NIF Technology Review

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Executive Summary

The technology review concluded that NIF can reach its original performance goals. although with some delay and at higher cost than originally projected, provided that recommendations offered from this review are followed.

Very significant progress has been made toward all of the major technological advances originally identified as required to achieve NIF. This progress continues to expose, however, the need for further technology development to reach ultimate performance objectives. The technology review reported herein covers the majority of the high-risk issues, but is not yet complete for the Final Optical Assembly design, diffractive optics or crystal growth and fabrication.

A summary of recommendations in four general areas follows below:

Test Facilities

- Futl exploitation of Beamlet capability at Sandia in support of NIF.

Scope of Science and Technology

- A significant numerical modeling group be established immediately.
- A major, centralized, optical damage R&D effort be organized.
- A materials R&D effort be undertaken to develop better materials and coatings for operation at 8-9 joules/cm2, and to determine operating reliability at such levels.

Deployment and Technology Development Strategy

- A very careful study of assembly procedures, with off-line testing, prototyping or mockups, to reduce technical risk of the lack of a complete prototype.
- A new deployment plan be defined, paced with technology and materials developments.
- Only minimal optical component deployment in NIF be committed before proof of clean installation, accurate alignment, and functional diagnostics.

Budget and Organizational Issues

- The budgeting process for technology development be defined, published and reviewed on a continuing basis, with feedback and open discussion of any concerns about technology status.

A summary of recommendations in four specific technical areas follows below:

Laser Glass Development and Production

- Proceed to production at both companies.
- Add capacitors to amplifier banks to compensate for any lower gain from OH absorption.
- A careful analysis of the potential requirement for small tool finishing.
- Measure and compare all relevant laser parameters on glass actually produced with glass used in AMPLAB experiments and with glass assumed in numerical models.

Laser Amplifier

- Scale up numerical modeling efforts substantially, with appropriate computer support, to undertake six key initial tasks within the next 12-18 months. These tasks are itemized in the main report. They are considered to be critical to the success of the NIF.
- Undertake an experimental effort to determine the emission and absorption of the flashlamps in spectral regions outside the neodymium pump bands.
- Use specialized test facilities, including small scale ones, where contributory to address cleanliness issues.
- Install a gas flow system for the amplifier discs to sweep out aerosols from each shot.
- Add capacitors to power system to compensate for low initial, or time-degraded, gain.

Beamline Architecture

- Restore the 11-7 configuration as baseline design for the two-phase option.

3 Omega Damage

- Consider alternatives to the current FOA design by “getting out of the box.”
- Commit to a high level science based optical damage R&D program.
- Establish a significant near term and long term materials science R&D program.

Concluding Emphasis

In summary, N1F damage studies and materials science should be pushed very aggressively. Today's damage and materials status should permit reliable operation at 3 joules/cm2. if these recommendations are pursued aggressively, operations at 4-5 joules/cm2 in Phase I could be projected. With continued work, operation at 8-9 joules/cm2 in Phase 2 will become realistic.

Introduction

At the request of Dr. George H. Millet, LLNL Associate Director for National Security, the Technology Resource Group (previously the supporting Core Technology and industrial interactions Resource Group) of the NIF council is undertaking detailed reviews of the status of the technology development which underlies the design of the NIF Laser System. Review meetings at LLNL were held on Sept 29,30 and Oct 6,19,1999.

While these reviews are not yet complete, we have examined the majority of what are perceived as the high-risk issues. Thus we believe that providing a status report of our work at this time could be beneficial as input to other ongoing reviews of the NIF Project. To date, we have reviewed the following topics:

- The development and production status of the neodymium laser glass
- The testing and performance of the prototype NIF laser amplifier
- The choice between the 11-7 (18 disc) and 11-5 (16 disc) beamline architecture
- The 3 omega optical damage problem (damage to optical components caused by the high power ultraviolet light output of the laser)

Our reviews have been characterized by intensively studying the designs and experimental data with the scientists and engineers actually conducting the work. Thus we are completely confident that we have access to all relevant data on the topics we review. In this regard, we would like to express our appreciation to the NIF Project staff for their complete cooperation and candor and for the very significant amount of their time that they contributed to these reviews.

In what follows, we first present our “big picture” observations and recommendations. We then proceed to the specific technical observations and recommendations in each of the specific topics listed above. The report is therefore presented in two main sections following this brief introduction.

The “big picture” should be viewed against the background history of the NIF Project. Several years ago, scientists at LLNL determined that fusion “ignition” should be achievable with roughly 1.5-2.0 megajoules of laser energy focused on a target containing fusion fuel. This realization drove the conceptual design of a laser large enough to accomplish it. The laser had to provide 60 times more energy than any such laser built to date. In order to build such a large system at an acceptable cost (then set by DOE at ~$1.1 Billion), eight major technological advances were conceived to accomplish it. Thus from the outset, to be successful, the NIF project had to undertake major science and technology development activities.

In the course of the NIF Project work to date, very significant progress has been made in all eight of the key technology areas. However, achieving full NIF performance requires completion of technology development objectives in all of these areas. Progress toward these objectives continues to expose technical challenges that require continuing investment in technology development. This process is typical of all advanced technology development projects that are predicated on significant advances in the state of the art.

While much work remains to be done, and many remedial activities both technical and managerial need to be undertaken, we are confident that with the help of recommendations contained in this report

NIF can reach its original performance goals, although with some delay and at higher cost than originally projected.

While the higher costs have yet to be determined accurately, we roughly estimate that the recommendations contained in this report may add as much as $50-80 million to the cost of the NIF Project over the next 8 years. The NIF Project staff can make a closer estimate of these “technology development costs” as they establish plans for implementing the recommendations in this report. Other sources of additional project cost (infrastructure installation, etc.) are not addressed in this report.

It is clear that the scope of the technology development effort required was not adequately recognized, or dealt with, in the original NIF budget. The technology development budget appears to have been exhausted by the end of fiscal 1998 with much work remaining if the NIF goals were to be achieved.

The comments we offer below are partly in hindsight about what should have been done, but their focus is primarily on what needs to be done going forward. This Technology Report does not call out individual management failures that happened in the past, but it does call out the need for major improvements in the budgeting and management strategy of large high technology projects like NIF. These projects require sound and supportive management of technology developments that stretch the state of the art, as well as the staff that undertakes these developments.

General Observations and Recommendations

1. Test Facilities

Observations

The NIF Project Plan did not include the construction of a prototype which would have been used to test the various components and technologies, evaluate alignment and diagnostic procedures, and to work out the assembly methodology in advance of NIF installation. Thus the project had to rely on component testing and careful planning to achieve successful system integration. Some of the component development and testing efforts were very successful, but others were not. The planning for installation and activation of the system was only minimally addressed. The Beamlet laser system, while not a NIF prototype, was the only partially relevant laser system at LLNL. It was very useful for some full-scale tests. However, it was shutdown and disassembled before being used further for resolving issues where it could have contributed significantly (e.g. the Final Optics Assembly function). This decision was made in response to Project/Program budget pressures.

Recommendations

At this point in time, we do not recommend that a prototype beamline be built, as it would require an enormous diversion of people and resources and a several year project extension. Thus it is not cost effective. Some valuable testing can be done on the Beamlet system once it is in operation at Sandia. We strongly recommend full exploitation of Beamlet capability at Sandia in support of NIF.

2. The Scope of Science and Technology

Observations

The Program and Project management appears to have greatly underestimated the amount of science and technology development required for achieving the very ambitious (though entirely appropriate) NIF performance goals. The management appears to have viewed NIF simply as a complex engineering project, rather than as the high science and engineering project that it really is. By the end of fiscal 1998, many of the technology development efforts were terminated because of budget pressures, although much work remains to be done and a few specific performance goals are yet quite distant. In addition, much fundamental science, scientific measurement capability, and numerical modeling activity, was hardly supported or never engaged at all, even though these activities are key, in our estimation, to the overall success of the NIF Project.

Recommendations

We recommend that a significant numerical modeling group (~10-15 staff members) be established immediately to support the NIF project. Numerical modeling and experiment are the two strong pillars that have supported the successful design and deployment of all of LLNL's major laser systems. NIF appears to have relegated numerical modeling to a nearly irrelevant activity which only occasionally is used to put a theory curve on an experimental result vugraph. Given the partial failures in some large test programs (e.g. the laser amplifier), and the unavailability of a prototype beamline, the very significant modeling capability, developed in earlier years in the LLNL Laser Program, shouid be resurrected to model most of the aspects that cannot be tested prior to initial system installation (i.e. amplifier prompt distortion, amplifier gain profile modification, beam propagation, diagnostics function, alignment function, etc.) The specifics of these recommendations are addressed later in this report.

We recommend that a major, centralized, optical damage R&D effort be organized within the NIF Project. NIF assumed an aggressive design goal fluence of 8-9 joules per square centimeter (joules/cm2), but then did not back up that goal with the R&D program necessary to achieve it. (It should be understood that all high power laser systems are designed close to the damage threshold, as the cost of the whole system can be reduced significantly by operating close to higher and higher damage thresholds). While there are several small efforts underway with excellent people, they are subcritical in scale compared to the critical importance of solving the damage problems, and they lack adequate test facilities. The program must commit the resources to quantitatively identify and eliminate these extrinsic sources of damage on surfaces and in bulk materials.

We recommend that a materials R&D effort be undertaken to develop some better materials and coatings for operation at 8-9 joules/cm2, and to determine under what conditions existing materials can operate reliably at such levels. The materials should be developed with an eye towards replacing or protecting the silica optical elements between the DKDP crystal and the target. It is our considered opinion that this will prove necessary if reliable and acceptable cost operation is to be achieved at 8-9 joules/cm2 in a vacuum and in the presence of target debris. The UV lithography community has done a lot of work in the last several years to develop crystalline fluoride materials as high quality optical components. This can be a starting place for NIF efforts that shouid also broaden into other materials. This materials R&D effort should be directed by experienced materials scientists and coupled tightly to NIF requirements. It is interesting to note that the major LLNL laser systems Shiva and NOVA each required the development of a whole new set of optical materials and coatings to achieve their design goals. The need for NIF to do the same should therefore not come as a surprise, nor should it be viewed with great concern.

3. Deployment and Technology Development Strategy

Observations

The original plan for deploying NIF called for sequential installation and operation as a target shooter almost immediately This plan assumed that all technology development and manufacturing process development was complete and that there were essentialiy no technical issues remaining. This scenario is unrealistic for such advanced technology.

Recommendations

We recommend, therefore, a very careful study of assembly procedures to help balance system deployment with the technology development program. This study should be undertaken as a high priority. In this regard we strongly encourage the construction of subsystem prototypes, or mock-ups of them, where clean assembly procedures can be evaluated, where laser system diagnostics can be evaluated, and where laser alignment procedures can be evaluated. We encourage an expansion of off line testing wherever practical although we realize that it is costly and time consuming.

We recommend that a new phased deployment plan should be defined, and that it be paced with the need to complete the many technology developments and materials developments. Assuming the recommendations in this report or their functional equivalents are implemented rapidly, we believe that operation at 4-5 joules/cm2 is a realistic goal for Phase 1 of NIF while operation at 8-9 joules/cm2 is realistic for Phase 2.

We further recommend that only minimal optical component deployment in NIF be committed to until it is proven that **a** clean installation, accurate alignment, and functional diagnostics can be achieved.

4. Budget and Organizational Issues

Observations

This review has recommended continued funding for several technology development areas that are considered essential for the future success of NIF. This recommendation reflects a strong position of the reviewers that the deployment and future economic operation of NIF will be determined primarily by the quality of the developed technology. While the engineering aspects of NIF deployment are challenging and important, and must be completed competently, NIF is primarily about “getting the science and technology right.”

Until the above position is understood clearly and adopted as a priority by LLNL and DOE management, the reviewers will not be comfortable about the stability and sufficiency of budget allocations to technology development. The reviewers would therefore like to discuss the following recommendations directly with management.

Recommendations

Specifically, we recommend that:

- The budgeting process, which must be flexible to account for both completions and development shortfalls, be defined and reviewed on a continuing basis
- Technology development budgeting be published in detail for the purpose of ongoing and regular external review
- Adequate and timely feedback be established between understanding the evolving limits of technology and the performance of NIF as an operational system
- Any concerns or issues about technology developments, and their budget implications, should receive open and frank discussion on a regular and scheduled basis with the AD for National Security and, in turn, with the AS for DP in DOE
- The NIF Project organization be designed to have a fail-safe openness for the discussion of such concerns and issues at any level, including the technical staff responsible for the technology developments
- To assist NIF Project Management on a continuing basis, progress in meeting these recommendations be reported back, on a timely basis, for external review and comment by the Technology Resource Group of the NIF Council

The reviewers feel that the specificity above is warranted by the following observations The ambitious performance goals for NIF, judged as feasible with hard work over an extended period, were based originally on an assumption that a competent LLNL staff would achieve these goals with appropriate support. The reviewers believe that this assumption has been strongly justified by the achievements to date of the technical staff and the promise that their capability will reach the ultimate performance goals of NIF. This belief would be undermined quickly if, through budget pressures and conflicting priorities or other diversions of interest, either funding or management support were to falter even briefly.

Specific Technical Observations and Recommendations

1. Laser Glass Development and Production

Observations

The quantity of neodymium laser glass required for NIF, taken together with the very low cost targets, implied that the glass would have to be produced with continuous glass melters rather than the pot melters used for all previous laser glass production. While continuous glass melting is the industry standard for high volume glass production, it has only really been applied to silicate glasses. Developing a continuous glass melting technology for the very low viscosity, highly corrosive, phosphate laser glasses was expected to be quite difficult, but achievable. The NIF program for developing this glass melting capability has been well planned with two capable industrial organizations and is proceeding fairly well. The last test runs of each of the continuous melters were close to achieving the desired results.

Without identifying specific problems with specific vendors, we note that several problems remain to be dealt with in the next test run. Fracturing of the glass strip during annealing was a problem, but it is our opinion that the remedial actions taken to resolve this problem are adequate. The water content of the glass must be reduced as it deactivates the laser active neodymium ion, reducing the gain of the laser amplifier. Water content is usually measured by the strength of the OH absorption in the infrared. The NIF spec for this absorption is < 2 cm2, while the last test runs showed 6-10 cm2. Studies at LLNL, and at the glass companies, have indicated ways to reduce this water content and they expect to achieve the NIF spec. Platinum particle content has been a problem to some degree, but the LLNL team believes that the source has been identified and a limited redesign has been implemented to solve the problem. And finally, the optical quality of the glass may be somewhat below the NIF spec, which may require some additional optical finishing work.

Recommendations

Rather than conducting another test run of both continuous melters, we believe that NIF should proceed to production at both sites, as test runs and production runs are really indistinguishable. To support this approach, it will be necessary for LLNL to establish a fast turnaround measurement capability to determine OH and platinum particle content in the glass so that decisions can be rapidly made to modify operating conditions during production, or to terminate the production run. Successful runs at either or both vendors should continue until melter destruction. If only a single vendor fails to achieve NIF specs on the next set of test runs, careful consideration should be given to a single vendor procurement strategy. Thus contracting methodology should be as flexible as possible to allow for two successful vendors, or just a single successful vendor.

While tests and analysis indicate that the NIF OH spec of <2 cm2 can potentially be achieved, we believe it may be an unrealistic expectation. It would seem to us that OH absorption of 2 – 4 cm2 is more realistic. Thus we would recommend that additional capacitors be incorporated in the NIF amplifier capacitor banks to compensate for the lower resulting gain. We will return to this recommendation in the sections on Amplifier and on Beamline Architecture.

If the optical quality of all of the glass is not sufficient to support simple flat finishing of the surfaces, some small tool finishing will be required. We recommend that a careful analysis of the potential requirement for small tool finishing, along with the schedules and production rates, be made to determine the desirability of facilitizing a second vendor to do this work It may be that a second small tool finisher would reduce the risks and costs of multiple handling of finished parts.

Finally, we recommend that all of the relevant laser parameters on the glass actually produced be measured and carefully compared with the glass used in the AMPLAB experiments and the glass assumed in the numerical models. This should be carefully documented and managed as a Project Change Control issue.

2. NIF's Large Laser Amplifier

Observations

The large laser amplifier determines the 1 micron performance of the NIF laser. It is a very massive precise optical element which must be assembled and installed in an extremely clean state, and only minimally degrade during operation. To develop this huge component, a special laboratory, AMPLAB, was constructed to test it, and a prototype amplifier was designed, built, and tested. The objectives were as follows.

- To measure gain and the spatial profile of the gain under a variety of operating conditions, and with two different types of laser glass

- To measure the prompt optical distortion of the amplifier, which determines the adaptive optic requirements and thus the overall beam quality of NIF

- To measure the evolution and relaxation of the long time optical distortion, which determines the allowable shot rate of the system

- To provide a facility to work out the amplifier cleanliness issues

While the AMPLAB experimental campaign was extensive and time consuming, only a limited subset of the above objectives was achieved. One, or at best a few, self-consistent gain and gain profile data sets is all that were successfully measured. The prompt optical distortion measurements essentially failed, as it could not be determined how much of the distortion was in the amplifier and how much was in the measurement optics outside the amplifier. In addition, a very low signal to noise ratio just increased the difficulty. The long time distortion measurements were hampered by the lack of a "zero time" temperature measurement of the discs, and by the fact that ultimately the measurement came down to measuring a 0.1 wave signal on top of 9 waves of static distortion.

The gain data, when combined with a numerical model of the actual NIF amplifier, indicates that a gain of 5.1 +/- 0.1 %/cm should be achieved, This measurement and calculation was with very dry glass (OH < 2 cm-1), new silver reflectors, new clean blast shields with good coatings, and new flashlamps. The NIF spec is 5.0 %/cm during system operation. Thus it is not clear that there is any gain margin under the most optimal conditions, and that if there is any gain margin at all, the water in real NIF glass will eliminate it. In addition, it is quite obvious that the required gain cannot be maintained in the presence of normal degradation during system operation. Since there is no opportunity to run repeated tests on an actual NIF amplifier in a realistic environment, the degradation rate cannot be determined at this time. Finally, it is unclear how the other detailed laser related characteristics of the glass actually produced for NIF compare with the glass used in the tests and assumed in the models.

The prompt optical distortion measurements showed distortion 2-4 times that seen on other amplifiers (e.g. Beamlet) but problems with the measurement noted above render any conclusion questionable. The NIF amplifier is pumped more heavily at the edges, to flatten out the gain profile, than is the case with the Beamlet amplifier. This may be the source of some of the additional distortion if the data is real. The real details of this distortion will have a large impact on our ability to compensate the distortion with a single adaptive optic, and ultimately on the useable fill factor of the amplifier. The total energy output of the laser is linearly dependent on the fill factor.

The successful development of large laser amplifiers depends critically on the synergistic coupling of sophisticated 3-D numerical modeling and sophisticated experiments. These two disciplines are the pillars that have supported the successful development of ail previous laser systems at LLNL. The NIF Project commitment to numerical modeling of the NIF ampfifier issues has been completely inadequate. While nearly $27 million has been spent on the experimental portion of the program (with limited results), less than $1.5 miilion has been spent to construct and exploit numerical models. What has been accomplished in the numerical modeling and data reduction effort is a tribute to two individuals who have worked tirelessly with grossly inadequate support. While we would normally expect to resolve many of the problems referred to above through numerical modeling, the project lacks adequate tools now when they are really needed.

Cleaning a big disc amplifier, and keeping it clean during operation is a really major challenge that is posed by the neodymium glass laser technology. To understand the problem, the amplifier can be viewed as a complex assembly of optical components and supports that is immersed in a 10,000°C furnace for half a millisecond when the flashlamps are fired. As might be expected, the impact is not trivial. In general, the solutions to the cleanliness problems are specific to the materials, manufacturing procedures, and assembly procedures. Thus with each new generation of laser technology the problems must be solved again. A strong effort is finally underway in the NIF Project to solve these problems and much progress has been made. However, the work is not yet complete.

Recommendations

The reviewers, as a resource group of the NIF Council, reviewed the amplifier development activity in August 1997. Some of the recommendations made at that time are repeated below, as they were not acted upon. Other recommendations have been addressed.

We do not recommend that a new round of NIF amplifier measurements be initiated in AMPLAB. That approach is far too costly, too time consuming, and without a much larger facility, might not yield better results. We believe that the majority of the high-risk issues can be satisfactorily addressed with advanced numerical models coupled with the AMPLAB data and some additional flashlamp data.

We very strongly recommend that the numerical modeling effort be substantially scaled up (10-15 heads) and provided with the appropriate computer support to undertake the following initial tasks within the next 12-18 months.

- Convert the current “backward” (glass to lamps) 3-D ray trace code to a “forward” (plasma to glass) ray trace code to allow self-consistent determination of energy flow and deposition in all elements of the amplifier. This code should be normalized to the AMPLAB gain data, the Beamlet amplifier data, and to NOVA amplifier data.

- Adapt the code for running on the main LLNL computer facility so that a large number of experimental cases can be run rapidly with adequate precision

- Build a self-consistent model of energy deposition in the glass and the resulting thermo-optic phase distortion

- Extend the codes for analyzing the long time thermal distortion and gas motion effects to self consistently use the thermal input to the discs, structures and connected beam tubes

- Extend the capability in d) to model the complete optical distortion along a beamline

- Provide numerical modeling support to all other portions of the NIF technology development program

The reviewers believe strongly that the above recommendations are of critical importance to the success of the NIF project. We believe that it is essential in this $1.5 billion project to have solid information on the optical aberration in the amplifier, and along an entire beamline, prior to installation and testing of the first bundle. Given NIF’s extremely limited beam diagnostics, diagnosing such problems on a beamline will be difficult and time consuming. if analyzing these problems, and then modeling and implementing solutions, has to await installation of the first bundle, the schedule and cost impacts to the NIF project could potentially be very large.

There are probably a few more numerical tools that are required but that have omitted in this report. However, the people involved can add these once the Project again embraces numerical modeling. With the numerical tools outlined above, the project should be abte to address and resolve a number of the outstanding key issues. The calculation of the absolute energy deposition in the glass, together with a thermo-optic model, can provide a real view of prompt thermal distortion and help sort out what was real and what was not in the AMPLAB measurements. If the real prompt distortion is too large, or has too great a first derivative towards the edge, it can be addressed with differential flashlamp loading, partial lamp baffling, or a variety of other techniques, once they can be quantitatively evaluated. This will also provide data on the average gain reduction these techniques will engender and which can be used to properly size the capacitor banks. The long term thermal distortion recovery is of critical importance to the whole utility of the system. The evaluation of the thermally driven gas motion in a complete beamline is thus of high importance to model and evaluate.

We recommend that an experimental effort be undertaken to determine the emission and absorption characteristics of the flashlamps in spectral regions outside the neodymium pump bands (UV and IR). This data is needed in support of the modeling effort above as this radiation both heats the glass and the structure. Obtaining this data should be trivial compared with any measurement on a NIF amplifier.

We recommend that the current efforts on amplifier cleanliness continue to be strongly supported. Further, we recommend the use of specialized test facilities where contributory. Specifically, it is very important to benchmark "the best you can do" on a small-scale test facility as a reference for efforts on larger structures. In addition, all use of organic materials exposed to fiashlamp light should be reviewed to minimize them to the greatest extent possible.

We recommend that a gas flow system in the disc portion of the amplifier be implemented to sweep out aerosols created on each shot. Of the two options presented for accomplishing the task, it was not clear to us what the quantitative difference might be. This requires further study and decision by the Project.

We recommend that additional capacitors be added to the pulse power system to compensate for the low initial gain and its degradation with time. It should also be sufficient to compensate for the real water content of the NIF glass, as well as gain reductions concomitant with modifying the pump profile if they prove to be necessary. (Note that this recommendation was also placed in the section above on laser glass to indicate that the excess water problem can be compensated.)

3. Beamline Architecture

Observations

A single beamline of NIF, of which there are 196, is comprised of two groups of neodymium glass discs. The current baseline design is comprised of 16 discs grouped as 11 and 5, and thus it is referred to as the 11-5 configuration. The original NIF design was for 18 discs on a beamline and is referred to as the 11-7 configuration. The 11-7 configuration exhibits additional gain and additional energy storage as compared to the 11-5 configuration. The additional gain can compensate for a gain shortfall in the amplifier, for higher than spec water concentration in the glass, and for other beamline losses that may have been underestimated. The higher stored energy of 11-7 configuration will allow the laser system to provide higher energies on target for the long pulses required by some SSP experiments.

Budget pressures forced the NIF design to be downscoped from the 11-7 configuration to the 11-5 configuration to reduce costs. Unfortunately, this downscoping has taken all of the margin out of the NIF design, making its performance susceptible to potential shortfalls in performance in any beamline component.

Recommendations

We recommend that the 11-7 configuration be restored as the NIF baseline design for the two-phase option for the completion of NIF. This will provide the necessary performance margin to compensate for component performance shortfalls already observed and those yet to be discovered.

As part of the same recommendation, and as mentioned in the Amplifier Section above, we also recommend the addition of capacitors to the amplifier capacitor banks to provide some additional gain, the combination of these two actions should assure full performance.

4. The 3 Omega Damage Problems

Observations

The NIF neodymium glass laser itself operates at a wavelength of 1.06 microns in the near infrared. This is referred to as the 1 omega portion of the NIF laser system. Just before the lens that focuses the laser beam onto the target, the 1.06 micron wavelength is harmonically converted to 0.35 microns in the ultraviolet by two nonlinear optical crystals. The 0.35 micron light is referred to as 3 omega light (the frequency of 0.35 micron light is three times the frequency of 1.06 micron light). In general, the damage thresholds of most optical materials are much lower in the ultraviolet region of the spectrum than in the near infrared. Thus the majority of optical damage problems faced in the development of the NIF system are associated with the optical components that are exposed to the 3 omega beam.

The optical components exposed to intense 3 omega light are the second of the two nonlinear optical crystals which is made of deuterated potassium dihydrogen phosphate (DKDP), the diffractive optics which are fused silica, the focusing lens and debris shield both of which are also fused silica. Each of these optical elements has surface coatings applied to them to reduce the reflectivity.

This set of optics is contained in the Final Optics Assembly (FOA) and therefore must operate in a vacuum.

The fundamental bulk damage thresholds of pure, homogenous DKDP and fused silica are far above any 3 omega light intensities expected in NIF. However, any interior particulate impurities or surface embedded absorbing defects reduce the damage threshold significantly and make the affected material vulnerable to NIF's 3 omega light intensity. For NIF's 3 omega optics to be successful, therefore, it must be assured that DKDP and fused silica bulk materials are robust to the 3 omega light in their interiors, and that their surfaces are also robust to this light. The surfaces must be fabricated in such a way that the surface damage threshold remains high. And finally, it must be assured that the anti-reflection coatings that are applied to the optics also have a sufficiently high 3 omega damage threshold.

The NOVA laser system was designed to operate at 2-3 joules/cm2 of 3 omega light. The NIF design requires operation At 8-9 joules/cm2. Thus significant materials R&D is required beyond that done for NOVA. The push for operation at the 8-9 joules/cm2 is an important part of what is required to effect the overall cost reduction per joule of NIF as compared to NOVA. (Note that the fluences quoted here are an average across the beam. The spatial noise on the beam increases this average level to a peak level 2-2.5 times as high.)

Most of the NOVA 3 omega optics are operating in air, while all of the NIF 3 omega optics operate in a vacuum in the FOA. About a year ago in Beamlet experiments it was discovered that high fluence 3 omega damage on surfaces in a vacuum was catastrophic; that is, it is not self-limiting but grows rapidly in extent with each successive laser pulse. In addition it was discovered that, in a vacuum, particles that are ejected from the surface (as a result of 3 omega damage) also damaged other nearby facing surfaces. In the current NIF FOA design, all of the optics are very closely spaced which means that damage to one surface will propagate to the next facing surface.

This review concludes that the Project and Program management did not fully understand the scope and project implications of optical damage. This technology development area was not adequately budgeted to allow for the high level of materials R&D and large optic damage testing that would be required to achieve reliable operation at 8-9 joules/cm2. In addition there was no one assigned, at a high level of management in the Project, with the responsibility for assuring that the basic science, materials development, fabrication development, and small scale and large scale testing were adequately supported and aggressively pursued. These responsibilities were left to individual members of the technical staff of NIF to find whatever support they could, to resolve these problems. By the end of fiscal ‘98, budget pressures had forced termination of many of these already under-funded but key efforts.

Recommendations

FOA Design

We recommend that design alternatives to the current FOA design need to be considered. If the majority of the 3 omega optics could be run in air or at a high enough partial pressure of oxygen to prevent catastrophic damage and surface-to-surface propagating damage, reliable operation could be achieved in Phase 1 approaching 4-5 joules/cm2 with the existing materials technology. Accomplishing this would require the focusing lens to be made thicker so that it could be used as a vacuum window, or a separate vacuum window would be required. This would, of course, limit the peak power of operation of the laser system because of the increased nonlinear phase aberration (ΔB) caused by thicker and/or additional optical elements, but then the peak power is already limited by 4-5 joules/cm2. We are aware that this suggestion may make the diagnostics problem and the ghost focus problem worse.

While the specifics of this suggestion may not turn out to be the correct approach, what we are proposing is that the NIF Project “get out of the box” in thinking about the FOA. Specifically, the Project should consider phasing in some alternatives that could be coordinated with technology advances and with the NIF deployment scenario. The objective would be to achieve the 8-9 joules/cm2 operating level in two or three steps, while assuring reliable operation at each level

Optical Damage

We very strongly recommend that the Project commit to a high level science based optical damage R&D program. The objectives of the program would be 1) to identify the initiators of both surface and bulk damage, 2) to devetop manufacturing and fabrication processes that eliminate these initiators, and 3) to provide the both small and large scale test facilities necessary for experimental work and for qualifying NIF components. This needs to be done ASAP. At this point It is important to have a lot of very high quality data. All of the existing activity in this area needs to be drawn together, expanded, and coordinated with regard to test requirements and techniques.

In studying optical damage, it is important not to be led astray by the problem of searching for a potential damage site in a huge optic, as that is somewhat like trying to find a needle in a haystack — possible but tedious. Damage itself finds the damage site and often ejects or encapsulates the anomalous material in a convenient form for study. it is of the greatest importance to fully take advantage of this fact, as it can profoundly reduce the total amount of work necessary to ultimately solve the damage problem.

The surface initiators could be identified in the plasma plume resulting from damage by sampling the plume with a time-of-flight (TOF) mass spectrometer, or by atomic emission spectrometry (AES) of the plasma plume itself. Either of these techniques could be integrated with a scanning laser damage test facility. There are probably a wide variety of other techniques that could be applied to the problem, but these two seem to be unusually direct.

Identifying the bulk damage initiators is somewhat different. Generally the damage sites are very small (several cubic microns) and the confined plasma density is high enough to probably preclude using AES to identify the inclusion. Thus we suggest that the femtosecond laser machining capability developed by the LLNL Laser Program be used to mill into an existing damage site, atomizing and ionizing the material removed. The material would then be sampled by a mass spectrometer and analyzed. If a repetitively pulsed laser and TOF mass were used, it should be possible to identify the anomalous material as the laser cuts through the damage site, Again there are other techniques to be considered but this one (SIMS) has almost worked with a focused ion beam as the milling tool (which cannot be focused as tightly as a laser) and continuous beam operation. The combination of a pulsed laser, tighter focusing, and a TOF spectrometer should improve the signal to noise ratio greatly.

In the case of KDP and DKDP it has been found that laser conditioning can raise the bulk damage threshold quite significantly. Laser conditioning is accomplished by illuminating the material with increasingly intense laser pulses. This process apparently spreads out the absorbing sites-in the material, weakening their absorption, and thus raising the single shot damage threshold, Depending on the specific details it may or may not be necessary to do this to achieve an adequate bulk damage threshold in the material. However, we recommend that laser conditioning be done on these crystals. It seems to us prudent to remove as many optics as possible from the list of potentially damaged components for high power laser shots. Ideally, in high power shots, only a single (and hopefully low cost) optic should be subject to damage. While this ideal may never be met, it is just common sense to remove as many optics as possible from the probable damage list.

In the case of surface initiators, once they are identified it should be straightforward to identify at which step of the fabrication process they are introduced. The fabrication processes can then be modified to reduce or eliminate the problem by adding or extending process steps, or by changing the fabrication materials, or both. In the case of bulk damage, which is primarily a problem in DKDP, identification of the impurity particle would allow a direct approach to mitigation. It might be found that increasing the purity of the starting materials with regard to this specific impurity, or modifying growth conditions to select against its precipitation, would solve the problem. At any rate, the solution of all of these damage problems should begin with identification of the offending material, and this needs to be accomplished ASAP.

In the case of coating damage, the same facilities and some of the same techniques will be useful. The study of the coating damage must be integrated with all of the other damage work to assure consistent results, and to assure integrated solutions to the NIF optical damage problems.

Materials Science Program

We very strongly recommend the establishment of a significant materials science R&D program in both near term and long term support of the NIF laser system. A very experienced scientist, with a broad background in diverse materials science problems, should lead this program. The program should be staffed by first rate individuals with both industrial and university research backgrounds. The outstanding people required will not be available without a long-term commitment to R&D in this area. The task of the research program should be to continually upgrade the materials and coatings used in NIF so that the system can ultimately operate reliably at and above the original design goal. The System performance leverage for accomplishing this goal is very large and so also is the payoff to the SSP.

The first task is to rebuild and expand the program's sol coating R&D expertise. Ian Thomas is retiring this year and should be encouraged to stay involved as much as he is willing. The existing staff is excellent but very small. Another senior and very experienced sol chemist should be hired to replace Ian and the group overall should be expanded by about a factor of three as it has to do the R&D and the production of NIF optics. At the present time there is not a complete solution to the DKDP coatings and progress has not been rapid. Overall the coatings are an extremely high leverage item in terms of laser system performance. Improvements in coating performance will improve system performance and reliability as long as NIF continues to operate.

The type of catastrophic damage being observed on fused silica at high fluence in a vacuum fundamentally calls into question whether fused silica can ever go the distance to reliable operation at full NIF fluence or above. There are a variety of conceptual candidates to replace fused silica, such as fluoride crystals, fluoride glasses, and others. The Deep UV (DUV) Lithography community and supporting manufacturers have done a lot of work on fluoride crystals for precision optical applications. That experience should be accessed as a starting point for an aggressive program to develop replacement options for fused silica. Note that the nonlinear refractive index of the fluoride crystals and glasses is a factor of 2-3 lower than fused silica which may allow more novel designs for the FOA. While fused silica is our materials of choice for Phase 1 operation at 4-5 joules/cm2, much better processing or a better material will be required to reach the full ffuence in Phase 2.

The debris shield is another major NIF materials problem. At present it is a coated fused silica plate at the highest 3 omega fluence point in the system, and has to operate in vacuum with some amount of target debris on one surface, At the present time it is unlikely that it would survive more than several shots at full NIF fluence before mandatory replacement, and they are not cheap. Clever ideas and better materials are clearly needed. Perhaps some combination of a single shot fluoride plastic film on rollers backed up by a fluoride glass or crystal plate would be a lower cost option. The proper solution is presently unknown, but developing better ideas and better materials should be a high priority for the materials R&D group.

As mentioned earlier, both the Shiva and NOVA laser systems each required the development of whole new sets of optical materials and coatings to achieve their design goal performance. Thus it is not a surprise that NIF will ultimately require the same. Nor is it a surprise that it could not be accomplished with minor modifications to NOVA materials and coatings. Project understanding of this issue was completely missing.

In summary, the NIF damage studies and materiats science must be pushed very aggressively. With today’s damage and materials status we would be comfortable with reliable operation at 3 joules/cm2. If the plans outlined above are aggressively pursued, we are comfortable projecting operation at 4-5 joules/cm2 in Phase 1. With continued work, operation at 8-9 joules/cm2 in Phase 2 is a realistic expectation.

Future Reviews

We are currently reviewing KDP and DKDP crystal growth, crystal fabrication, and the diffractive optics of the FOA as well as other FOA design issues. We will provide our observations and recommendations when these additional reviews are complete.

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