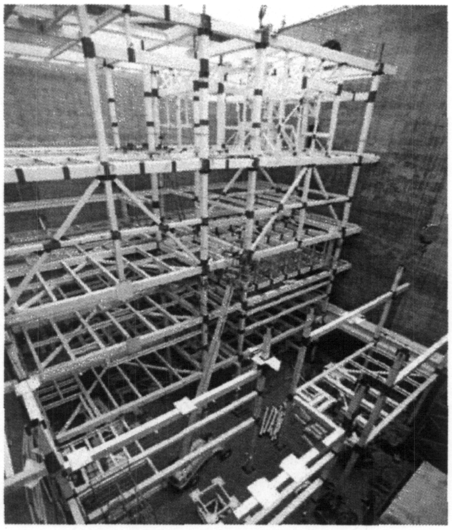

Figure 7. SY support structure

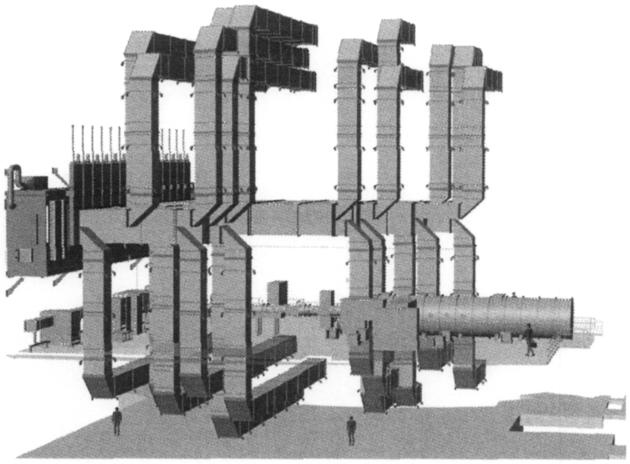

Figure 8. SY beampath computer model

Each of the switchyards is essentially a 7-story concrete building that is 30 meters square and 30 meters high. Walls are 1 meter thick to provide stiffness and thermal insulation. As in the laser bay, a 2-meter-thick concrete slab was poured at the floor elevation to provide a stable platform on which the optical support structure would be mounted. External concrete stairwells were constructed at the midspan of the two external walls to provide for personnel access, but also to strengthen the wall for earthquake safety.

Figure 7 shows the concrete structure and the steel spaceframe structure that was erected inside it to provide the mounting platforms for the laser transport mirrors. This structure is attached only at the floor and corners of the vertical concrete walls. This minimized the amount of vibrations transported to the optics from rotating machinery and wind. Within the switchyard the laser beams are transported vertically and horizontally and then into the target bay, Figure 8. To perform this function, the laser beams are transported in long, rectangular beam enclosures. It is vital to maintain a constant temperature of these enclosures to prevent internal convection currents inside the beam tubes, which would have deleterious effects on the wavefront quality of the laser beams. This type of structure, with floor gratings at each of the seven levels, provides for good vertical air circulation and relatively uniform temperature conditions.

Like the switchyard the target bay is a concrete structure but it is cylindrical with 2 m thick walls for neutron absorption, Figure 9. It is 30 meters in diameter and about 25 meter tall. Unlike the switchyard the elevated floors in the TB are concrete and are integral with the wall construction. Vertical air flow in the TB was deemed impossible given the amount of equipment that was anticipated to be required. Thus, horizontal air flow was implemented and the solid concrete floors used to provide a very stable platform for all of the TB transport mirrors.

The target chamber is located in the center of the TB. It is a 10-meter-diameter aluminum vacuum vessel that rests on a concrete pedestal in the middle of the TB. It is covered with about 30 cm of borated concrete to assist in absorbing neutrons that are generated during experiments. With this added mass and the weight of the final optics assemblies that are also mounted on the target chamber, the fundamental bending mode of the system was calculated to be too low to meet stability requirements. For this reason, lateral supports connecting the target chamber to intermediate floors were installed to resist the cantilever bending modes.

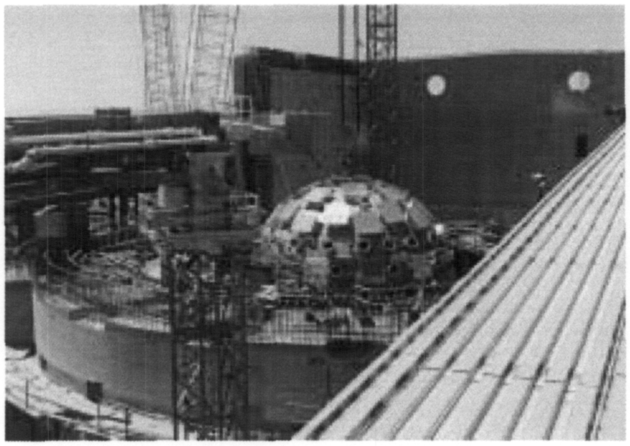

Figure 9. TB under construction

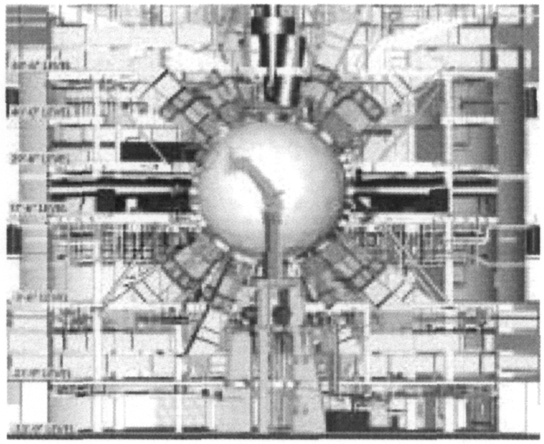

Figure 10. TB layout

Laser transport mirrors mounted on the floors of the TB direct the laser beams into the target chamber. Their vibration stability is critical to meeting pointing requirements on target. Initial finite element calculations indicated that there would be unacceptable vertical vibrational modes in the floors. To improve the stability of the mirrors vertical columns and 45-degree truss elements, shown in Figure 10, were added. These supports were optimally located by analysis to minimize their number and impact on material transport within the TB.

5. BEAMPATH CONSTRUCTION

In the year 2002, sufficient progress had been made in the facility construction that it was possible to start installing laser beampath hardware into the LTAB. This effort began in LB2.

5.1 Laser Bay

The facility construction effort provided the stable concrete platforms on which the laser beampath was to be installed. Referring back to Figure 3, one can see there are a large number of varied optical assemblies that the beampath is required to support in the laser bay. This necessitated several different types of structures to accommodate the special needs of each optic.

The LB beampath can be divided into 2 types: air and vacuum. The air beampath elements contain laser slabs that amplify the main laser pulse, deformable mirrors to correct for wavefront distortions, and transport mirrors/polarizer/Pockels cell to inject/extract the laser pulse into the main amplifier cavity. Vacuum beampath elements support the spatial filter lenses that relay the optical images and focus the laser beams through pinholes in the Cavity and Transport Spatial Filter vessels.

The air beampath elements consist primarily of amplifier, periscope, and beam enclosure structures. Figure 11 shows the amplifier beampath element being installed. Laser slabs and flashlamp LRUs are mounted into this Frame Assembly Unit (FAU). For all of NIF, 48 FAUs were installed. They were assembled and aligned in an offline facility and then transported to the LTAB where they were placed into position with alignment accuracy of about 3 mm. During this entire process, care was taken to maintain a constant stiffness of the handling hardware to assure undisturbed alignment conditions. This construction strategy minimized the amount of work performed in the LTAB, which was critical in maintaining a cost and schedule efficient operation in the LTAB, where hundreds of people were working. In full production mode, the entire installation process was completed in about four hours per FAU with a team of about six workers.

Figure 11. FAU installation

The periscope structure houses transport mirrors, polarizers, and Pockels cells. Shown in Figure 12, the periscope is a large welded steel structure formed with internal trusses and a welded external steel skin. The structure extends across one-half the width of a laser bay, about 15 meters. Too large to be manufactured offsite and transported to the LB, this structure was constructed in situ. Each structure required about four months of intense effort by a team of about 6–10 workers. After the structure was welded out, welds were passivated, mounts attached, the structure precision-cleaned, and then sealed with removable covers.

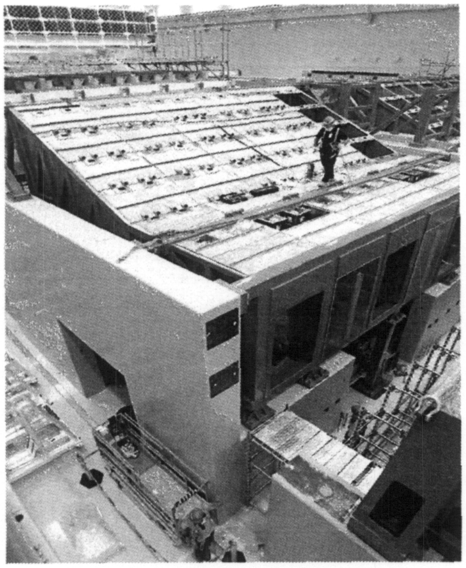

Figure 12. Periscope structure construction

Figure 13. LB beampath enclosures

Connecting many of the air beampath elements are beam enclosures like those shown in Figure 13. These particular enclosures connect the power amplifier to the transport spatial filter. The enclosures are rectangular in cross section, 2 m × 3 m, and vary in length from 2 m to about 4 m. In the LB, the enclosures are aluminum monocoque construction using thin sheet metal panels with welded stiffeners. More than 200 of these units were installed for all of NIF. At the end of each enclosure, p-seals are provided to minimize air leakage and the cost of the equipment supplying air to each beampath.

In the LBs there two groups of vacuum enclosures, the cavity and transport spatial filters. The design of each is similar except for their length; the cavity filter is 22 m long and the transport spatial filter is 60 m long. At the ends and in the middle of the spatial filters are large, rectangular stainless steel vacuum vessels. The end vessels house the lenses that focus the laser beam into the middle of the center vessel. Connecting the vessels are either rectangular or circular tubes to contain the vacuum and laser beams that propagate through them. Figure 14 shows a 25-m section of beam tubes being installed. Preassembly work had been performed in a nearby capacitor bay that had not yet been filled with equipment.

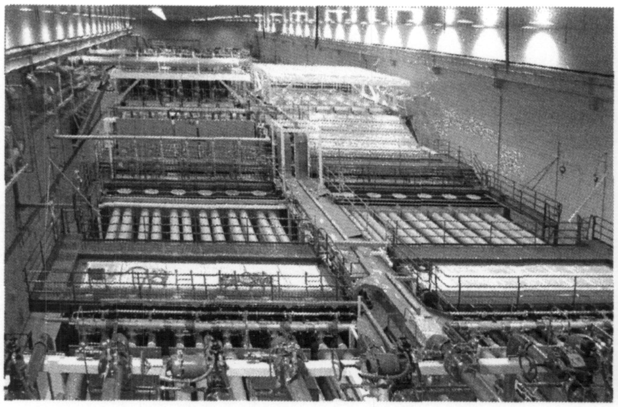

Figure 14. Transport spatial filter beam tube

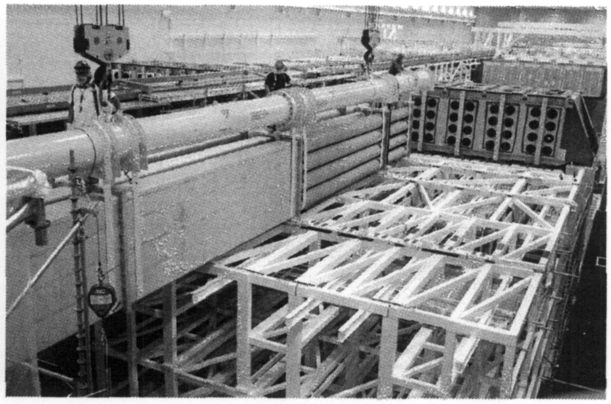

Figure 15. LB beampath

A view of a completed beampath looking from above the main laser amplifier toward the TB is shown is Figure 15. The hardware is very densely packed but sufficient access to the equipment is provided by corridors extending down the length of the LB, work areas underneath the beampath, and work platforms that are distributed over the top of the laser. These platforms provide access to the laser equipment and to the utilities that are distributed from the main utility spine located down the center of the laser bay.

5.2 Switchyard

The main function of the SY beampath is to provide an argon atmosphere for the laser beams and the transport mirrors that direct the laser beams from the LB into the TB. Shown in Figure 8 the laser beams are transported horizontally from the LB to the LM4 mirrors that direct the beams vertically. At the proper elevation LM5 mirrors then reflect each laser beam horizontally into the TB. In each switchyard there are 24 LM4 mirror assemblies directing groups of 4 laser beams and 48 LM5 assemblies.

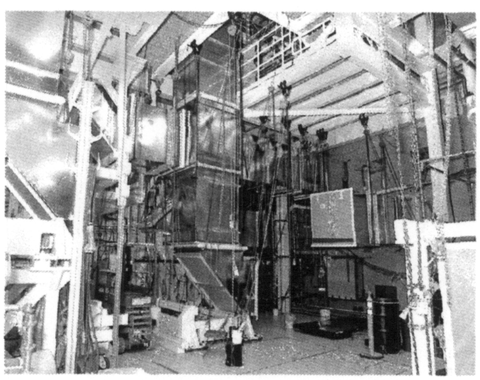

Figure 16. SY beampath

The beampath in the SY presented an unexpectedly difficult construction challenge. The beam enclosures and their support structures are positioned in a very densely packed arrangement. In each switchyard more than 200 enclosures were assembled and precleaned to Level 80 surface cleanliness. They were then transported to the SY and rigged into approximate position. When the appropriate collection of neighboring enclosures were in place, crews specializing in clean connections would connect enclosures. Following successful connection, permanent steel support elements were attached to hold the enclosures in their precise position. The interconnectivity between beampaths, the 3-mm placement tolerances of some components, and the requirement to maintain cleanliness requirements while other steel construction activities were being performed made the logistics of this effort one of the more challenging in NIF. The initial rate of installation began as a few per week but improved to two per shift for a well-trained crew near the end of construction.

The beam enclosures in the SY are similar in construction to the aluminum monocoque enclosures in the LB. Vibration isolators attach the enclosures to their steel supports. Airflow in the facility that is required to maintain cleanliness and temperature requirements is sufficient to vibrate the thin enclosure panels. This vibration energy is attenuated by the isolators, which permit the nearby transport mirrors to meet their stringent stability requirements.

5.3 Target Bay

All 192 laser beams are focused into the center of the target chamber. The laser beams arrive in groups of four in the TB in horizontal beam enclosures that are located above and below the target chamber. Two or three transport mirrors are needed for each laser beam to radially direct each beam towards the target while maintaining proper beam orientation and polarization, see Figure 17. These mirrors are located in mirror frames that are located on the floor levels where the beams enter the TB.

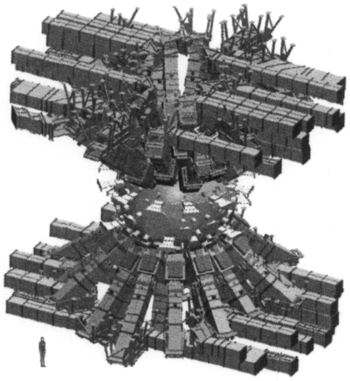
Figure 17. TB beampath computer model

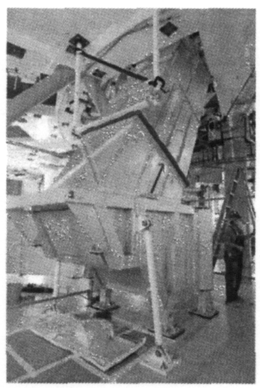
Figure 18. Mirror frame assembly

The manufacture of the mirror frames were among the most challenging for NIF. Three vendors were qualified and utilized to deliver all of the units required. This provided backup options in case of substandard vendor performance and also enabled rapid delivery over the relatively short time frame demanded by the construction schedule. Since the geometry of the laser system morphs from orthogonal to spherical at the mirror frame, the design of the mirror frames necessitated many skew angles. Further complicating the construction is the close proximity of the mirror frames to each other and nearby beam tubes. The precision demanded by this design necessitated intense LLNL presence at each of the vendors, and thorough QA inspection.

Forty-eight rectangular apertures were formed into the target chamber to permit all of NIF's 192 laser beams to enter the chamber, see Figure 19. As the beams enter the chamber, the 1-micron laser light is converted to 0.35-micron light as they pass through the Final Optics Assembly (FOA). Several of these units can be seen in Figure 20. Thermal and vibration performance of these assemblies were analyzed in detail to assure compliance with stability requirements. Results indicated that the target chamber provided a stable enough platform with the proper isolation of vacuum pumping hardware and that local water cooling would be required in the FOA to maintain temperature uniformity requirements.

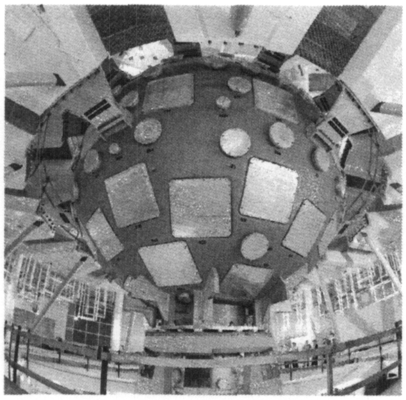

Figure 19. Target chamber

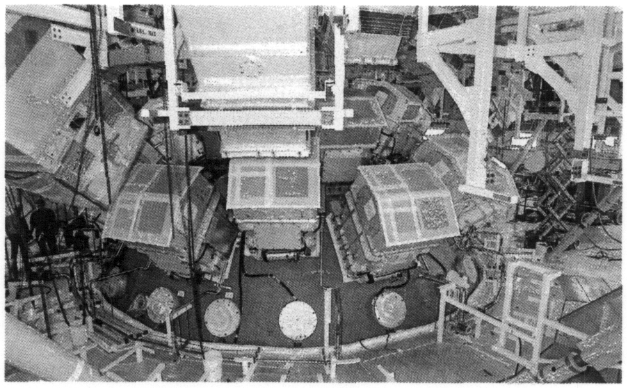

Figure 20. Final optic assemblies

5.4 Alignment and stability

Achieving the NIF alignment and stability requirements required an extremely comprehensive and well-coordinated effort from the Conceptual Design Review through construction completion. Key to the success was the early flow-down of requirements to each relevant subsystem and the persistent monitoring of compliance with the lowest level requirements. Although only four of NIF's 192 laser beams have beam activated, the alignment and stability results have been excellent. As examples of this success, Figures 21 and 22 are provided.

Figure 21 shows the positional accuracy achieved for all of the amplifier Frame Assembly Units. The overall placement requirement was ±1.5 mm. As can be seen better than 0.5 mm was achieved on all FAUs except for one. This nonconformance was later corrected using the adjustment capability that had been provided. Similar results were achieved on all of the other large structures for NIF. Intense interaction between the construction crews and LLNL engineers was critical in this success.

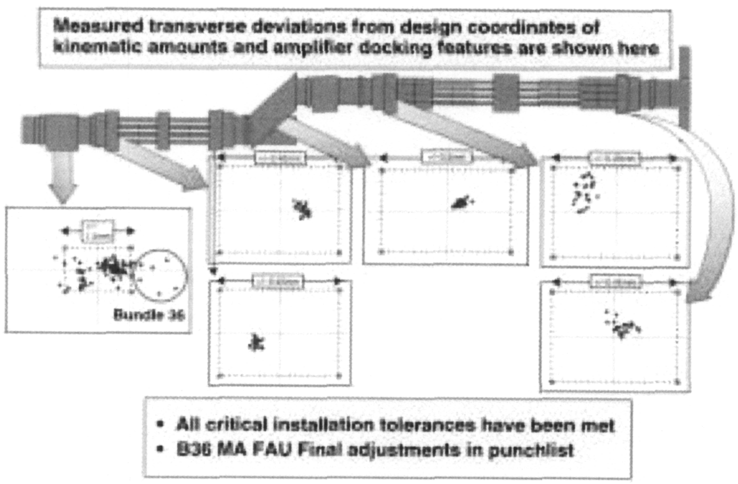

Figure 21. Placement accuracy of FAU's

The success of maintaining the vibration stability of the optical components is shown in Figure 22. This data shows measurements of the pointing of an alignment beam on a sensor located at target chamber center. Numerous measurements were made over a 1-hour time frame. All of the data falls well within the 50 micron rms requirement.

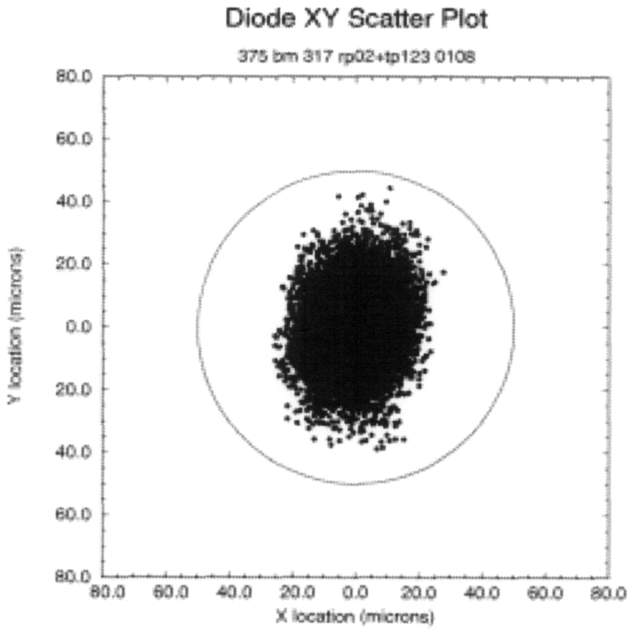

Figure 22. Laser beam positional stability

5.5 Cleanliness

A comprehensive cleanliness program was initiated early in the NIF design phase. Every component was assigned an as-installed surface level requirement. The engineering, production and construction staffs were trained with procedures that were developed to achieve the overall requirement of level 100. To achieve this many techniques were used depending the component and requirements. Several large clean rooms similar to Figure 23 were purchased and located strategically in not-yet-used areas of the facility. Frequently, temporary clean rooms formed from inexpensive low-outgassing sheets of polyethylene and HEPA filter fan units were erected to permit beampath connections. By the end of the project, this process became routine, inexpensive, and very effective. In some cases where a connection could be made quickly and ambient conditions were better than Class 5,000, connections could be made without a clean room. This is shown in Figure 24. Together, all of these techniques provided a very effective process for connecting all of NIFs beampath hardware.

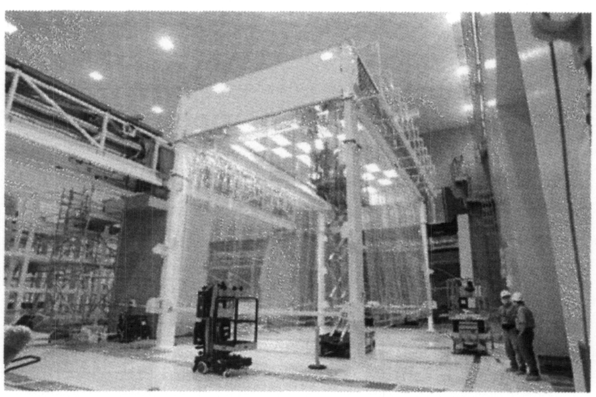

Figure 23. Temporary clean room

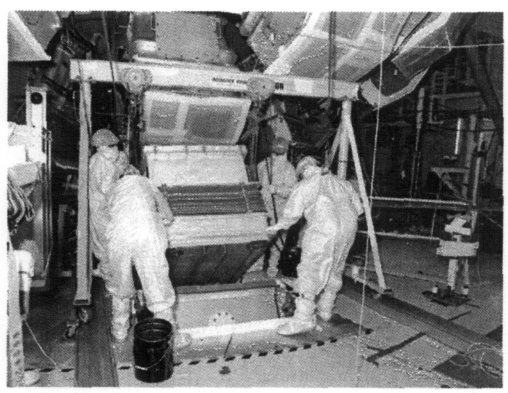

Figure 24. Clean "quick" connect

Measured cleanliness data of LB hardware, shown in Figure 25, indicates the success with which these processes were implemented. Nearly 2000 cleanliness swipes were taken on hardware installed in LB2. The peak values of this data are required to fall below Level 160. With the exception of a very small percentage of points, this requirement was achieved. When the nonconformance points were realized, corrective action was taken which included additional cleaning and, in some cases, acceptance of the nonconformance if it was found in a benign location.

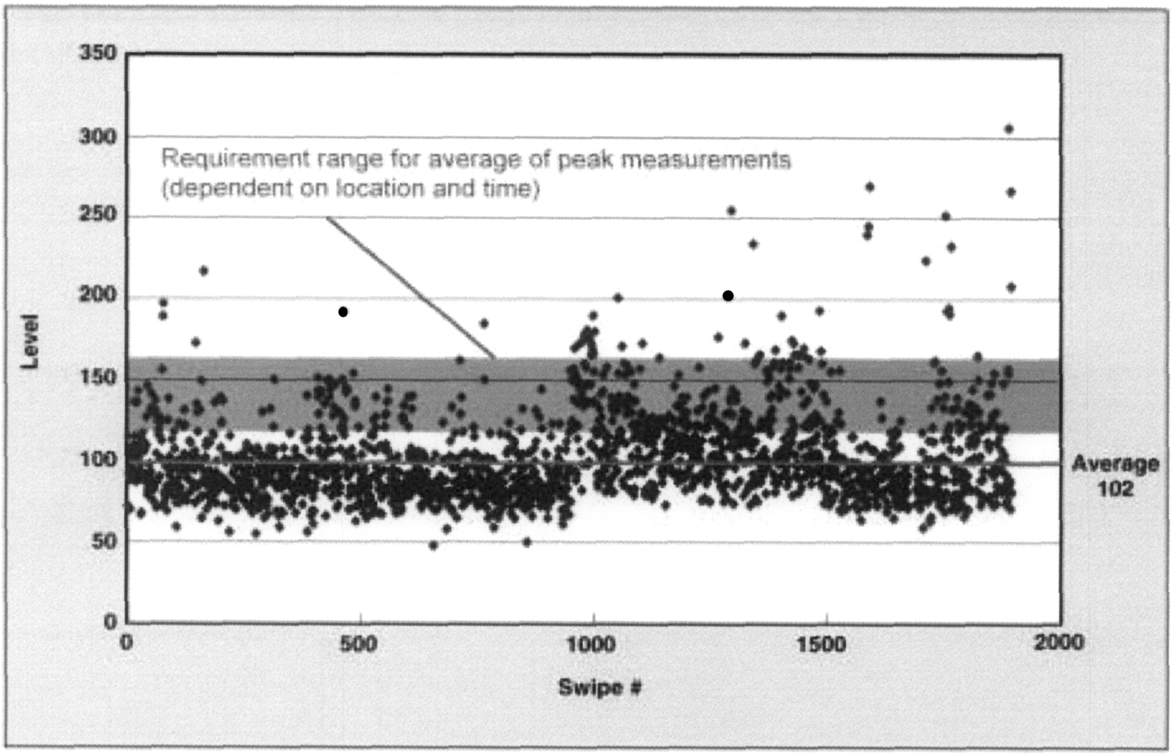

Figure 25. Measured LB surface level cleanliness

6. SUMMARY

The NIF Facility/ beampath has been successfully designed, fabricated, and constructed for all 192 beampaths over a 9-year time span. Four of the beampaths have been commissioned and demonstrated to comply with all mechanical requirements. During the remaining five years of the project, the remaining hardware will be activated in parallel with the commissioning of the laser hardware. A relatively small staff of engineers, designers, and construction staff will assist in completing this last phase of the project. Based on the success of the deployment of the initial hardware, the project has developed high confidence that the remaining hardware will meet all requirements.

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