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ENGINEERING THE NATIONAL IGNITION FACILITY

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ABSTRACT

The engineering team of the National Ignition Facility (NIF) has developed a highly optimized hardware design that satisfies stringent cost, performance and schedule requirements. After a 3-year effort, the design will culminate at the end of FY98 with the completion of major Title II design reviews. Every element of the facility from optic configuration, facility layout and hardware specifications to material selection, fabrication techniques and part tolerancing has been examined to assure the minimum cost per joule of laser energy delivered on target. In this paper, the design of the major subsystems will be discussed from the perspective of this optimization emphasis. Focus will be placed on the special equipment hardware which includes laser, beam transport, opto-mechanical , system control and target area systems. Some of the unique features in each of these areas will be discussed to highlight how significant cost savings have been achieved while maintaining reasonable and acceptable performance risk. Key to the success has also been a vigorous development program that commenced nearly 4 years ago and has been highly responsive to the specific needs of the NIF project. Supporting analyses and prototyping work that evolved from these parallel activities will also be discussed.

I. INTRODUCTION

The NIF Project has forged ahead rapidly since completing its Title I (preliminary) design in December of 1996. NIF is arguably the largest and most complex laser project of its kind ever undertaken. It is easily the most challenging laser-target interaction system ever constructed anywhere in the USA and, most likely, anywhere in the world. With a primary requirement to deliver 1,800,000 joules of ultraviolet laser energy at a peak power of 500 TW, NIF must exceed the Nova laser, currently LLNL's largest ICF experimental tool, by factors of 40 in energy and over 10 in peak power. The power of all 192 NIF laser beams together will be about 1000 times the total electric generating power of the United States. The cost of this extraordinary facility would be prohibitive without a highly optimized design and a closely-coupled technology development program. The Title II engineering design, which has evolved over the past year, has implemented the advances of a 4-year development effort and evolved a design that will achieve the lowest cost per unit of laser energy delivered than any laser system previously deployed at LLNL. Figure 1 shows the dramatic improvement in cost-effectiveness that has been achieved in the NIF design. In terms of the unit cost of laser hardware needed to deliver 1 joule of 1 micron laser light we have improved by a factor greater than 20. Labor costs are not included in this figure.

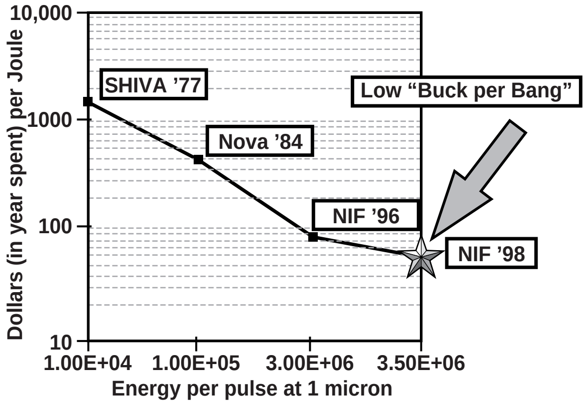

Figure 1. The "buck per bang" of the NIF facility is significantly lower than any previous LLNL laser system.

II. LASER ARCHITECTURE

It is very important to minimize the cost of laser hardware for a project as large as the NIF. The minimum cost system will have the largest practical beam aperture, even though that choice results in lower amplifier stored energy per unit area and requires larger individual optical components. A major reason for this minimum is that a system with the largest practical optical aperture has the minimum number of beams, and the costs of many features of the system (mechanical hardware, alignment and diagnostics, and assembly labor, as examples) are proportional to the number of beams but much less sensitive to their aperture. Large beams also minimize the fraction of the optical aperture devoted to edge effects such as apodization of the intensity profile or edge distortions in amplifiers. Current technology for laser glass and crystals dictates an aperture size of about 40 cm for the major laser optical components.

The NIF laser design groups optical components into large arrays ("bundles") composed of apertures stacked two wide and four high, with six of these units close-packed together to form a 12 wide, 4 high cluster of beams.

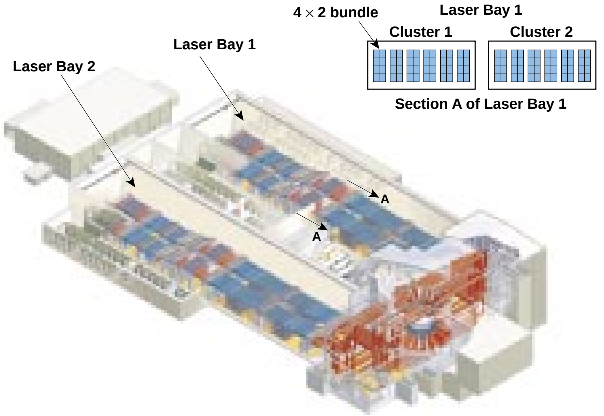

Figure 2. The NIF laser architecture is based on a 4x2 beam bundle which is replicated 24 times.

These compact assemblies minimize the number of components such as flashlamps, and the overall building volume. The hardware cost would be reduced somewhat if the 12 wide, 4 high cluster were a single mechanical assembly. However we segmented that array into individual bundles to reduce the risk of cross-contamination between beams and to make it easier to fire partial system shots that use only a subset of the 192 beams. The individual beams are optically independent, though supported by common mechanical hardware and pumped by common flashlamps. The 4-high configuration is convenient for operating two large xenon flashlamps in series (so that all electrical connections can be made at one end of an array) with a low enough voltage to minimize the cost of the pulsed power for the flashlamps.

These compact arrays drive the system to use square optical apertures for more efficient close-packing of components. Rectangular components are somewhat less convenient for fabrication than circular components, but the savings in mechanical hardware and building volume easily outweigh this inconvenience and many components (amplifier slabs, polarizers) in a system having round beams will not be round in any case.

Most large glass lasers designed for inertial fusion experiments are single-pass master oscillator/power amplifiers (MOPA). It is a familiar and well-proven design that can be assembled and tested in stages, so performance risk is low. Cost and complexity, however, are high. There is a very large number and variety of components: the Nova laser at LLNL, as an example, contains one rod amplifier and five sizes of elliptically-shaped slab amplifier (a total of 41 slabs) in each of ten independent laser amplifier chains, with relay telescopes and isolators between all of these, plus eight additional rod amplifiers of several sizes, and several telescopes between the oscillator and the amplifier chains. Even at the time Nova was designed (late 1970's) it was well understood that a multipass design could eliminate many of these components and would be significantly less expensive.

However, multipass amplifier requires a method for separating input and output beams in the amplifier cavity, which is not necessary in single-pass systems. For NIF we have chosen a combination of far-field angle and active polarization switching in the final amplifier stage, as shown in Figure 3, with four passes (two round trips) through the system. The four-pass configuration for the final amplifier makes the preamplifier small enough (~3J/beam) that the cost savings from any further reduction would be negligible. Also a larger number of passes leads to larger coherent addition of aberrations and to larger off-axis angles, reducing the beam size.

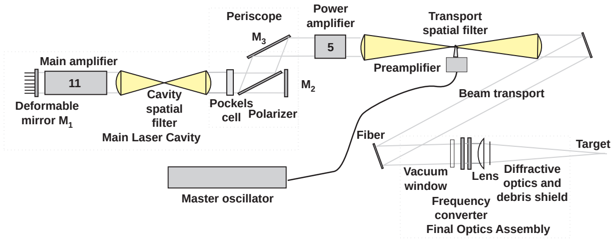

Figure 3. The multi-pass architecture of NIF significantly reduces the number and types of components that must be fabricated.

III. SYSTEM/COMPONENT DESIGN

A. Facility Design/Beam Transport System

The Laser and Target Area Building (LTAB) and the Beam Transport System are the primary infrastructure for all other systems in the National Ignition Facility. Their primary functions are structural support, hermetic enclosure, environmental control, and utility supply for all major subsystems. Together, they comprise the worlds largest optical bench, capable of thermally and mechanically stabilizing thousands of optics and diagnostics in their relative positions to direct each of the 192 laser pulses to the target.

The building is divided into 10 major bays, which provide isolation for electrical, laser, and radiological safety zones, see Figure 4. Four Capacitor Bays store and transmit pulsed power to the two Laser Bays, where laser light is amplified, conditioned, and propagated to the Switchyards. Each of two Switchyards provides the spatial transition from the dense arrays in the laser bays to the distributed Final Optics in the Target Area. In addition, a staging bay called the OAB Corridor is provided between the Optics Assembly Building (OAB) and the LTAB. Finally, a Diagnostics Building is located adjacent to the Target Area to provide logistics support, an Environmental Protection System, and auxiliary space for technical operations.

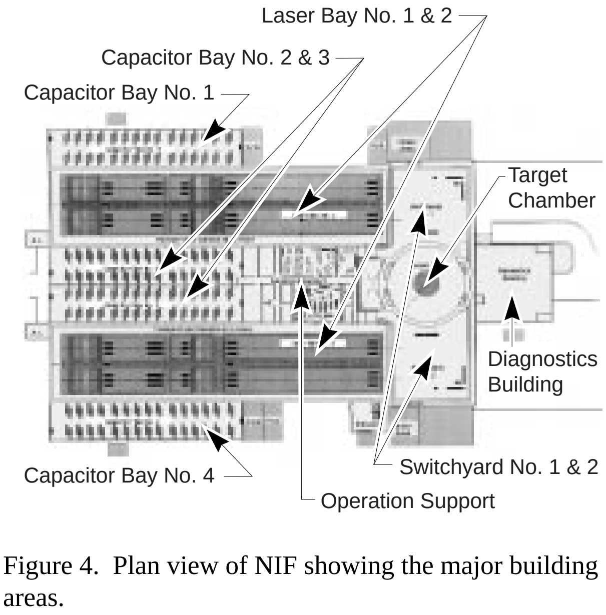

Figure 4. Plan view of NIF showing the major building areas.

The NIF optical system requires extremely accurate pointing stability (< 50 micron rms for all 192 laser beams) to successfully illuminate and ignite a target. The facility structure design was greatly influenced by requirements to isolate the laser hardware from thermal and mechanical disturbances. Thermal stability was attained in the large laser bays by using surrounding walls as return air plenums for the HVAC systems. This created an effective insulation boundary to the outside world, while carrying transient heat loads directly to heat exchangers. This reduced the amount of insulation and cost required to maintain the tight temperature controlled environment (±0.3 °C) inside the building.

The combination of heavy and deep foundations, thick concrete shear walls in support structures, and high stiffness-to-weight ratio superstructures minimizes the affects of ambient vibrations. Some optics are held eight stories above the foundation, requiring uniquely rigid and highly damped support systems. Others are densely-packed into heavy space frames, hundreds of tons of steel weldments fabricated and aligned to machine-tool tolerances. In all cases, the design of the building and its internal optics support structures have been optimized as one system to meet stringent stability requirements. Costs have been kept to a minimum by using traditional structural material while optimizing each design through extensive use of finite element structural analysis.

The massive optical supports inside the building, shown in Figure 5, underwent intensive technical performance and value engineering studies to meet stringent requirements at minimum cost. After an aggressive campaign to apply the most efficient combinations of materials, structural shapes, and fabrication methods, a configuration was chosen which optimized the use of both reinforced concrete and welded steel space frames. This approach, which capitalized on concrete's damping properties and steel's relatively light weight and low cost, was consistently applied for every structure in each Laser Bay and Switchyard.

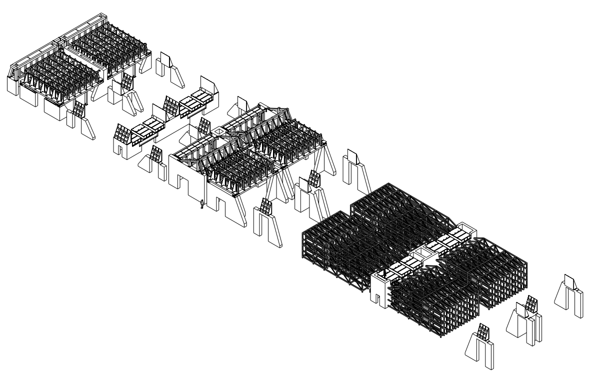

Figure 5. The laser bay structures have been highly optimized to provide maximum stability at low cost.

NIF optics are subject to laser fluences near their damage-threshold and have highly sensitive coatings. For these reasons, they require extensive provisions to minimize organic and particulate contamination. The first level of protection for all optics in the main laser cavities are the hermetically-sealed enclosures provided by the Beam Transport System for all beam paths in the Laser Bays and Switchyards. These gas-filled enclosures are pressurized with nitrogen or argon to minimize the intrusion of contaminants. Secondary protection is provided by the LTAB's multiple HVAC systems, which create a down-flow cleanroom environment consistent with protocols established on other successful laser systems. These air handling systems also assure temperature stability, which minimizes optic pointing errors induced by thermal distortion of the large support structures.

Approximately half the path of the laser resides in evacuated spatial filters, which require thousands of tons of stainless steel vessels to enclose the beams, and large dry pumping systems to maintain low pressures and stringent cleanliness conditions. The ends of these large vessel assemblies support lenses that form the boundary between the evacuated space and the adjacent gas-filled cavities. This requires a stiff, flat mounting face to assure stability and interchangeability of lens assemblies. Each vessel, the size of a trailer home, was optimized for stiffness, weight, and constructability. Internal brake-formed walls, free of stiffeners which could trap contamination, allow each bundle of eight laser beams to be operated independently. A total of 48 individual volumes (up to 93000 liters each) are pumped by a distributed roughing system combined with local high vacuum pumps.

Detailed fabrication, transportation, storage, and installation planning was an essential element of the design process. Fundamental decisions on building cranes, access points, and lay down space were made early, allowing development of an integrated construction schedule for Conventional Facilities and Special Equipment. Critical path studies illuminated the need for long lead procurement of 2300 tons of stainless steel plate, and more than 1000 tons of structural steel purchased directly from mills. Riggers, weld inspectors, construction planners, safety officers, and quality assurance personnel contributed to numerous design decisions.

Amplifiers and adjacent beam tubes are filled with highly purified nitrogen gas, to minimize corrosion of the polished silver reflectors within the amplifiers and to maintain stringent cleanliness and temperature control of the laser path. A 100,000 cfm closed loop nitrogen circulation and filtration system is provided for cooling the amplifier flashlamp cavities between shots, in order to minimize the thermal distortion of the amplifier slabs.

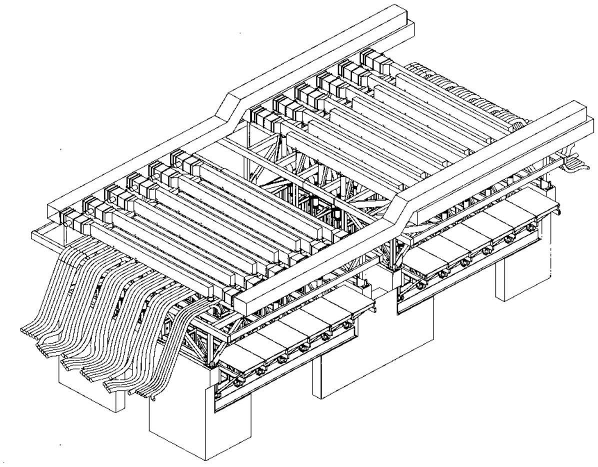

Figure 6. A precision, low-cost gas cooling system has been designed for the amplifier to reduce thermally induced laser distortion.

Although this system is unique and complex, the final design of all components was achieved without inventing new technology, manufacturing methods, or materials. Standard tolerances for structures and machinery, plus simple adjustment capability, were applied in a highly disciplined and creative manner to assure a safe, reliable, and low risk configuration.

B. Laser Components

While the NIF laser represents the latest step in a line of increasingly powerful ICF facilities, the approach taken on the design of most of the laser system components has been far from incremental. In many instances, the requirement to minimize the overall cost of the system has resulted in component designs that are substantially different from their historical counterparts. In most cases, the improved "buck per bang" is achieved through a careful trade-off of the hardware and operating cost vs. acceptable technical risk. Some examples of the results of these cost/risk design studies are described below.

1. Optical Pulse Generation System. The NIF team successfully demonstrated operation of an optical pulse generation system comprising an advanced master oscillator, a new regenerative amplifier, and a new 4-pass amplifier. These system components now meet or exceed the critical NIF injection specifications for output energy, wavefront, contrast ratio, and square-pulse distortion. The

master oscillator system, shown in Figure 7, employs an "all fiber" design in order to reduce cost and complexity compared with traditional bulk optic systems.

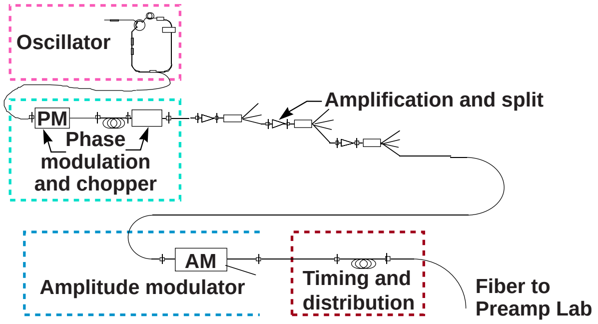

Figure 7. Schematic of the “all-fiber” master oscillator system for the NIF.

The traditional functions of mirrors, beam-splitters, gratings and polarizers are performed by fiber components instead of individual optics in mounts. Amplitude and phase modulation of the beam is accomplished via integrated electro-optic waveguide chips operating at a few volts, rather than traditional high-voltage Pockels Cells. Besides reducing the size and cost of the oscillator system, the all-fiber approach improves systems stability by eliminating many sources of alignment drift. oscillator system output of 180 picojoules is deliver via a fiber-optic cable to the preamplifier system, consisting of two amplification stages and beam conditioning hardware.

The NIF preamplifiers modules (PAM) must amplify the input pulse in order to deliver 3 J to the main amplifier cavity for each of NIF’s 192 beamlines. In a trade between ultimate experimental flexibility and cost efficiency, NIF will have a total of 48 of these independent PAMs, (Figure 8). Naturally, an independent preamplifier for every NIF beam would give the greatest experimental freedom; however, NIF’s beams enter the target chamber in 48 “quads” of four beams each and the amplifier module size restricts NIF to firing at least eight beams at a time. A substantial cost savings is realized by reducing the total number of PAMs to 48 and by increasing the required output energy accordingly. A 1-to-4 split is required at the output of each PAM in order to distribute the pulse to the individual beam lines. As currently designed, the experimenter will be able to specify an independent pulse shape for each of these 48 quads since each one is fed by its own preamplifier system.

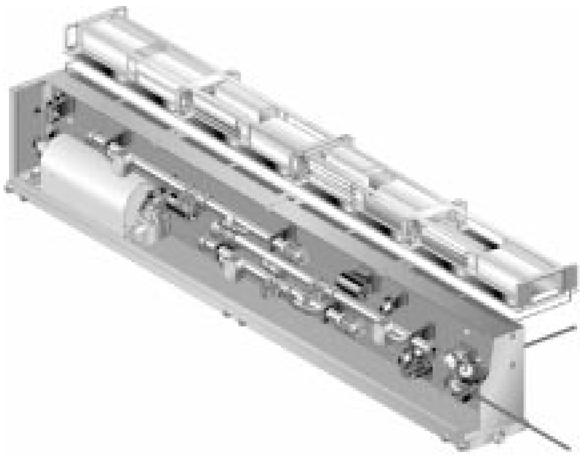

Figure 8. Layout of the NIF preamplifier. Each of the 48 PAMs will produce a 22 J output pulse.

2. Amplifier. The role of the main amplifiers is to boost the 3 J pulse from the preamplifier to approximately 10 kJ. The basic requirements are to provide adequate gain without distorting the wavefront of the beam and with high efficiency to reduce the amount of pulsed power required. Experience has shown that large close packed apertures housed within the largest practical amplifier unit deliver the largest bang for the buck. Substantial cost savings, relative to amplifiers in earlier ICF lasers, are realized in the NIF design by combining the amplifier hardware for eight beam apertures into a single mechanical assembly, called a “bundle”, shown in Figure 9. Geometry suggests rectangular laser apertures; NIF has chosen 40 X 40 cm square apertures, limited by amplified spontaneous emission de-pumping. This approach reduces the hardware cost in several significant ways. Laser slabs are stacked on top of one another (four-high) with simple metal “cushions”, eliminating precision-machined support hardware (Figure 10).

Figure 9. A section of an amplifier “bundle” consisting of eight laser apertures in two 4-high columns.

The overall parts count and complexity is reduced compared with a single-beam-amplifier approach since some components (flashlamps, reflectors, cooling system, blast shield, enclosures and support structures) are designed to support all eight apertures. New, large bore flashlamps that cover the length of the four stacked beams were developed in collaboration with industry (Figure 11). The risk of using such large lamps is off-set by the cost savings associated with a reduced number of individual electrical circuits, cables, connectors, flashlamps and other electrical components required to deliver the amplifier pump light.

Figure 10. A slab cassette containing a four-high column of laser slabs that are inserted and removed from the amplifier as a unit.

Figure 11. A 4.8 cm diameter, 2 meter long NIF flashlamp, one of approx. 8,000 in the laser amplifiers.

Maintaining a very high degree of cleanliness on the optical surfaces exposed to laser and flashlamp light is extremely important to minimize damage to the optics. The selection of the large, eight-aperture enclosure increases the risk due to contamination. A line-replaceable unit (LRU) approach is used to mitigate this risk by designing the hardware so that the critical optical assemblies can be easily removed and replaced between laser shots.

The effort to reduce the cost of the mechanical hardware was complemented by a development program with the goal of meeting the minimum performance requirements with the highest possible efficiency. This is important since the pulsed power system that drives the amplifier flashlamps costs about as much as the amplifier hardware (not including laser slabs). The amount of required pulsed power was reduced by about 25% compared with previous systems through several efficiency-enhancing design features. Specially shaped reflectors are used to tailor the flashlamp irradiance profile to maintain the amplifier gain and wavefront quality while providing a 15% efficiency improvement. Sophisticated ray-trace codes were developed, in collaboration with the French CEA, in order to optimize the design of these reflectors. Anti-reflective coatings are used on the blast shields that separate the flashlamp and laser slab regions of the amplifier. These coatings improve efficiency by roughly 7% by reducing the amount of pump light returned to the flashlamps. A cost vs. performance study of several reflector materials resulted in the selection of silver due to the efficiency improvement associated with its high reflectance across the pump spectrum. The optical properties and cooling rate of the design were validated using a full aperture prototype shown in Figure 12.

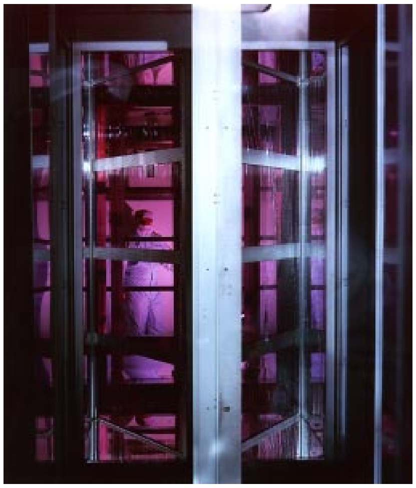

Figure.12. End view of the NIF prototype amplifier.

3. Power conditioning. The optimized NIF amplifier requires up to 400 MJ of energy delivered to the flashlamps to meet the laser performance requirements. While the performance requirements could be met by

updating the designs of earlier capacitor banks, aggressive cost goals motivated a more innovative approach to the problem. An analysis of the cost centers in previous bank designs, performed by the Sandia National Lab Power Conditioning team. focused the NIF cost reduction effort in three areas:

1) Fixed costs of capacitor bank modules that don't scale with stored energy such as controls and diagnostics, preionization hardware, charging supplies, safety systems
2) Components required in very large quantities, primarily those that correspond directly to the 4,000 flashlamp pairs in the amplifiers
3) The capacitors themselves which are the largest cost in the power conditioning system.

Maximizing the energy stored and delivered by each module, thereby reducing the number of modules can minimize the "fixed" costs associated with modular capacitor banks. We define a "module" as the unit of the capacitor bank that is switched from a common switch assembly. Reducing the number of modules saves money by minimizing the number of control systems, charging power supplies, switches, triggers, safety systems, primary AC power branch circuits, cable assemblies and other components that are purchased on a "per module" basis. For the NIF capacitor bank, a trade-off between this cost advantage and the risk associated with developing high-current switches with adequate reliability resulted in the selection of a 2.1 MJ, 550 kA module design point. A switch development program narrowed the field of candidate switch technologies to gas spark gaps and solid-state (thyristor) arrays. Spark gaps were chosen since they demonstrated adequate reliability with the lowest cost. Figure 13 shows the compact design of one of the 192, 2.1 MJ capacitor modules for the NIF.

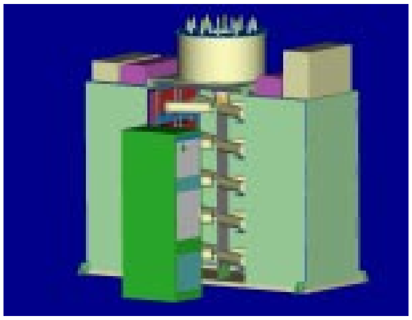

Figure 13. Layout of a 2.1 MJ capacitor module including energy storage, charging, switching, and control systems.

Special attention was paid to the design of the components that directly correspond to the 4000 flashlamp circuits since a modest reduction of $50 in the cost of these components reduces the system cost by $200k. Examples of these parts are the ballast inductors that encourage current sharing among the flashlamps, pulsed power transmission lines and high-current connectors. Extensive testing was performed at normal and fault-mode operation conditions in order to cost-optimize the design without sacrificing reliability. The ballast inductor cost, for example, was reduced by over 60% by minimizing the thickness of the force-bracing, careful selection of epoxy filler material and a low-cost end-connector design. In addition, the conductor was designed to resemble an industrial coil-spring that could be wound inexpensively on standard machines, and sized to utilize standard fiberglass tubing to provide the primary force brace.

The largest cost center in the pulsed power system is the energy storage capacitors themselves, which represent as much as 25% of the total system cost. The strategy for minimizing the cost of these critical components is twofold: encourage market competition by assuring that there are several qualified sources, and develop a capacitor specification that is carefully matched to the project requirements. A multi-year capacitor development effort has assured that multiple vendors can produce capacitors that meet NIF requirements. Several design/test iterations of prototype capacitors gave prospective suppliers and NIF personnel confidence that the designs meet NIF requirements.

Capacitor reliability is a major concern since the NIF requires all 4000 of the 24 kV, 84 kJ capacitors to work every shot (>10000 shot mean time between failure (MTBF)). Previous systems achieved similar reliability by purchasing capacitors with characteristic lifetimes 10 to 100 times the expected system shot life in order to achieve the MTBF. This approach would be cost prohibitive for the 400 MJ NIF bank. A new capacitor technology that relies on self-healing dielectric systems will allow the NIF capacitors to achieve the required reliability while maintaining high lifetime. The self-healing technology uses a thin metallized dielectric instead of discrete aluminum foils as the electrodes. In the event of a dielectric fault, the current and energy delivered to the short circuit is limited by the resistivity of the thin metallized layer. The arc is quickly extinguished as the metal vaporizes and the result is a negligible loss in capacitance. By contrast, a dielectric fault in a traditional capacitor results in a catastrophic arc and destruction of the entire capacitor. The "soft" failure characteristic of these new capacitors allows the system designers to specify the capacitor life very near the desired system lifetime. An operational benefit of the soft failure mode is that the capacitance loss can be continuously monitored and weak or "failing" capacitors can be replaced during scheduled maintenance periods, leaving the system reliability unaffected.

4. Pockels Cell. The Plasma Electrode Pockels Cell (PEPC) is the device that enables NIF's main amplifier cavity to operate in a multi-pass arrangement. It is distinct from traditional Pockels Cells due to the large aperture size, which necessitated the development of transparent (to the laser pulse) plasma electrodes to charge the crystal in about 100 ns. Traditional devices use electrodes around the perimeter of the crystal to achieve the required axial electric field, however that requires the crystal thickness to be greater than its aperture – not an option for the 40 cm x 40 cm NIF beam.

PEPCs, developed over the past several years at LLNL, have traditionally been built with dielectric housings since the device requires creation of a plasma in the regions on either side of the crystal, and then application of a 20 kV pulse across the two plasma "electrode" regions. Although this approach is feasible for the NIF PEPC, substantial cost savings are realized by building the housing from aluminum with an anodize layer to provide insulation from the plasma. The cost is further reduced by doubling the size of the PEPC to cover two apertures, and by mounting two PEPCs into one housing, thus creating a four-aperture line-replaceable-unit (LRU). Doubling the size of each PEPC halves the required number of electrical pulse generators. Mounting two PEPCs in a single housing eliminates many vacuum pumps and controllers resulting in substantial savings. This somewhat risky approach has been successfully tested at full scale (Figure 14) and performance exceeds the NIF specifications.

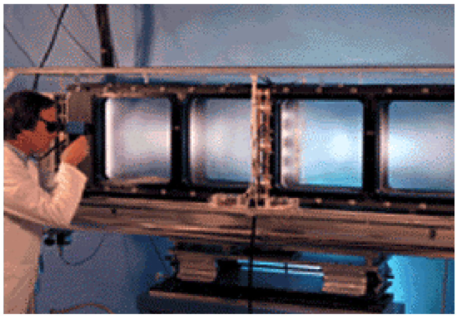

Fig.14. NIF's PEPC prototype electro-optic switch uses polarization to gate high power light pulses out of NIF's amplifiers.

IV. SUMMARY

The NIF engineering and scientific teams have collaborated during the past 3 years to evolve a highly cost efficient integrated facility design. Close coordination was required during every step of the design evolution. Extensive use of computer modeling/simulation, value engineering, laser system optimization, and excellent engineering was essential in the ultimate success of this process. The result of this effort has lead to the achievement of a very low cost per unit energy of laser light delivered on target.

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