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# Preliminary Report
# NIF Laser Bundle Review*

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# PRELIMINARY REPORT

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**NIF**
*The National Ignition Facility*

Classification of Report:
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# NIF LASER BUNDLE REVIEW

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# SUMMARY

This committee determined whether there are compelling reasons to recommend a change from the NIF CDR baseline laser bundle design based on a tradeoff between cost, technical risk, and other operations and maintenance issues. The baseline design building block is a 4x12 bundle (48 individual laser beams), which is replicated four times to create the required 192 beams. The entire bundle review effort was performed in a very short time (six weeks) and with limited resources (15 personnel part-time). This should be compared to the effort that produced the CDR design (12 months, 50 to 100 personnel). Because of this reverse constraint, the cost-estimated contained in this evaluation are top down and none of the design alternatives are detailed to the level of the baseline. The committee agreed in general that smaller bundle size is more desirable for many reasons explained below. However, when considering the cost of a smaller bundle versus benefits obtained, the committee is more divided. The majority of the committee (~80%) feels that there are sufficiently compelling reasons to recommend that the NIF CDR baseline design be changed to the 4x4 bundle configuration that was considered. The projected increase in PACE costs is small (~$22M, no escalation, no contingency) compared to the total project cost ($583M, same basis), which seems reasonable in light of the flexibility and operability improvements that would be realized. Although the majority feels that a modest increase in cost can be justified for the smaller bundles, the 2x2 and 4x2 concepts have too large of an increase in cost over the baseline ($78M and $56M) to justify their recommendation.

A smaller fraction of the committee (~13%) feel that additional cost can be justified for these smaller bundle configurations (2x2 or 4x2) due to improved flexibility, maintainability, and operability. Further optimization of these designs could reduce the projected cost increases. This minority recommends additional effort be applied to appropriately scope these possibilities.

One committee member (~7%) feels that no change to the baseline design should be recommended, and that additional project funding would be better spent on increasing the number of beams, such as the 240-beam configuration proposed in the CDR.

There are distinct advantages with the smaller bundle sizes (2x2 and 4x2) over the 4x4 bundle with respect to constructability, activation, operability, and maintainability. The 4x2 concept also has the best component access along the length of the laser: any component can be removed laterally if desired in a one-component-deep assembly. In light of the general conclusion that smaller bundles are better, we felt compelled to review the NIF project costs to determine whether they could be reduced to better justify a 4x2 bundle from a cost standpoint. An alternate 4x2 bundle configuration was conceptualized using an in-line building arrangement to reduce some of the more significant cost drivers. Very little effort went into producing this estimate due the limited time available.

Nevertheless, the total cost differences between the 4x2 concept and the 4x12 baseline design reduce from ~$56M more for the U-shaped building layout to ~$20M more for the in-line 4x2 concept. This is because the building cost increment reduces, the spatial filter cost dropped further, and the laser structural support cost increment reduces. This alternate 4x2 concept using an in-line building design offers a significant number of improvements over the baseline design for a relatively modest cost increase (~$20M). However, there is a concern among the committee members that this cost estimate may be unrealistically low, due to the limited effort that produced it. And, the cost benefit of the in-line concept (if proven viable) could also be applied to reducing the cost of the 4x4 concept. Further design development is required to verify that the in-line concept is viable and the costs are indeed correct before a recommendation can be made to change the baseline design to this concept.

## 1.0 Introduction, Scope, and Review Plan

As requested in the guidance memo[1], this committee determined whether there are compelling reasons to recommend a change from the NIF CDR baseline laser bundle design based on a tradeoff between cost and technical risk. The baseline design building block is a 4x12 bundle (48 individual laser beams), which is replicated four times to create the required 192 beams. The baseline amplifier design uses bottom loading 1x4 slab and flashlamp cassettes for amplifier maintenance and large vacuum enclosures (2.5m high x 7m wide in cross-section) for each of the two spatial filters in each of the four bundles. The laser beams are arranged in two laser bays configured in a u-shape around the target area. The entire bundle review effort was performed in a very short time (six weeks) and with limited resources (15 personnel part-time). This should be compared to the effort that produced the CDR design (12 months, 50 to 100 personnel).

This committee considered three alternate bundle configurations (2x2, 4x2, and 4x4 bundles), and evaluated each bundle against the baseline design using the seven requested issues in the guidance memo:

- Cost
- Schedule
- Performance risk
- Maintainability/operability
- Hardware failure cost exposure
- Activation
- Design flexibility

The issues were reviewed to identify differences between each alternate bundle configuration and the baseline.

Each of the three bundle configurations offered different advantages that made them appear to be attractive. The 2x2 bundle was specifically requested to be considered in the guidance memo. It is the smallest practical bundle size (only a 1x1 and 2x1 are smaller) and is the size the French are recommending for their Laser Mega-Joule (LMJ) facility. The 4x4 bundle was considered to be a minimal revision to the baseline 4x12 design and provided improved maintenance features (improvement of some of the less-desirable aspects of the baseline without requiring a significant design modification). The 4x2 concept maintained the cost advantages of a 4-high design but has the operation and activation flexibility of a smaller 2-aperture wide design.

Due to limited resources, we developed one concept for each of the three bundle configurations, based on the experience of the committee members. Each concept was developed by a small team (two or three people) who resolved issues brought up by the other committee members. For each bundle configuration we did not consider all possible design options for laser components such as the amplifier, spatial filter, or power conditioning. We did evaluate different aspects of the baseline design to determine any weaknesses and whether there were other concepts that could offer better solutions to address the issues of concern.

The amplifier design for the three bundles is different, although they could all conceivably be similar. The 4x4 amplifier concept incorporates the same bottom-loading 1x4 slab and flashlamp cassettes as in the baseline design. The 2x2 concept is designed to use the same bottom-loading concept for slab and flashlamp maintenance, but could also be adapted to permit a side removal concept such as the French are proposing. The 4x2 concept places the amplifiers near the support floor and allows removal of a 1x4 amplifier module as in the Beamlet laser. This concept is intended to improve system operational functions while requiring a limited amount of amplifier development. For all amplifier concepts, the pulsed-power requirements were determined by the number of flashlamps required. The smaller the bundle, sizes required more lamps and, therefore, required a larger capacitor bank.

The spatial filter concept for the three bundles addressed concerns of operating a large vacuum vessel: time to vent/pump the enclosure, type of access to repair pinholes and lenses, and consequences of catastrophic failure (re: Beamlet spatial filter lens failure). Maintenance on components inside the transport spatial filter in the baseline design requires venting and pumping a large enclosure (>1000 $m^3$) which is time consuming (approximately eight hours just for the vent/pump cycle); repair must be done inside a critically clean environment by personnel wearing clean room suits; 25% of the total beams are unavailable while maintenance occurs; and failure of a single lens can potentially contaminate or damage all 96 lenses in the bundle. The 4x4 concept cuts the volume down by three, which means that its venting/pumping time is 1/3 the baseline using the same vacuum system design. Maintenance or accidents on a 4x4 spatial filter means that for a single isolated failure, at most 8% of the total beams are unavailable. The 2x2 and 4x2 bundles offer additional benefits: 2% or 4% beam loss per failure, and 1/12 or 1/6 of the vent/pump time. It is also possible to have individual spatial filter tubes for each beamline on the 4x2 concept because of the side access feature, which would reduce failure loss to a single beamline and further reduces the vent/pump time.

Consideration of a smaller bundle size in general causes an increase in the size of the building. This is due to the space needed around each bundle for maintenance access and additional structural supports, this increases the overall building size since there are more bundles. The primary effect of building size is construction cost.

After development of the three concepts, we used the CDR WBS structure as the basis for evaluating an alternate bundle configuration to the baseline. That is, we reviewed design issues for laser WBS elements such as optical pulse generation (WBS 1.3.1), amplifier (WBS 1.3.2), spatial filters (WBS 1.3.3), etc. Some WBS elements were reviewed in a minor fashion or were ignored entirely if we determined by inspection they had little effect on the bundle decision. WBS elements that were not reviewed include: 1.1 Project Office, 1.3.9 Final optics system, and 1.4 Target Area. WBS 1.5 Controls and 1.6 Optics were reviewed and found to have a relatively minor effect on the outcome compared to the other laser WBS elements. We developed comparison charts that listed advantages and disadvantages for the seven committee issues listed above for each of the three bundle configurations.

We then reviewed the seven committee issues listed in the comparison charts and attempted to make evaluations on a quantitative basis where possible. We developed differences in project costs and CS&T costs for each of the three bundles (1st committee issue), and estimates of project schedule delay due to a change in the baseline design (2nd committee issue). The effect on laser performance (3rd committee issue) was a subjective evaluation but quantified according to a numerical scale. Maintenance and operational ease (4th committee issue) was also a subjective evaluation, but we gave different weights to a number of maintenance and operational issues for each different WBS element, to obtain a better overall evaluation. We evaluated operational risk (5th committee issue) by considering cost to recover from two catastrophes (spatial filter lens implosion and flashlamp explosion). Evaluation for activation risk (6th committee issue) was subjective, but was weighted in a similar manner as was done for maintenance and operational ease. Design flexibility (7th committee issue) was also more subjective. The evaluations for the seven committee issues were used along with the bundle comparison charts to help guide us to a final bundle change recommendation.

## 2.0 Bundle Comparison Rationale

We reviewed the three concepts for component acceptability and developed cost differences between them and the baseline design. The rationale for performing this comparison is explained below using the CDR WBS as a guide.

### 2.1 Site and Conventional Facilities

The rationale for this section is summarized in Appendix A along with the detailed cost estimate.

### 2.2 Laser Components

### 2.2.1 Optical Pulse Generation

The majority of the OPG system is not impacted by changes in the bundle size and configuration. The MOR systems are unaffected provided there is not a large increase in distance from the MOR to the Preamplifier Module (PAM). In general, the PAM electrical and optical design is not changed, however, different bundle configurations have access and packaging implications on the PAM. Specifically, the designs were evaluated for their impact on the PAM (relative to the baseline) with respect to:

- Access - Some bundle configurations improve or inhibit access to the optics and electronics relative to the baseline. The baseline design provided for access to both sides (regenerative amp. and 4-pass amp.) of the PAM for minor repairs or diagnostics prior to removing the entire module for service off-line.

- Relaying - The PAM output is optically relayed to the pinhole in the transport spatial filter. The baseline design accomplishes this with either one or two spatial filters on the output of the PAM. Some modules require two filters in the baseline due to the physical offset provided to maintain access to both sides of the PAM. Some alternate bundle configurations result in PAM layouts which reduce cost since they do not require the second relay.

- Support Structure - The cost of the new PAM support structure is estimated for each alternate bundle configuration relative to the baseline.

- Required re-design - The magnitude of additional effort to advance the PAM design to the state of the CDR design is evaluated for each alternate bundle configuration.

These impacts are summarized on the comparison and evaluation charts in sections 3-6.

### 2.2.2 Amplifier Segments

For this review, amplifier designs for bundle sizes of 2x2, 4x2, and 4x4 were analyzed relative to the 4x12 NIF baseline design. Properties analyzed include project cost, development cost, risk of schedule slip, performance risk, ease of operation and maintenance, cost exposure to single-event hardware failures, activation risk, design flexibility relative to the baseline, and activation.

#### 2.2.2.1 Amplifier Project Costs

Project costs for the amplifiers were estimated by the same methods used for the NIF CDR. Only the costs of the mechanical hardware and flashlamps are included in this WBS element. All three alternative designs considered used the same size apertures, the same diameter flashlamps, and the same numbers of flashlamps in the central and side flashlamp cassettes (8 and 6, respectively) as the baseline design.

For amplifier designs that are similar to the Beamlet or NIF baseline designs, the cost/part depends only weakly with height. This is because most of the fabrication costs of the key amplifier parts, such the flashlamp cassettes and slab cassettes, is in their ends. See Figure 2-1, which shows two flashlamp cassettes, a slab cassette, and a frame assembly unit for the baseline design. These parts are fabricated by machining parts at the top and bottom, then welding or bolting these expensive parts together using relatively inexpensive, extruded elements. Consequently, a 4-slab-high amplifier is almost as expensive as a 2-slab-high amplifier that holds half as many slabs. For a laser system with a fixed number of slabs, a 4-slab-high amplifier costs only slightly more than half as much as a 2-slab-high amplifier.

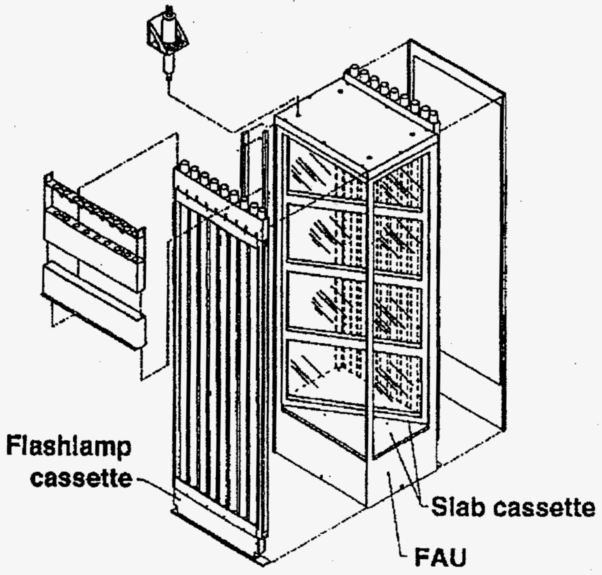


Figure 2-1 Amplifier Hardware for the NIF Baseline Design

Amplifier costs depend only weakly on bundle width. The primary cost factor is the number of flashlamp cassettes relative to the number of slab cassettes, which decreases as the width is increased. For example, a one-slab-wide amplifier has 2 lamp cassettes per slab cassette, while a twelve-slab-wide amplifier has only 1.0833 (13/12) lamp cassettes per slab cassette.

### 2.2.2.2 Amplifier Development Costs

Estimated costs for developing the NIF baseline amplifiers total $18M. These costs cover several development areas:

- Designing, building, and testing prototype amplifiers ($6.8M);
- Purchase and test $CO_2$ spray-cleaning equipment for in-situ cleaning of the prototype amplifiers ($1.3M);
- Designing, building, and activating a new amplifier/flashlamp testing facility ($4.5M);
- Developing improved pump-cavity designs ($2.3M);
- Developing flashlamps (($2.1M); and
- Preliminary mechanical engineering and tests (thermal control, in-situ cleaning, in-situ slab insertion, guillotines - $1.1M).

Development costs were estimated for the three alternative amplifier designs. In making these estimates, the possibility of using existing facilities -- and eliminating the need for building and activating a new amplifier/flashlamp testing facility -- was considered. Also, the impact of prototype amplifier size on the size and cost of the test facility (and its pulsed power system), and differences in the use of new technologies (such as in-situ cleaning, guillotines, and in-situ slab installation and removal), were taken into account.

### 2.2.2.3 Amplifier Performance Risk

Performance risk falls as amplifier designs become smaller and more similar to Nova or Beamlet experience.

### 2.2.2.4 Amplifier Maintenance, Operational Ease

Maintenance and operation ease are affected by several factors:

- The size of the parts which need to be handled (smaller is better)
- The number of parts which need to be maintained
- Ability to inspect, remove and replace parts without disturbing neighboring parts
- The precision with which the parts need to be installed
- The number of slabs per cassette, which determines the number of slabs that need to be refurbished when a single slab needs to be replaced.

#### 2.2.2.5 Amplifier Cost Exposure to Hardware Failures

Two different possible failures were considered: 1) implosion of a spatial filter lens; and 2) a flashlamp explosion at the end of amplifier A3. The spatial filter lens failure would result in refinishing a large fraction of the facing laser slabs, and replacement of lamps in several exposed lamp cassettes. In addition, each of the exposed slab cassettes and lamp cassettes would need to be refurbished. A flashlamp explosion at the end of amplifier A3 would contaminate the exposed optics, including laser slabs, mirrors (LM3), polarizers, and Pockels cells. These parts would need to be refurbished.

#### 2.2.2.6 Amplifier Activation Risk

Smaller amplifier units offer several advantages during activation:
- Smaller support structures can be installed and cleaned more easily.
- Assembly and installation of disk modules can be scheduled more efficiently.
- Maintaining cleanliness of assembled amplifier bundles during subsequent assembly is easier.
- Testing of a first assembled unit is easier.
- Ability to test fire small units makes testing simpler.

### 2.2.3 Spatial Filters

All of the bundle configurations use two spatial filters per beamlet, a cavity and a transport filter. The cavity spatial filter is located between the main cavity amplifiers and the switch amplifiers. The transport spatial filter is located between the boost amplifiers and the LM4/LM5 switchyard. The average transport spatial filter beamlet elevation lies in the horizontal target plane for all bundle sizes.

Cavity and transport spatial filter cost estimates for the three alternate bundle sizes are based on a scaling of the baseline costs published in the NIF CDR with variations as noted. Cost estimates listed in Appendix B.3 are developed using the following criteria and assumptions:

- The baseline CDR design, without improvements, is the basis for comparison
- Aperture and focal length are the same as the baseline.
- Alignment and diagnostics requirements are the same as the baseline.
- Average beam centerline height from the facility foundation interface is the same as the NIF baseline, since the concrete spatial filter support posts are not a system cost driver.
- The vessel fabrication method is commensurate with smaller vessels.
- Formed vessel walls are assumed for the 4x4 and 4x2 bundles.
- The 2x2 vessels are assumed round.
- No "log pile" segmented designs are considered.

- Transportation cost savings due to reconfiguration of individual vessel segments is included.
- Installation costs are adjusted for simplified installation of more, but smaller modules with partial assembly at the fabricator site.
- Motors and some portions of the drive mechanisms for internal components are relocated outside the vessels where applicable, with appropriate cost adjustments made for motors, mechanisms, and their installation.
- Filter, internal mechanisms and components are installed and maintained from the outside the vessels wherever possible, whereas the baseline assumes persons entering the vessels.
- Lens replacement is conducted manually from outside the vessels using installation tools whose cost is the same for all bundle options.
- The degree of vacuum and total pumping volume are the same as the baseline, with internal surface area appropriately adjusted for each bundle option.
- Total gas load is adjusted to account for relocation of some motors and mechanisms.
- System implementation options such as building floors below the vessels or a change of system elevation relative to grade are neglected since they are applicable to all bundle sizes.

A 2x2 and 4x2 bundle size makes maintenance of spatial filter motors and mechanisms significantly easier than in the baseline since most can be located outside of the vessels. A 4x4 spatial filter may require some internal motors.

Lens replacement in 2x2, 4x4, and 4x2 spatial filters is easier than in the baseline. In a 2x2 spatial filter, 2x2 lens arrays can be removed vertically or from the side. All bundle size options also offer an opportunity to greatly simplify the lens installation process and tooling relative to the baseline. Two-lens wide arrays can be removed from the side.

Personnel do not enter a 2x2 or 4x2 spatial filter vessel for any normal maintenance operations, thereby significantly improving system cleanliness and safety. Personnel may occasionally need to enter a 4x4 vessel to perform maintenance, however, some degree of improvement in cleanliness over the baseline is achieved.

Pumping of the spatial filters for the smaller bundle sizes is reduced assuming the ganging of system pump capacity. This improvement could also be applied to the baseline if it were segmented. The smaller bundle sizes offer advantages in construction scheduling. Installing component upgrades during the lifetime of the laser is easier due to the minimal system impact per installation.

### 2.2.4 Cavity Mirror Assemblies

Cavity mirror assemblies are located at either end of the laser cavity. LM1 deformable mirrors are located farthest from the target. LM2 cavity mirror is located closest to the target. Cavity mirrors are mounted in vertical array frames that encompass the entire bundle. Various alignment diagnostic systems are located behind and/or in front of the cavity mirrors.

The cavity mirror assembly cost estimates listed in Appendix B.4 are based on a scaling of the baseline estimate using the following assumptions:

- The cost of engineering the cavity mirror array frames is the same for each bundle size.
- The tooling needed for installing individual cavity mirrors into array frames is the same for all bundle sizes.
- The cavity mirrors are maintained from behind just as was done in the baseline.
- The cost of manpower to install a larger number of smaller cavity mirror array frames is accounted for.

The smaller bundle sizes do not offer an advantage over the baseline for maintenance since all cavity mirrors are accessed from the back by personnel outside the laser.

LM1 cavity mirrors are vulnerable to debris damage from an A1 blastshield failure and LM2 mirrors are vulnerable to A3 debris. Smaller bundle sizes reduce this potential damage.

### 2.2.5 Transport Turning Mirrors

There are at least five, and sometimes six, transport turning mirrors in each beamline. LM3 elbow mirrors are located in the laser bay in slanted array frames whose size matches that of the bundle. LM4 and LM5 mirrors are located in the switchyards. LM6, LM7 and LM8 mirrors are located in the target room. Only 32 of the 192 beams require an LM6 mirror.

Transport turning mirror mount cost estimates listed in Appendix B.5 are based on a scaling of the baseline estimate using the following assumptions:

- The cost of engineering the transport turning mirror array frames is the same for each bundle size.
- The tooling needed for installing individual turning mirrors into array frames is the same for all bundle sizes.
- The LM3 turning mirrors are maintained by removal of mounted optics from the side. Individual mounts were removed from behind in the baseline.
- The LM4, LM5, LM6, LM7 and LM8 transport turning mirror array frames are identical to the baseline since all proposed bundle configurations reduce to the same subsets beyond the transport spatial filter.
- The cost of manpower to install a larger number of smaller transport turning mirror array frames is accounted for.

The 2x2 implementation offers more maintenance options than the baseline since individual LM3 elbow mirrors or pairs can be removed either vertically or horizontally. The 4x2 also offers access options not present in the baseline. The 4x4 offers the fewest new maintenance options, however, the removal of 4x4 LM3 arrays is superior to the baseline procedure in both risk and ease. No advantage is seen for turning mirrors beyond the laser bays since they are in quad mounts or pairs for all bundle sizes.

LM3 elbow mirrors are vulnerable to debris damage from an A3 blastshield failure. Smaller bundle sizes or segmentation of the baseline system reduce this damage potential.

### 2.2.6 Pockels Cell Assemblies

The primary issue for the Plasma Electrode Pockels Cell (PEPC) related to the bundle is whether the fundamental PEPC module is 1x2 (as in the baseline) or 1x1 cells. While 1x1 modules cost slightly more, they are preferred by the PEPC group due to lower risk and access and maintainability advantages. The choice of the 1x1 also simplifies and reduces the cost of the PEPC development effort. Some of the proposed bundle configurations provide the option of 1x1 PEPC modules, and it is assumed in this report that 1x1 is chosen in these cases.

The additional cost of the 1x1 modules results from the need for more pulse generators both for creating the plasma and for switching the polarity of the beam. While the number of pulsers is larger with the 1x1 cell, the capacity of each is reduced. The increased cost is ,therefore, the product of the increased number of pulsers as in the baseline, and the reduced per-pulser cost of each. The development program savings is estimated from the fraction of the planned PEPC effort that would not be required if the 1x1 were selected. The results of these calculations are summarized in the comparison and evaluations charts in sections 3-6.

### 2.2.7 Polarizer Assembly

The polarizers are located in the laser cavity between the Pockels cell switches and the LM2 cavity mirrors. They are mounted in slanted array frames whose size matches that of the bundle.

Polarizer mount assembly cost estimates listed in Appendix B.7 are based on a scaling of the baseline estimate using the following assumptions:

- The cost of engineering the polarizer array frames is the same for each bundle size.
- The tooling needed for installing individual polarizers into array frames is the same for all bundle sizes.

- The polarizers are maintained by removal of mounted optics from the side. Individual mounts were removed from below and behind by entering the laser system in the baseline.
- The cost of manpower to install a larger number of smaller polarizer array frames is accounted for.

The 2x2 implementation offers more maintenance options than the baseline since individual polarizers or pairs can be removed either vertically or horizontally. The 4x2 also offers access options not present in the baseline. The 4x4 offers the fewest new maintenance options, however, the removal of 4x4 polarizer arrays is superior to the baseline procedure in both risk and ease.

Polarizers are vulnerable to debris damage from an A3 blastshield failure. Smaller bundle sizes reduce this potential damage.

### 2.2.8 Interstage and Beam Transport Hardware

Interstage and beam transport hardware consists of the noble gas boxes in the switchyards, isolation shutters located at both ends of each component system, and the enclosures that isolate the laser optical components from the building atmosphere. Transport tubes enclose bundles of beams. Shutters as presently conceived address vertical columns of beams within a bundle. The noble gas boxes in the switchyards have complex shapes that enclose beamlines and facilitate LM4 and LM5 maintenance.

Interstage and beam transport hardware cost estimates listed in Appendix B.8 are based on a scaling of the baseline estimate using the following assumptions:

- The increased size of the noble gas volume needed in the switchyards is accounted for.
- The increased material and installation cost for interstage segments and isolation shutters is accounted for.

Smaller bundle sizes or segmentation of the baseline system reduce the damage to beam transport caused by a spatial filter lens failure.

### 2.2.9 Final Optics System

This system is not impacted by the alternatives considered.

### 2.2.10 Structural Support System

The laser structural support system consists of all structures in the laser and switchyard bays needed to maintain optical component positions and stability as specified in the system design requirements while providing maintenance access and emergency egress. Individual optical and diagnostic components interface to the support structures through the component mounts or array frames. The structures interface to the conventional facility at the foundation level. Supported systems include amplifiers, power conditioning, cavity mirrors, turning mirrors, polarizers, Pockels cells, auxiliary systems, beam transport (noble gas box), alignment diagnostics, and performance diagnostics.

The laser structural support system cost estimates listed in Appendix B.10.1 are based on a scaling of both 192-beam baseline estimate using the following assumptions:

- The cost of engineering the structural support system for any of the bundle sizes is the same.
- The cost to build and install the laser support structures scales with the edge-to-edge width of the total beam pattern emerging from the transport spatial filter. This cost scaling is verified by comparison of two independently audited cost estimates for 192-beam and 240-beam switchyards.
- The component distribution between the laser bays and other areas of the laser and target area buildings are assumed to remain unchanged from the baseline.
- A normalized average beam height above grade is used for cost estimate scaling for all bundle configurations based on a maximizing of target chamber depth.
- The effect of resolving any system interface conflicts for the 4x2 and 2x2 designs is accounted for as a schedule impact.
- The cost of meeting system design requirements for component stability in the 4x2 and 2x2 designs is accounted for as a schedule impact.
- System implementation options such as building floors below the amplifiers and spatial filters or changing the system elevation relative to grade are not included since they are applicable to all bundle sizes.

Structural.system costs for all bundle sizes are first calculated by scaling the construction cost of the baseline by the ratio of beam array total widths in a laser bay. An accuracy of better than 10% was found by comparing the scaled cost of the 192-beam baseline with a separately estimated 240-beam support system. Although the 2x2 and 4x2 systems use laser area structures different in concept from the baseline, all bundle sizes use similar switchyards. In the baseline, switchyards account for 50% of the support structure construction costs, hence the scaling algorithm is accurate for the major cost driver in each structural system.

The beam array widths used in the scaling algorithm do not include the distance from the outside of the last beam in an array to the building wall, and are, therefore, less than the building widths. The beam array widths used for cost scaling are as follows: 696 inches for the baseline 4x12, 985 inches for the 4x4, 1,296 inches for the 2x2, and 1,368 inches for the 4x2.

The 2x2 implementation uses a series of concrete structures connected by lateral support members. A finite element model of this concept applied to the LM1 cavity mirror area shown in Appendix B.10.2 provided a basis for estimating the degree of effort needed to modify the structural parameters such that all components meet stability requirements. Since significant time is needed to refine all structural component sizes and locations, the beam array width cost scaling algorithm is used. The cost uncertainty due to this assumption applies only to the non-switchyard structures.

The 4x4 structural support system is nearly identical to the baseline, therefore, the structures as estimated will meet all component stability requirements with very few modifications. Both the 4x4 and the baseline use six structure types that are repeated in each laser bay. The six structure types are identified by their supported components. The LM1 cavity mirrors are on structures that are isolated from A1 amplifier flashlamp mechanical shock. The A1 main amplifiers are isolated on their own structures. A2 switch amplifiers share structures with Pockels cell switches since the flashlamps generate mechanical shock and the Pockels cell pumps are potential vibration sources. The polarizers, LM2 cavity mirrors and LM3 turning mirrors share structures due to similar stability requirements, proximity of all, and the need for isolation from amplifiers. The A3 boost amplifiers are on isolated structures. The LM4 and LM5 turning mirrors are supported on switchyards which are space frames located in separate bays on either side of the target area. The switchyard bays are deeper and taller than the laser bays to facilitate beam transport to the bottom and top of the target chamber. It is mechanically isolated from facility wall wind loads.

The 4x2 and 2x2 structural supports have not undergone the same level of system integration and analysis as the baseline and 4x4, hence their compliance with system design requirements in their currently estimated form is not assured.

The 4x2 implementation uses elevated floors as integrated laser support structures. The cost of providing this deck system is estimated by comparing it with similar previously estimated structures.

After the scaling algorithm is applied for each bundle size implementation, adjustments are made in the 4x2 system cost for the elevated concrete decks.

The 4x2 implementation uses a two-level deck system that serves as an integrated laser support structure. The cost of providing this deck system is estimated by observing that the multi-deck construction and stiffness requirements are similar to the concrete portion of baseline switchyard structures. The baseline switchyard has been verified to meet all system design requirements for optical stability of LM4 and LM5 turning mirrors, therefore, a scaling with respect to the concrete portion of a switchyard will account for the cost of achieving the required stiffness of the deck system for supporting laser mirrors, lenses and pinhole hardware.

The scaling algorithm for structural concrete decks in the 4x2 implementation is based on the assumption that concrete multi-deck structures that meet the same stiffness requirements have the same cost per unit volume of enclosed volume. A detailed explanation of this calculation is in Appendix B.10. Applying the algorithm yields a concrete deck system cost of \$1.2M per bay or \$2.4M total. This construction cost is about \$1.06 per cubic foot of enclosed volume.

The \$2.4M construction cost for a deck system assumes that no vibration excitations over and above the ambient ground motion spectrum used in the baseline are present. The laser structural system WBS 1.3.10 costs for the 4x2 tabulated elsewhere reflect only the volume of concrete needed to provide local support for component structures. The cost increment for mitigating system integration conflicts such as vibration crosstalk is ignored.

An cost summary itemized by structure type is found in Appendix B.10. The baseline structure costs are included for comparison.

### 2.2.11 Laser Auxiliary System

The laser auxiliary system is described in Section 5.3.11 of the NIF CDR. The major portions consist of the beam transport gas system and the slab amplifier gas system.

The beam transport system backfills the beam transport tubes from the transport spatial filter to the gas window at the target room with an inert gas or other mixture in order to suppress SRRS. As the laser bundle size decreases, more duct work and a larger number of valves would be required, which would increase hardware costs (about \$100K). However, the size of the duct work and the size of the valves would decrease with decreasing bundle size which would make installation, activation, and maintenance easier.

The NIF amplifier gas system is a nitrogen backfill operating at 20 torr pressure and a flow rate of 75 $m^3$/min during the purging stage, with a steady state flow rate of 7.5 $m^3$/min. A bundle size of 4x4 or smaller would slightly decrease baseline costs (\$100K), since the backfill volumes would decrease and it is assumed that the equivalent of a 4x12 volume would not be opened at one time. Overall steady state leak rates are assumed to be similar. (Note: This analysis and the CDR do not consider the cost of an active gas cooling system for the amplifier.)

It is judged that installation, activation, operation and maintenance would be similar to the baseline design for any of the bundle sizes, although the smaller bundle sizes would be more flexible to accommodate design changes.

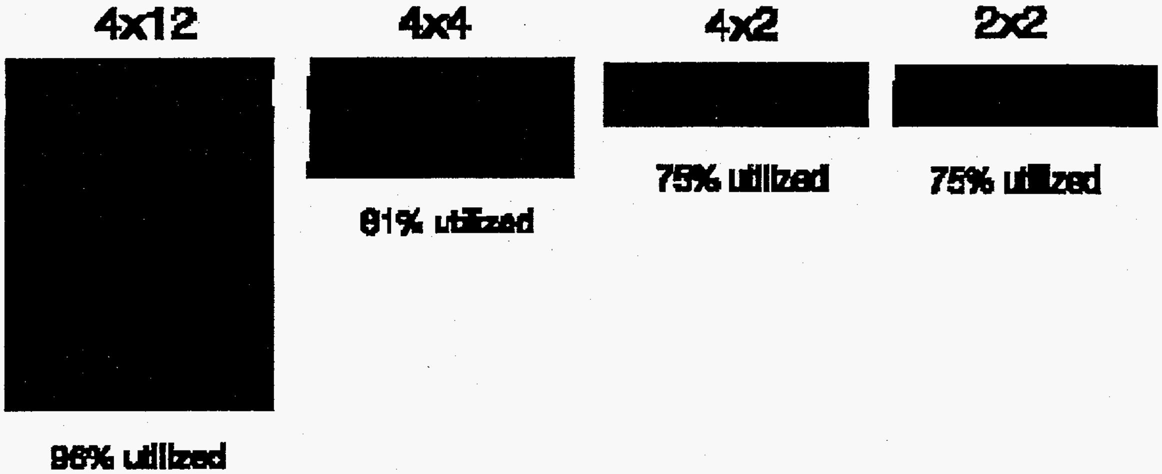


Figure 2-2

Comparison of Utilization level of Capacitor Module for various bundle sizes. Beam travel is horizontal (plan view).

In addition to the cost impact, the relationship of the bank to the bundle size has an effect on operability, maintainability and activation. The integral correlation of bank modules to bundles results in a smaller system impact if a bank module is out of service for smaller bundle designs. Activation is simplified for smaller bundles since flashlamp light from a given module is contained within a smaller volume without the need for temporary walls or shields in the amplifiers. Smaller bundles may also improve maintainability of the junction boxes. Access to these boxes could be improved since the flashlamps are distributed over a larger area than in the baseline so that the boxes could be spaced farther apart.

The final power conditioning cost impacted by the bundle size is the power transmission lines. The bundle configuration can affect the cost by changing the path length of the cable route from the capacitors to the amplifiers. The complexity (number of turns) can also impact this cost. In this exercise, it is assumed that the path length changes for the 4x4 and 2x2 designs are negligible. The path length is significantly shorter in the 4x2 design than in the baseline, however, since the bank is located directly under the amplifier. A cost savings of roughly half of the transmission line and installation cost could be realized by the 4x2 relative to the baseline.

### 2.2.13 Beam Control and Laser Diagnostic

Beam control consists of wavefront control and alignment. Since wavefront control hardware is completely coupled to single beamlines, there is no impact for altering the laser bundle size. The major impact on alignment revolves around the input/output alignment sensors. The CDR design couples these packages to a 4x2 set of beamlets, so there would be no cost impact for the 4x2 or

### 2.2.12 Power Conditioning System

The primary bundle-related impact on the power conditioning system is the difference in total energy required to drive the flashlamps. This is primarily a function of the ratio of side to central flashlamp cassettes in the bundle. Side cassettes have more flashlamps per slab than central cassettes (because they are expected to be less efficient), and, therefore, require more pulsed power. The cost of this added pulsed power, relative to the baseline, was calculated by estimating the recurring portion of the CDR bank costs per joule (excluding design cost) and multiplying by the amount of additional energy required. The following simplifying assumptions were made in this exercise to facilitate a timely estimate of relative bank costs of various bundle sizes:

- The flashlamp bore remains the same as the baseline in all bundle configurations.
- The (baseline) capability to independently adjust the bank voltages of side and central flashlamps is retained.
- Power conditioning will provide capability to drive all flashlamps to 20% of their explosion energy, regardless of their nominal operating energy.
- The fundamental pulsed power circuit concept will remain the same for all bundle concepts (rigid coaxial transmission lines terminate in junction boxes near the amplifiers).
- The number of lamps in side and central flashlamp cassettes is the same for all designs, i.e., 6 lamps per side cassette, 8 lamps per central cassette.

A secondary but significant effect on power conditioning cost is the efficiency with which the power conditioning modules map onto the amplifiers. It is assumed that a given bundle is powered by an integer number of bank modules. Bundles with smaller numbers of flashlamps typically have a lower utilization of the capacity of the modules driving each bundle of amplifiers. This is illustrated in Figure 2-2. The squares represent central cassettes and the rectangles represent side cassettes. Cassettes powered by a common pulsed power module have the same shading. Each bank module can power forty 180 cm lamps (4xN) or eighty 90 cm lamps (2xN). This underutilization results in increased cost since the number of modules increases (with the corresponding controls, chargers, enclosures etc.) for a given stored energy relative to the baseline. The requirement that side and central lamps must be powered from separate modules exacerbates this problem for smaller bundle designs. However, this feature is deemed necessary since bank voltage adjustments may be needed to compensate for the decay in efficiency of side lamp cassettes (with large silvered reflectors) compared with central lamp cassettes. The utilization fraction is used to calculate the additional cost, relative to the baseline design, of the capacitor bank for smaller bundles due to underutilization.

4x4 designs. The 2x2 design calls for a beam transport system to be installed between 2x2 arrays for transport of the alignment beam allowing for use of the same 4x2 style sensor packages with only a modest cost increase ($100K). It is judged that activation and maintenance would be easier for the smaller arrays due to improved access. For example, it should be straightforward to work on an alignment mirror in the middle of a 4x2, or even a 4x4 array, whereas special hardware or procedures would be necessary for the baseline design.

The laser diagnostics consist of several components, but most items would not be affected by changes in laser bundle size to the proposed sizes. For example, the beam sampler behind each M2 cavity mirror is independent of bundle size, and the 3ω diagnostic at the target chamber is already in a 2x2 array, so there would be no impact if the bundle size were altered. However, the pick-off mirror system for the target plane diagnostic and the mechanism which translates the full beam calorimeter are both designed based on a 4x12 array. It is assumed that beams or a diagnostic mirror would be translated by a gantry mechanism similar to what has recently been utilized on the OMEGA laser. As a result, the overall impact for different bundle sizes would be small, essentially just a larger gantry system for the smaller bundle sizes since the beams would be further separated for those cases. The additional cost of the larger gantry is estimated to be $50K for the 4x4 and $100K for the other arrays. It does not appear that there would be any noteworthy impact on the activation, operation, or maintenance of these diagnostics for the various bundle sizes.

### 2.2.14 Laser Integration

The three bundle size options as presented include system implementation variations from the baseline that are applicable in some degree to all bundle configurations.

The most apparent system implementation variable is the system elevation above grade. The system elevations above grade for the baseline, 2x2, 4x4 and 4x2 implementations are itemized in Appendix B.14. Any of these implementations could assign a variable to the target elevation above grade and perform an optimization between the cost of localized berms, excavations, retaining walls, building volume, and support structure heights.

The 4x2 bundle implementation uses a series of elevated decks to support laser components and offer the potential for moving capacitors closer to the amplifiers. This tradeoff is applicable to all bundle sizes, including the baseline. System integration issues that would bear on this optimization are the need for clear access to amplifier cable connections, requirements for fire protection, zone volume needed for support piers, stairwells, elevators and egress aisles, and the isolation of the decks from laser structures that may be incompatible with the induced vibrations. A compatible solution for each bundle size clearly exists, however, the costs of verified implementations are not developed in this study.

The 4x2 bundles do not show the lateral braces across the structures that the 2x2 bundle design indicates. Either system could benefit from selective use of lateral bracing where clear vertical access is not needed.

The bundle segmentation of one component can vary from one component to the next in a hybrid system. The spatial filters for the baseline and alternates use single vessels to enclose entire bundles. A hybrid system could combine 4x4 or 4x2 amplifiers with 2x2 or 1x1 log-pile spatial filters to reduce operational risk.

Pulsed power cables to the amplifiers are routed overhead in the baseline and in the 4x4 and 2x2 systems. The 4x2 presents the capacitors above grade but pulsed power cables entering amplifiers from below. Each presents advantages and disadvantages that are not linked to bundle size. Capacitors in the baseline, 4x4, and 2x2 implementations are located in fire-isolated side structures, however, cable runs must carry across half or the laser bay to reach the central amplifiers. The optimum configuration of capacitors and cable runs will most likely be similar for all bundle sizes since they share many of the constraints.

The aisle widths in the 2x2, 4x4 and 4x2 implementations are based on side access. Component maintenance schemes that use top or bottom access can be applied to these bundle sizes, thereby providing corresponding savings in facility costs.

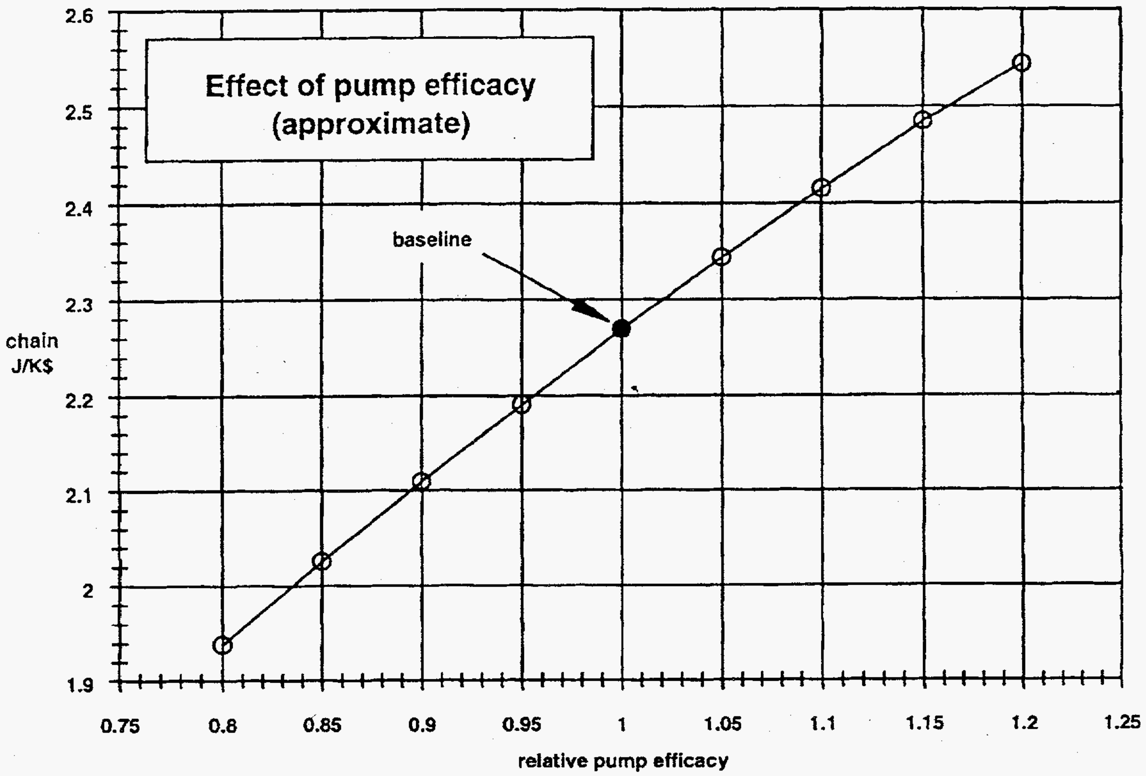
## 2.3 Laser Performance

The major influence of bundling design on laser performance is in the area of pumping. The efficiency and uniformity of gain, and the amount of pump-induced distortion, vary as the bundling geometry is varied. This happens because of the difference between side flashlamp arrays and center flashlamp arrays. The extreme cases are the 2x2 and 4x2 bundle, which have two side arrays and one center array, and the 4x12 bundle, which has 2 side arrays and 11 center arrays.

We have calculated the effect of pumping efficiency on overall laser performance for the CDR. All the effects of pump-related parameters (pump cavity quality, glass absorption, decay, quenching and fluorescence line shape) have the same amount of influence, since they act in unison to change pumping efficacy without having other effects. Increased pump efficacy rapidly increases chain cost effectiveness; it is our strongest lever for system improvement.

| Pump / LG-750 | 0.80 | 0.85 | 0.90 | 0.95 | 1.00 | 1.05 | 1.10 | 1.15 | 1.20 |
|---|---|---|---|---|---|---|---|---|---|
| Chain J/K$ | 1.9384 | 2.0259 | 2.1095 | 2.1901 | 2.2692 | 2.3432 | 2.4151 | 2.4847 | 2.5441 |
| Ratio to LG-750 | 0.8542 | 0.8928 | 0.9296 | 0.9651 | 1.0000 | 1.0326 | 1.0643 | 1.0950 | 1.1211 |

The plot of this relationship is nearly linear:



We see that increased efficiency is very important to NIF. A 5% change in pump efficiency will lead to a 3% change in performance if cost is fixed (eating a good fraction of our performance margin), or will require about $20M in laser cost change to keep the output constant. These values assume that the laser chain is redesigned and rebuilt for each change in pump efficiency; if the design is unchanged than the impact is larger (this case has not been calculated).

The pump uniformity is also very important, but the effects have not been quantified. The great change in gain across the Beamlet amplifiers is not tolerable for NIF, because of the required precision in the input apodizers and alignment system.

The pump-induced distortion in the Beamlet amplifiers is also at the limit of tolerance for NIF. An in-cavity adaptive mirror can largely correct for the present level of distortion, but at the cost of a distorted beam at the pinholes that requires smoother edge apodization and a resulting lower fill factor. In addition, the risk of pinhole closure is increased by some unknown amount.

All three of these factors push us strongly in the direction of the flashlamp arrays that produce the highest efficiency with high uniformity and low distortion. At present, this would be the center arrays, and so performance would strongly favor the 4x12 array. However, we are engaged in an intensive computational and experimental effort to completely redesign the present arrays, since we know them to be very far from optimum. This effort is in progress, and its final result is still unknown. This puts us in the unenviable position of knowing that array performance is very important, but not knowing which array type is better.

There is reason to believe that more improvement is possible for the side arrays than for the center arrays. This is because the improvement comes from changing lamp spacing and reflector shape. Since there is more space per lamp in the side arrays, there is more freedom to put the lamps where they work best than in center arrays. Since there is more reflector area per lamp in the side arrays, there is more freedom to shape the reflectors for the desired effects. Whether this hypothetical extra room for improvement will actually lead to side arrays that are better than center arrays is unknown at present. We will have computational predictions, normalized to present experimental data (with lower-quality arrays) in a few months. We will have experimental data by late Spring 1996.

In summary, we know that bundling is very important to laser performance, and to the risk that the specified performance will not be reached. We do not, however, presently know whether the center or side arrays now in design will turn out to be better. We are thus unable to choose among the various bundling concepts based on performance, or performance risk. We consider it likely that there will be significant differences between bundles with many center arrays, and bundles with few.

Finally, it should be noted that these differences are more important for direct drive than for indirect drive. The addition of angular variation to the beam (for SSD) makes the desire for high gain and low distortion larger than it already is for indirect drive. In fact, if it turns out that side arrays are better than center arrays, then direct drive will want a 4x1 bundling (all side arrays) to take advantage of side-array benefits.

## 3.0 2x2 Bundle Concept

### 3.1 2x2 Bundle Description

### 3.1.1 Overview

An important factor to be considered in selecting the optimum NIF laser design is the cost and risk of installing, activating and maintaining the equipment for the lifetime of the facility. It has been proposed that the smaller the laser bundle size the easier it will be to perform these activities. Opposing this concept of smallness are the facts presented in the NIF CDR that suggest that larger bundle sizes provide higher laser efficiency and lower construction costs. The 2x2 bundle configuration described below presents an alternative to the baseline 4x12 bundle configuration and attempts to take full advantage of small modular line replaceable units that can be quickly and easily replaced while minimizing unavoidable cost increases. The extent to which this is achieved is discussed below.

In general, the proposed design is intended to be conservative providing ample space for structures and anticipated operational activities. This was purposefully done so as not to present an unrealistic option that would be revealed later to be more costly than projected.

The concept presented below is similar to and has been influenced by the design recently adopted for LMJ. Deviations from that 2x2 design are proposed to minimize cost and improve operability.

The laser bundles are assumed to be located in a U-shaped Laser and Target Area Building (LTAB) similar to the layout described in the NIF CDR. A 2x2 layout for alternate building configurations (i.e., "in-line" configuration) is not considered.

### 3.1.2 Facility Layout

An elevation of one of the two laser bays view looking in-line with the laser beam is shown in Figure 3-1. This sectional view is taken through either the A1 or A2 amplifier bundles. The laser beams are arrayed in bundles two apertures wide and two apertures high. Each group of four beams can be operated independently of the others. The amplifier bundle cross-sectional area is about 1.2 meters on a side. Groups of four 2x2 bundles are mounted on a common support structure, stacked two high and two wide. This assembly (bundle group) of four bundles (16 beams) is duplicated five times to create a total of 24 2x2 bundles in a laser bay, 96 beams in total. Since there are two identical laser bays in the U-shaped building this totals to the required 192 beams.

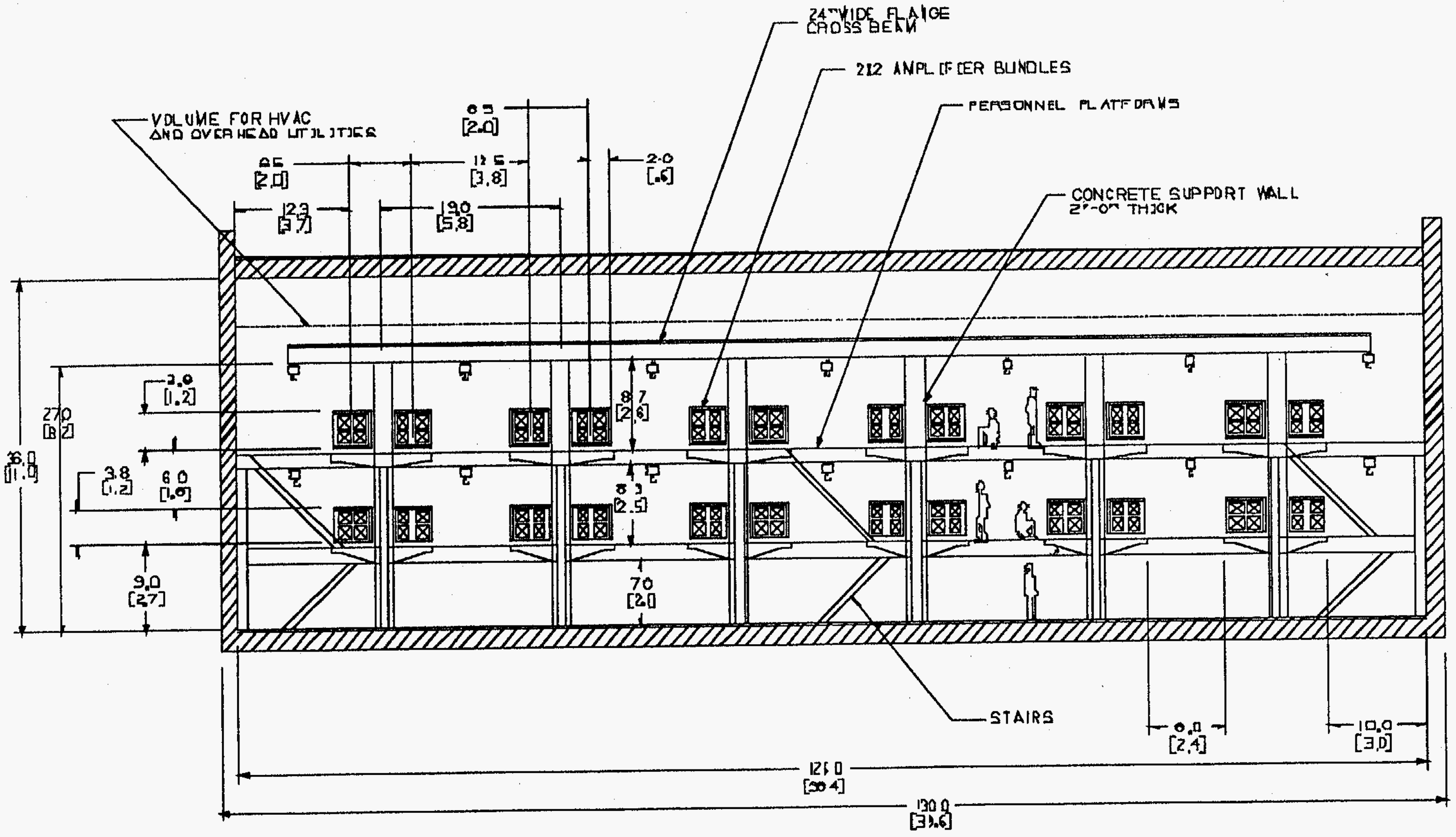


Figure 3-1  Amp1/Amp2 elevation view

Each bundle group is supported on 2 feet thick concrete walls that are 8.2 m (27 ft.) tall. Concrete will provide high stiffness and good damping to help provide optimum optical stability of critical laser elements. Cantilevered off of the support walls are steel support arms, about 1.2 m (4 ft.) long, which are bolted to the concrete surface. All laser bundle components are kinematically supported on these struts which are located at numerous locations down the length of each laser bundle.

Attached to the tops of the concrete support structures perpendicular to the laser beams are 24 inch wide flange, steel beams. About 2.1 m (7 ft.) of space is located above these beams to provide room for HVAC ducting, power conditioning transmission lines and other laser utilities. The beams have two functions: 1) to connect the concrete walls together providing increased lateral structural stiffness, and 2) to provide support points for the rail system of the overhead cranes. The overhead cranes, one in each corridor, are used during construction and during maintenance activities of the laser special equipment.

In between each bundle group is a corridor 2.4 m (8 ft.)wide (3 m for the outside corridors). These corridors provide convenient side-access to the laser equipment. To enable workers to get the height required, elevated platforms constructed from steel girders and floor gratings are installed. Two elevated floors are provided one for each of the two levels of lasers. The lowest laser bundles are elevated 2.1 m (7 ft.) above the ground for two reasons: 1) to permit the possibility of bottom loading the amplifier slabs, and 2) to provide lateral movement of workers underneath the lasers enhancing the accessibility of the equipment to nearby maintenance facilities. Stair cases and an equipment elevator are provided at the end of the corridors. If side loading of the amplifier can be achieved and if lateral human mobility under the laser is determined by further evaluation to be not essential then the entire height of the laser can be reduced by 2.1 m (7 ft.). This option is shown in Figure 3-2. The cost differential between these two options is not large enough to be an influencing factor in this evaluation. If the 2x2 option is adopted, the decision on the amplifier slab loading orientation can be determined at a later time with no impact on facility floor space requirements.

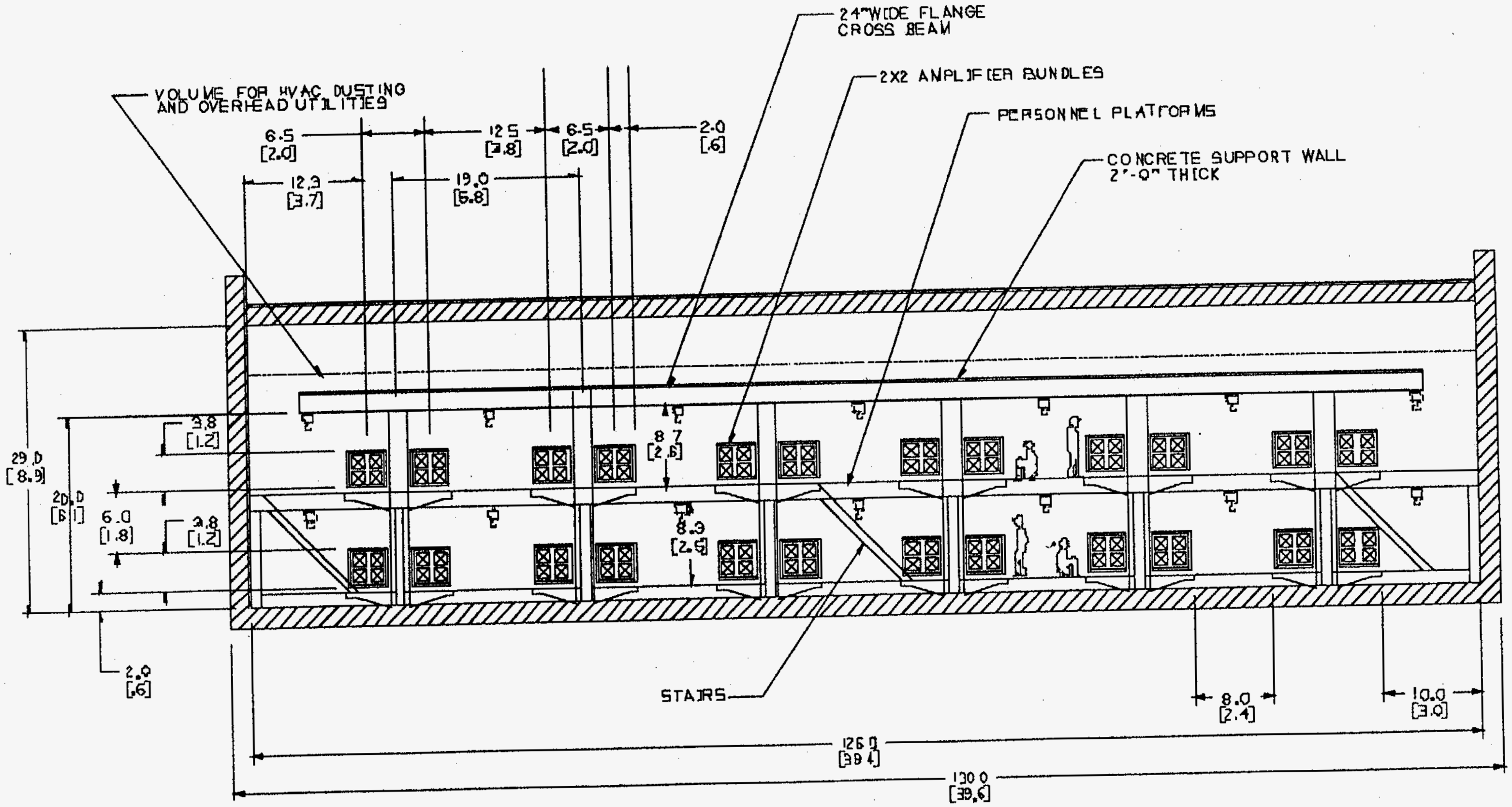


Figure 3-2 Amp1/Amp2 elevation view with top loading amplifiers

The laser bay width and height required to provide space for all of the special equipment and personnel platforms is 38.4 m (126 ft.) and 11 m (36 ft.) respectively. The bay width is 14 m (46 ft.) more than required in the baseline 4x12 design. This increase is unavoidable for the 2x2 concept unless a taller facility which stacks more laser bundles vertically is provided. A taller facility would have significant negative affects on optic stability and is highly undesirable.

The increased width of each laser bay results in the LTAB layout shown in Figure 3-3. The total width of the building is 107 m (352 ft.), 38.3 m (126 ft.) for each laser bay and an additional 30.5 m (100 ft.) for the mechanical equipment area in the center of the building. Since the outermost 2x2 laser bundles are further away from the target area than in the baseline the optical path length is increased and, therefore, the length of the spatial filter must also increase to properly relay the image of the beam to the frequency converter. The increase is about 14 m (46 ft.). This increases the length of the laser bay to 141 m (463 ft.) and the total building length to 179 m (587 ft.).

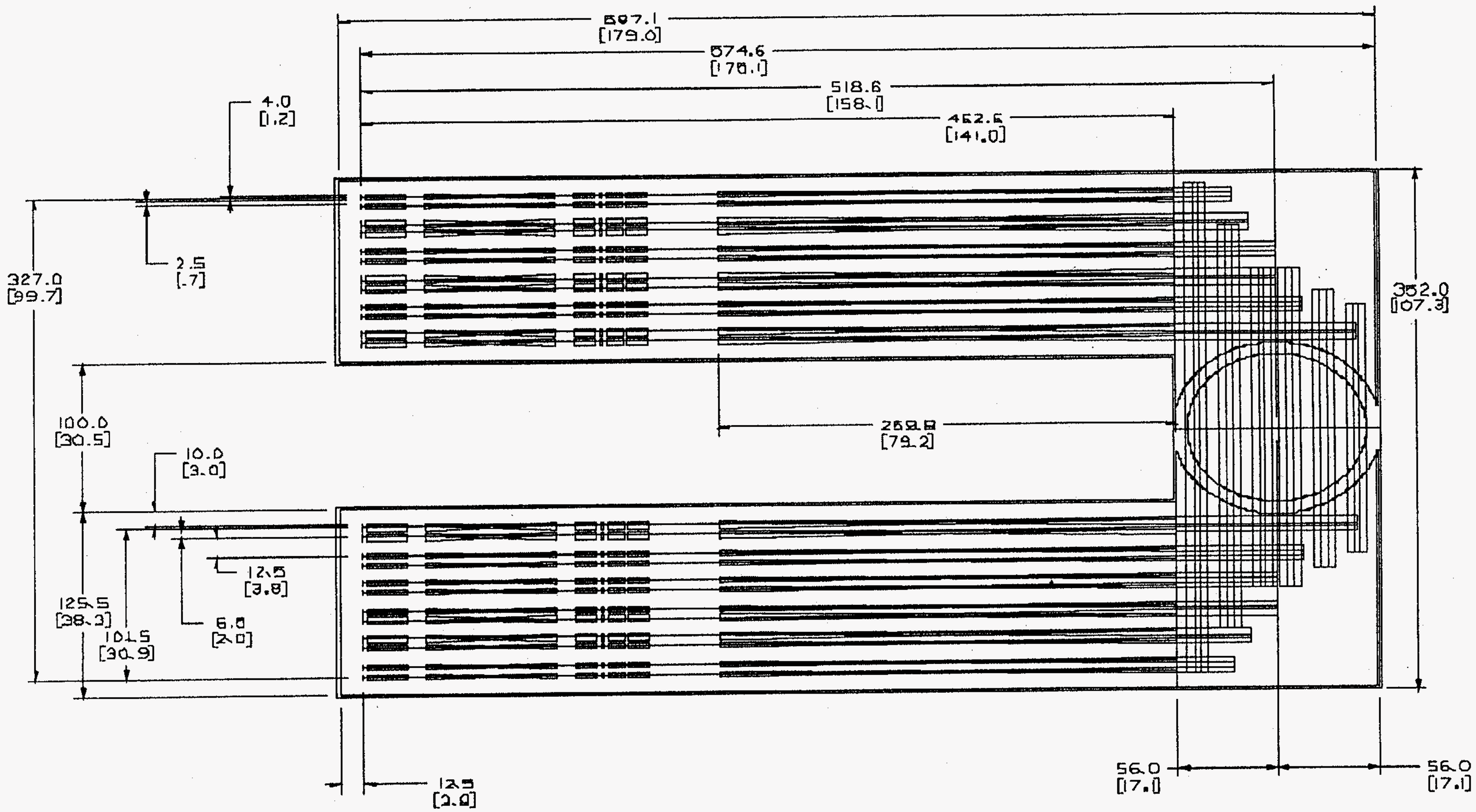


Figure 3-3 Plan View

A side elevation view of the laser bay, Figure 3-4, illustrates features of the building along the length of the building. The exterior building profile is approximately rectangular with a 1.5 m (5 ft.) jog in the floor and the roof to accommodate the vertical rise in the laser bundle centerline at the polarizer. The roof is also raised 2.4 m (5 ft.) in a small section above the center of the transport spatial filter to permit the output sensor diagnostic packages to be located above the transport spatial filter. The interior ceiling height is a constant 10.7 m (35 ft.) from end-to-end. The floor is designed to be 0.9 m (3 ft.) thick and flat except for a 1.5 m (5 ft.) rise in the area of the polarizer.

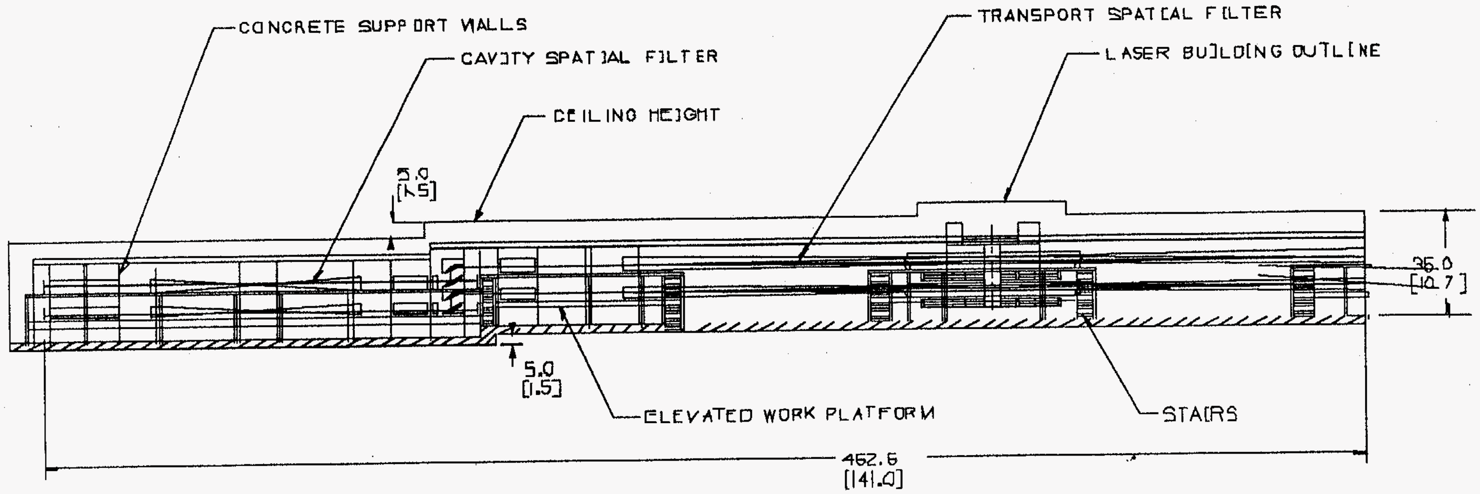


Figure 3-4  Side elevation view

Figure 3-4 indicates that the concrete support walls for the laser components are not constructed continuously from one end of the laser bay to the other. Further details shown in Figure 3-5, specify the number and size of these walls. Each laser bundle group requires 11 walls ranging in length from 0.6 m (2 ft.) to 10 m (32.9 ft.). Each wall is 0.6 m (2 ft.) thick and is constructed using low cost, standard concrete forming processes. Each wall is rigidly connected to the concrete floor with formed in-place rebar. To improve optical stability it may be feasible to embed piers into the ground underneath each concrete wall. This would closely couple the support structures to more quiescent soil conditions and increase foundation stiffness.

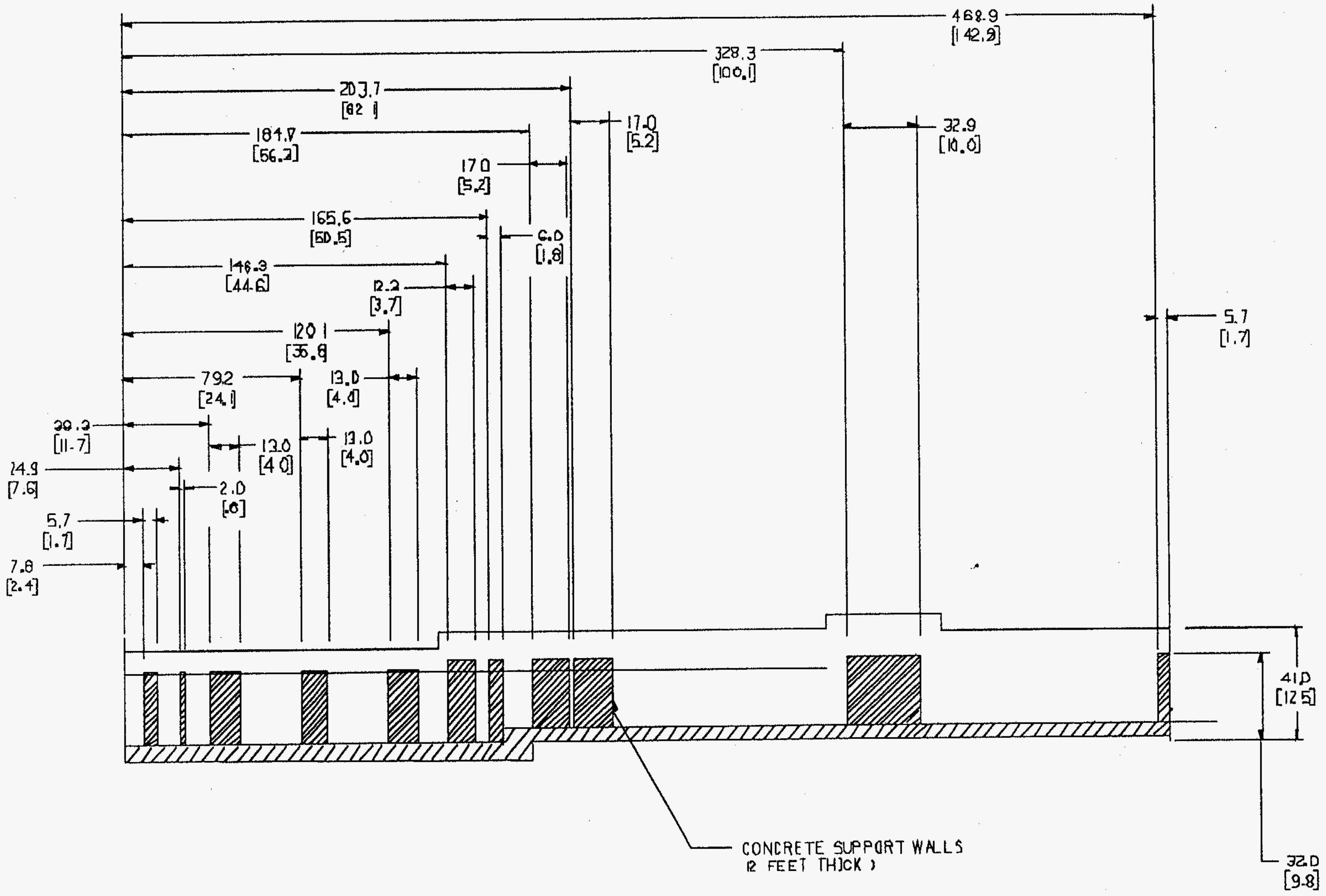


Figure 3-5 side elevation view of laser support walls

Also shown in Figure 3-4 are the elevated platforms that provide personnel access to the laser bundles. Figure 3-6 shows more clearly that for each laser bay there are three discrete platforms: 1) cavity equipment platform, 2) beam injection equipment platform, and 3) spatial filter lens platform. The platforms are constructed of horizontal and vertical steel girders that are bolted into the concrete floor. Vertical girders are located in between concrete walls to avoid blocking space in the laser access corridors. Also, there is no direct structural connection between the laser support walls and the work platforms. This will minimize vibration transmitted from the work platform to the laser hardware. This will be important during laser alignment operations when precision aligning may be performed on one laser bundle while another nearby bundle is undergoing maintenance.

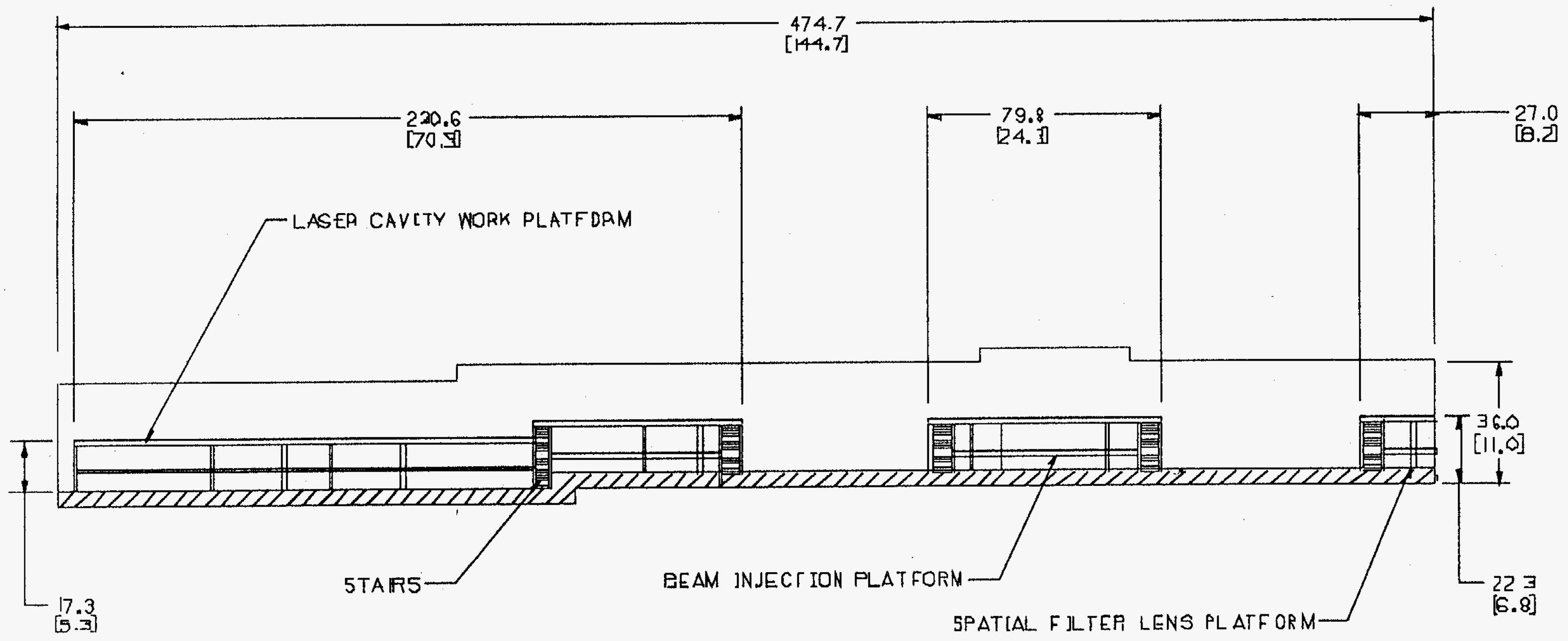


Figure 3-6 Side elevation view of personnel access platforms

Figures 3-7 and 3-8 provide end and side elevation views of the laser hardware near the center of the transport spatial filter. Located underneath the pinhole assembly of each laser bundle are the preamplifier modules, input sensor packages, and the beam transport assemblies. The low energy laser pulse from the master oscillator room is delivered to the preamplifier packages. The light is amplified and shaped by the preamps, and directed vertically upward into the injection mirror near the pinhole plane of the transport spatial filter. Above the laser bundle group and supported on beams attached to the concrete laser support walls are the output sensor packages. Diagnostic light from each beam line travels vertically in beam tubes to these output sensor packages in a manner similar to the baseline configuration.

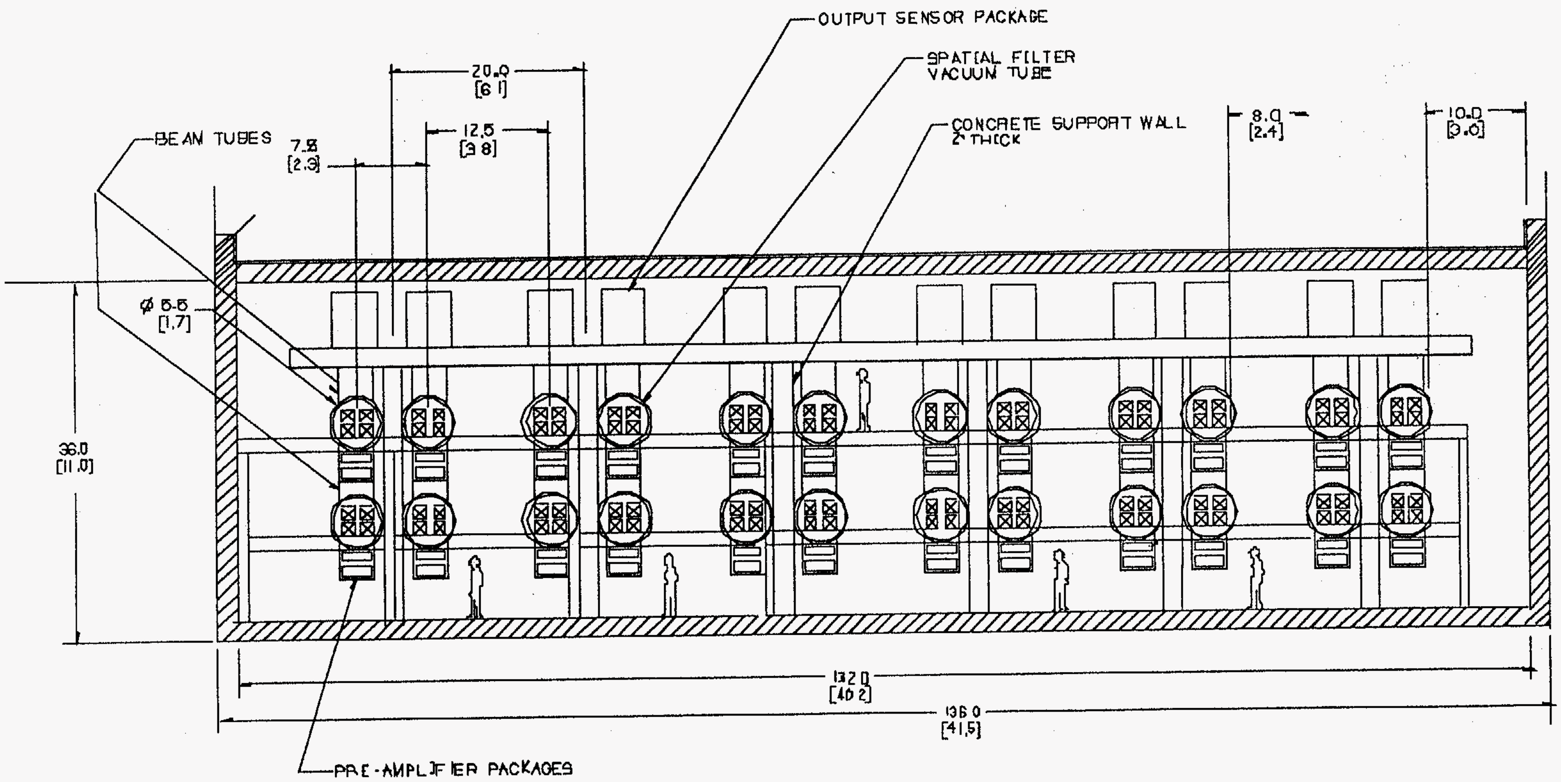


Figure 3-7 Transport spatial filter end elevation view

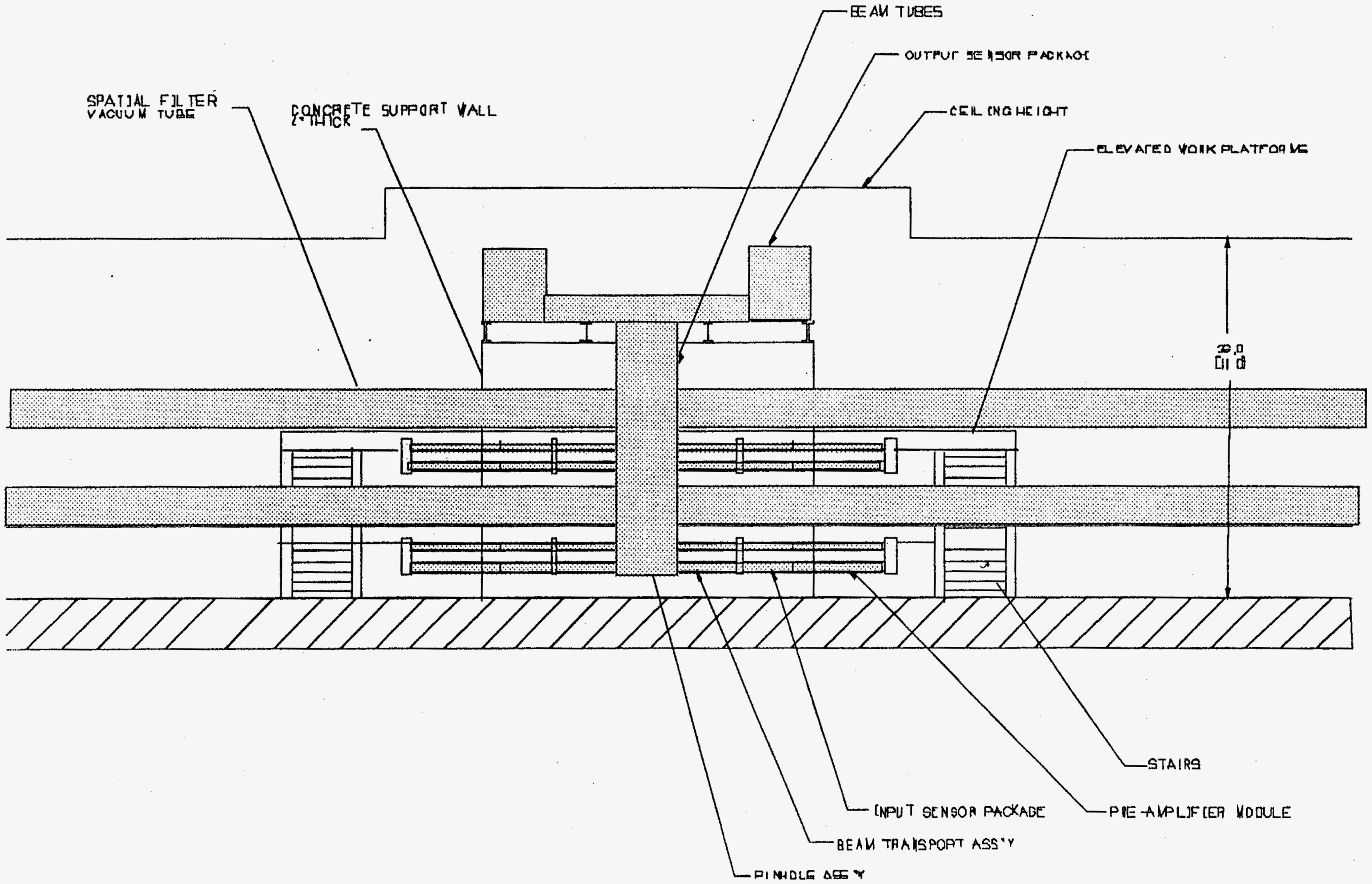


Figure 3-8 Transport spatial filter side elevation view

Figure 3-9 shows the laser hardware and the support walls in the vicinity of the A1, A2, Pockels cell, polarizer, and LM3 mirrors. Five support walls are required in this area. The elevated platform will have to be ramped or stepped in this location to accommodate the laser elevation rise. This will hamper operations in this area but it is believed that with careful design of maintenance equipment this difficulty can be successfully managed.

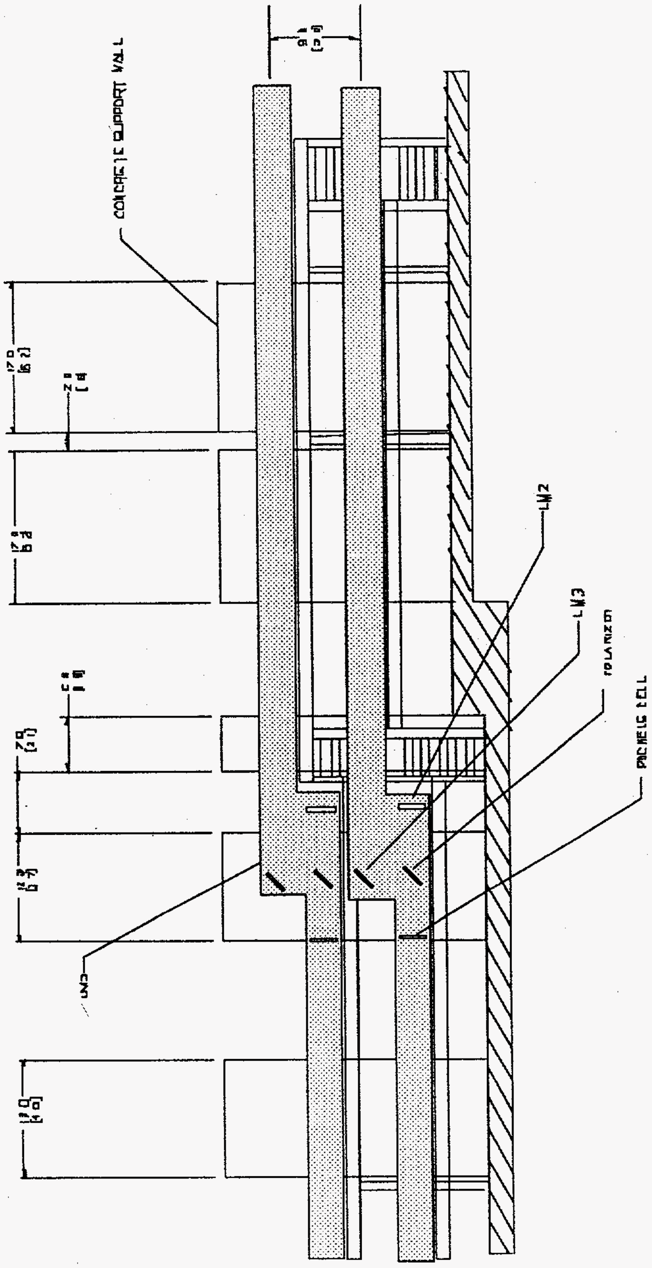


Figure 3-9 Side elevation view of A1, A2, polarizer, Pockel cell and LM3

The switchyard area design for the 2x2 configuration remains conceptually the same as the baseline design. The only difference is that the width building and the mirror support structure is 46 feet wider and will consequently cost more.

### 3.1.3 Component Description

Preamplifiers and beam injection optics are located directly underneath the spatial filters, Figure 3-10. Each preamplifier module (PAM) is kinematically supported at its ends. In between preamplifiers on opposite sides of the center line of the transport spatial filter is a another optic package that transports the preamplifier laser beam into the spatial filter. This package and the preamplifiers are self-contained line replaceable units that are easily removed using a customized forklift which has convenient access from the side. The output sensor package is located above the bundle group. The design of these packages is similar to the baseline design. In order to get the diagnostic beams from the spatial filter to these packages vertical beam tubes are provided. Beams originating in the lower laser bundles must pass through the upper laser bundles. Windows in the vacuum chamber are provided to permit this.

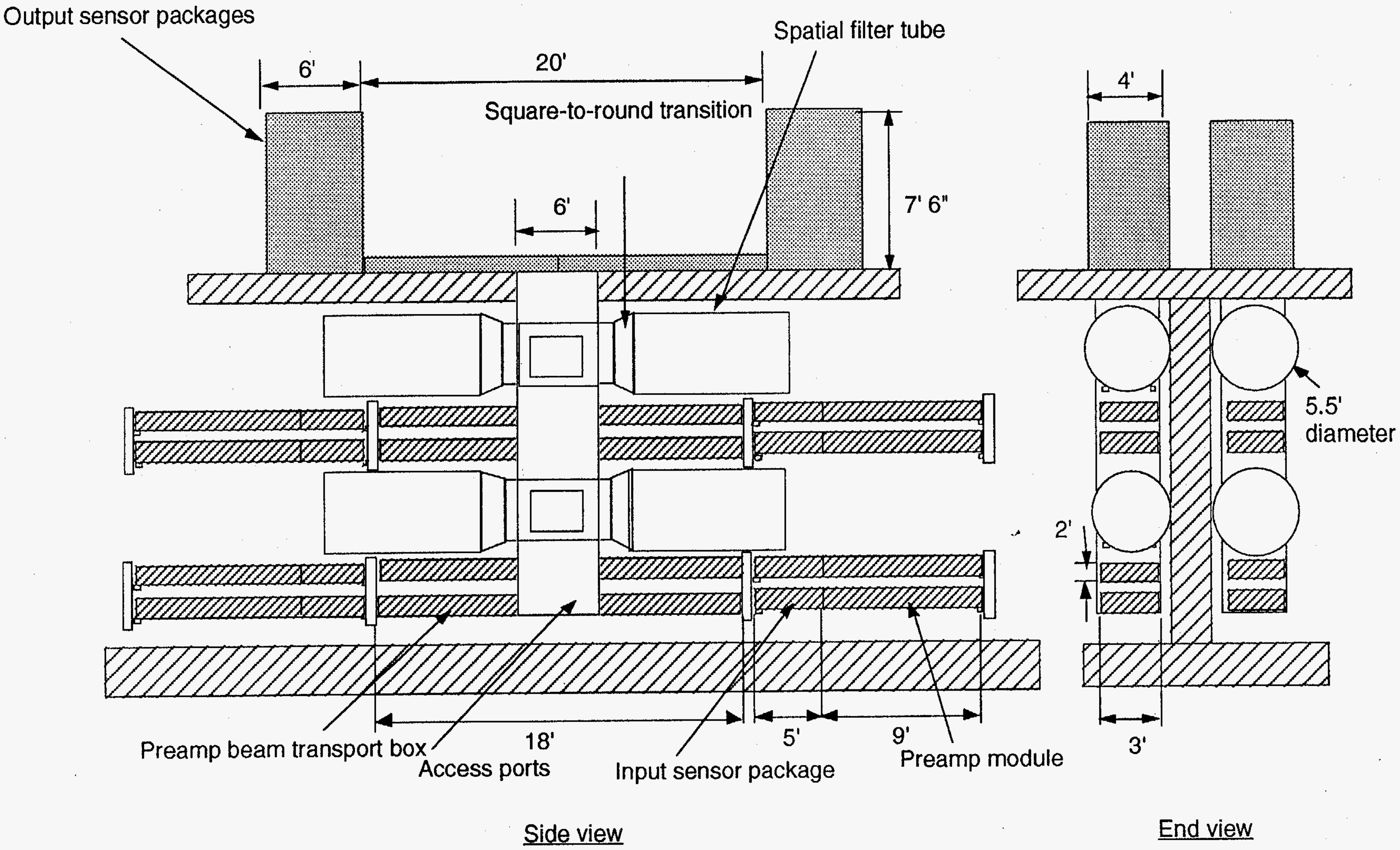


Figure 3-10 Preamplifier and beam injection system

The design of the PAMs are the same as the baseline design except for two differences. In this configuration the PAMs are oriented with the thinnest dimension of the module in line with gravity. This orientation is rotated 90 degrees from that of the baseline, which may require stiffening of the module structure to maintain alignment requirements. Also, access is limited on the modules that are located between a lower box and the spatial filter. A new strategy for implementing in-situ diagnostics for these modules will, therefore, have to be developed for the 2x2 design.

### 3.1.3.2 Amplifier

The amplifier frame assembly units (FAU) will be constructed in modules that are either 5 or 4 slabs long. These modules consist of 1) an outer shell providing structural support for the internal frame and a cleanliness barrier around the laser slabs 2) the internal frame which supports the slab and flashlamp cassettes which are inserted vertically from the bottom, and 3) guillotines. FAUs are assembled and cleaned in an off-line facility and then delivered to the laser bay with a transportation cart. During transport the ends are protected from contamination with guillotines. The FAU will be mounted on brackets which are attached to nearby concrete support walls (see Figure 3-11). Note that the FAU is unsupported along its length except at its ends. This provides space between the concrete walls through which utilities including power conditioning cables will be routed. Utilities are assumed to be located above the concrete support walls.

Flashlamps and slab cassettes are installed using the same procedures that have been developed for the baseline 4x12 design. The process requires the development of a custom lifting device shown in Figure 3-11. This unit must be designed to lift a small cassette extraction assembly (CEA) and translate it horizontally to a precise location beneath the FAU. Self-centering pins will provide for easy alignment. After the CEA is located under the FAU, a door at the bottom of the FAU is opened exposing the bottom of either a flashlamp or a slab cassette. Inside the CEA is a lifting mechanism that can vertically translate a component located inside. With this unit either a flashlamp or slab cassette can be extracted from the FAU. If a flashlamp cassette is removed, the CEA is then translated horizontally and the cassette replaced with a new unit. The CEA is then relocated under the FAU and the new flashlamp cassette inserted into the previously vacated position.

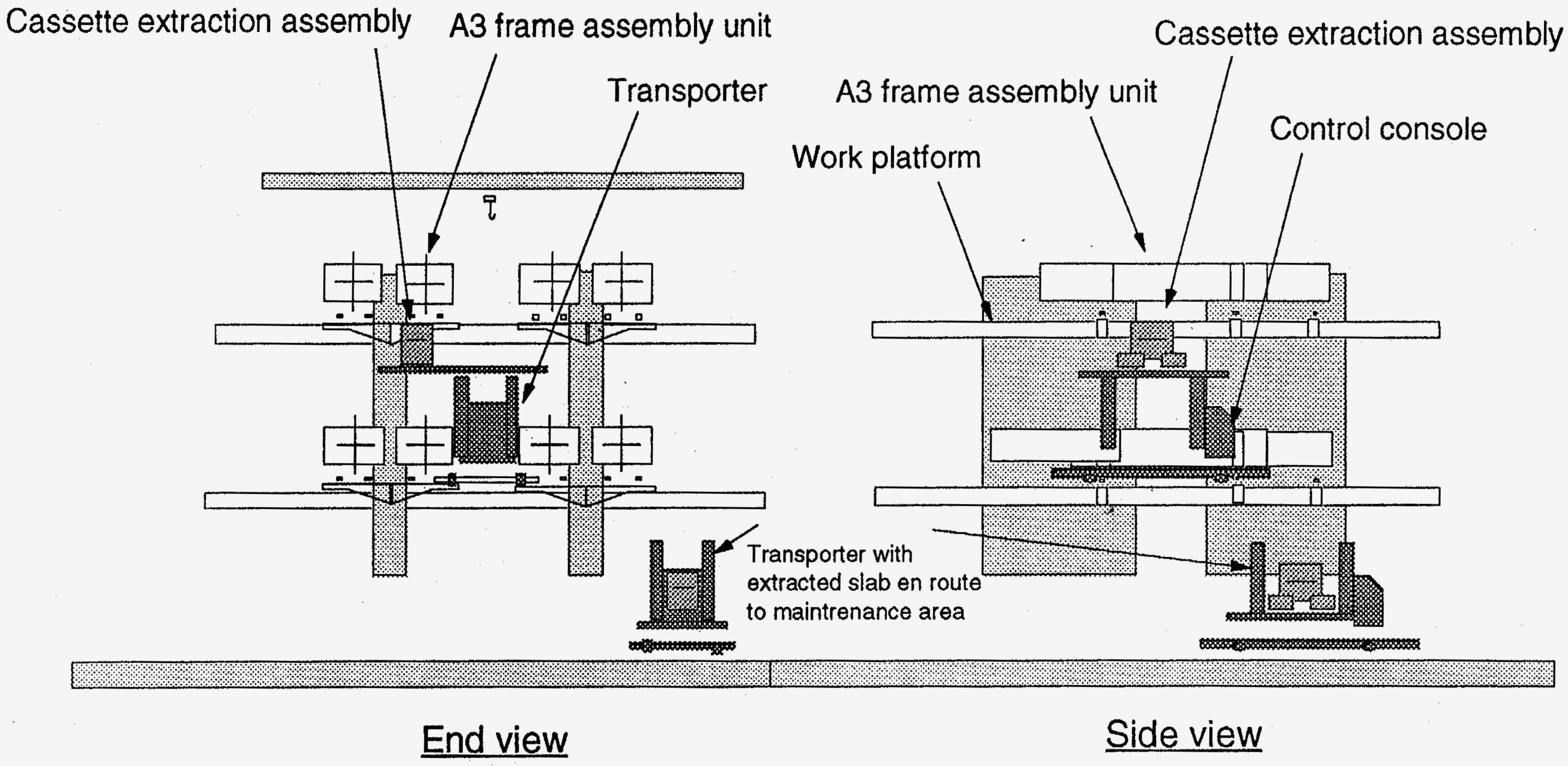
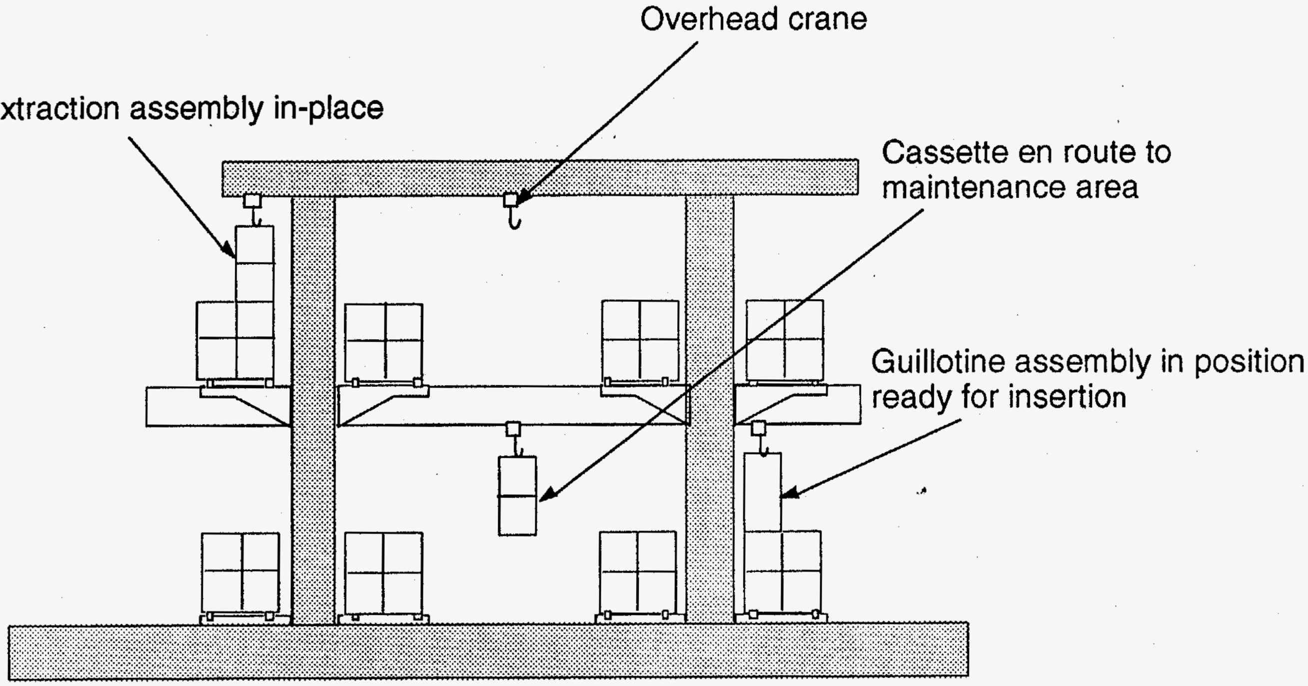


Figure 3-11 Bottom loading amplifier concept

For amplifier slab insertion, the process is more complicated and will require more stringent cleanliness conditions. First, using the CEA, two guillotines are installed to isolate the slab cassette from its neighbors. Then, a 1x2 slab cassette is removed using the same CEA as with the flashlamp extraction except that it has been cleaned to tighter cleanliness requirements. After the slab cassette has been removed a clean slab cassette is installed into the CEA. The slab cassette is sealed, i.e., it has blastshields attached and a guillotine protecting each end. Then, the cassette is located under the FAU, lifted into position and locked into place. Finally, the guillotines (two on either end of the slab cassette) are removed and the door at the bottom of the FAU is closed.

In the case of a flashlamp and debris shield failure a major fraction of an FAU will have to be cleaned. In this condition, the entire FAU is removed from the laser bay and transported to the local maintenance area. The laser slabs and flashlamps may be in the FAU during this operation if desired. No in-situ cleaning of the FAU is required and replacement of the FAU can be rapid, which aids in maintaining high system availability.

The process described above could also be deployed using overhead cranes as shown in Figure 3-12. In this case the CEAs are lifted, transported and positioned above the beam bundles using the cranes. The advantage of this concept is that the elevation of all of the laser bundles is reduced by about 2.1 m (7 ft.) resulting in lower cost and improved optical component stability. The disadvantage is that since maintenance operations are now performed above the laser slabs the risk of contamination to the slab and slab frame is probably greater. Also this concept eliminates personnel mobility transverse to the direction of the laser beam. Long corridors are formed by the laser bundles forcing workers to walk from one end of the laser bay to the other when servicing components in the transport spatial filter area. Trenches in the floor of the laser bay could be added at extra expense to ameliorate this difficulty.



End view

Figure 3-12 Top loading amplifier concept

### 3.1.3.3 Spatial Filters

The spatial filter vacuum vessel for the 2x2 concept can be constructed using standard tube forming processes. In the proposed design, the vessel is 1.7 m (5.5 ft.) diameter rolled tube that has been seam welded. If the tube is round, atmospheric pressure can be resisted with a minimum thickness structure and no welded reinforcement. This should result in significant cost savings. Also, these tubes can be painted, cleaned, and otherwise be completely prepared for installation in an off-line facility. After preparation these units can be then transported to the laser bay, positioned on their mounts and then be ready for operation with little extra work. This will help to significantly facilitate installation activities in the laser bay.

Pinhole positioner assemblies will be assembled off-line in 2x2 units. The pinholes will be supported in a sturdy frame that will be located in a square vacuum box. The box will have guillotines protecting the ends of the assembly from contamination during transportation from the assembly area to the laser bay. In-situ maintenance is enabled with access ports that will be provided on one side of the vacuum box. This type of maintenance will be kept to a minimum. If extensive maintenance is required on any internal component the 2x2 assembly can be easily removed and replaced with a pre-prepared replacement unit.

### 3.1.3.4 Other Optical Components

With the exception of the amplifier slabs and flashlamps, the other optical components are all installed and replaced in a similar manner. Shown in Figure 3-13, each optical component is separated from its neighbors with a guillotine assembly. During installation and replacement of each component guillotines are used to protect neighboring components from contamination. Prior to component replacement, two guillotines in protected enclosures are transported to the laser bay. They are installed on either side of the optical assembly to be replaced. The assembly is then removed exposing the guillotines to the ambient environment. A replacement optical assembly, with two guillotines, one protecting each end, is then positioned and bolted in place. Before extraction of all four guillotines, their surfaces are cleaned with clean gas flow. $CO_2$ cleaning techniques similar to that proposed for the LMJ could be used.

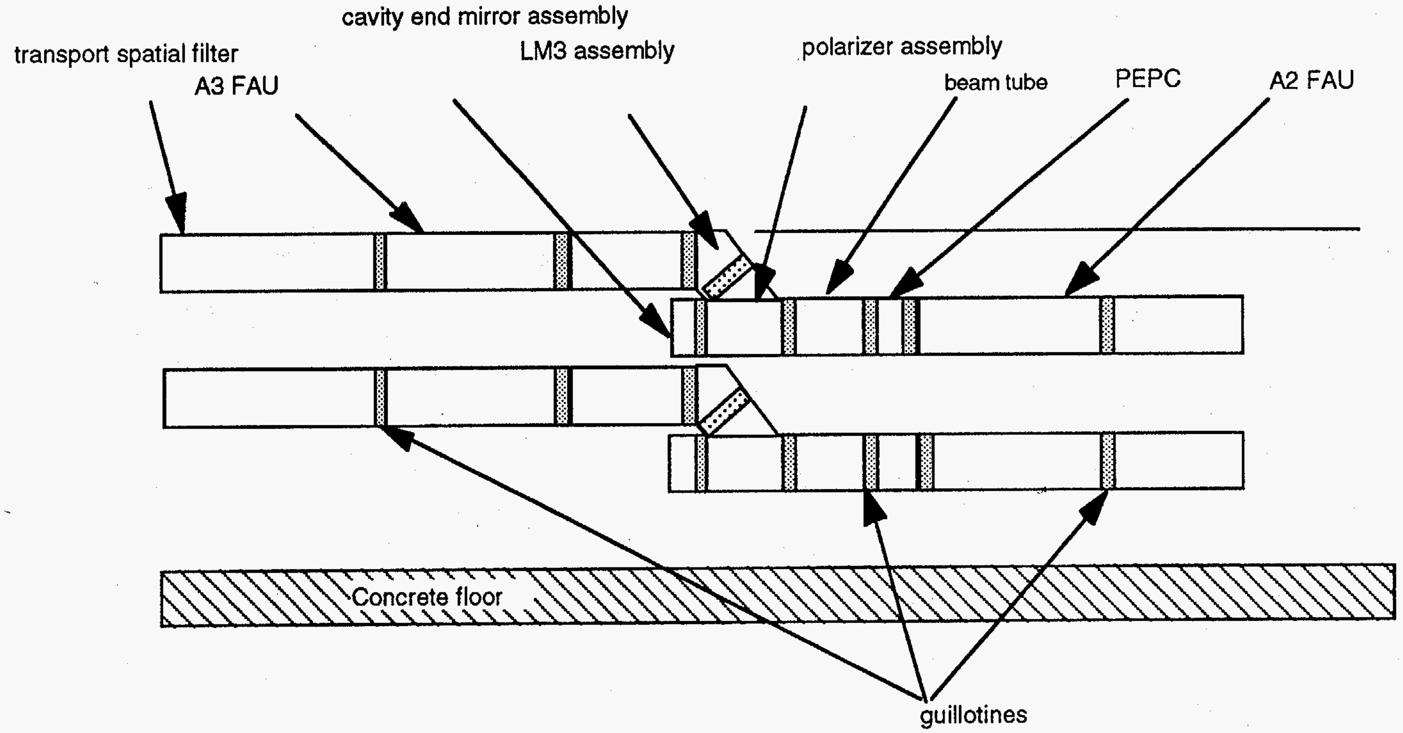


Figure 3-13 Optical components and guillotines in the region of the Pockels cell

Since all of the optical assemblies are accessible from the side and are constructed in portable 2x2 arrays, they can all be removed using the process discussed above. Fixturing will be similar for each assembly and procedures can be shared. This will help to facilitate installation and maintenance operations, minimize operator training and reduce cost.

## 3.2 2x2 Bundle Comparison

Table 3-1 summarizes the advantages and disadvantages that the 2x2 design has compared to the baseline 4x12 configuration. The entries in the table were collected and agreed upon by all members of the evaluation committee.

### 3.2.1 Cost

Although some of components of the 2x2 design will be less expensive (i.e., spatial filter) and some development costs (amplifier and Pockels cell) will be less, overall costs of the 2x2 design will be higher. This is driven mainly by the larger facility size requirement, increased amplifier component cost, and increased pulsed power requirement caused by reduced amplifier efficiency. Higher cost cannot be avoided in this design although, with further optimization, it is conceivable that the projected cost increase could be reduced. The cost estimates that were provided in some cases did not have sufficient detail to provide high confidence in the values. Uncertainties in the total estimate is not less than the $10M that was requested in the committee charter.

### 3.2.2 Schedule

The 2x2 facility design deviates significantly from the baseline and will require time and effort to advance the proposed concept to the state of maturity of the 4x12 design. It is estimated that it will take about 6 months to generate all of the top level assembly and component drawing to confirm overall facility size requirements and cost estimates. On the positive side the 2x2 design will shorten amplifier and Pockels cell development schedule, both of which are on the critical path. Also, because the module size is smaller than the baseline, it is likely that the first fully operating NIF beam bundle can be brought on line sooner than the baseline which will allow more time to react to unforeseen difficulties and reduce schedule risk.

It was also judged that the smaller module size provides flexibility to the schedule during installation and activation. During this time multiple teams of workers can be simultaneously working on many bundles. Many different types of activities can be ongoing unconstrained by the coupling of the interaction of a large number of beams.

### 3.2.3 Performance Risk

Performance risk was deemed to be less for the 2x2 than the baseline for four reasons. The first and primary reason is that the design deviates less from the Beamlet experience. Two-by-two amplifier structures have been built and operated (although not in a multi-aperture mode). Secondly, each aperture will have a side flashlamp cassette which has reflectors which can be optimized to direct flashlamp light in such a way as to minimize gain non-uniformities. It is believed, without a confirming detailed evaluation, that this is desirable even though overall efficiency may drop slightly. Thirdly, the design accommodates a Pockels cell assembly that does not require the plasma discharge to cross two apertures. A 1x2 large aperture Pockels cell has not yet been developed and thus the risk associated with this development is eliminated. Finally, maintenance of the pinhole positioners inside the spatial filters does not require human access into the vacuum vessel. This reduces cleanliness risk to lenses and other internal components and thereby reduces performance risk.

### 3.2.4 Maintainability and Operability

The largest advantage that the 2x2 design offers is in the overall operability of all of the systems. In general access to equipment is easier because platforms can be installed to position components within arm's reach and access ports can be conveniently located to permit easy viewing and minor maintenance operations to internal components. Also, it is possible to repair one beam bundle while preparing the other 188 beams for the next experiment. Loss of that one beam bundle during a shot would reduce laser energy delivered on-target by only 2%. It has been estimated that uniformity on target could still be achieved even with the loss of one beam. It is also conceivable to deliver a subset of the total number of beams and still maintain useful beam energy for experiment. For example, it is possible to use only 50% of the beams in one experiment and then, a short time later, use the other 50% for another experiment. This could increase beam availability and the number of shots executed in a year.

Amplifier maintenance is simplified because no in-situ maintenance of the frame assembly is required. If the unit becomes contaminated then the slabs can be removed and the entire FAU replaced with another unit that has been cleaned in an off-line facility. Further, during slab replacement only 2 slabs are removed at a time. The slab cassette is smaller, easier to handle and as a result poses less of a threat to contamination.

The spatial filter has a sufficiently small cross sectional area making it possible to consider mounting some of the pinhole positioning hardware outside of the vacuum. For example, motors used to position the pinhole could be mounted on the exterior of the vessel and connected to the positioner via a flex cable. The flex cable passes through a feedthrough in the vessel wall. The motors no longer have a vacuum compatibility requirement, can be replaced without pumping down the vessel and do not pose a contamination risk. It is also possible with the smaller vacuum vessel design to achieve more rapid pump down time with lower hardware cost. The vacuum system can be designed to direct available pumping power to the specific beamline.

### 3.2.5 Hardware Failure Exposure

The cost exposure of the 2x2 design is less than that of the baseline. If a spatial filter lens implodes or if a flashlamp/debris shield fails, the amount of equipment in the beamline is less than the 4x12 and consequently replacement cost is likely to be significantly less. This advantage is somewhat reduced by the fact that operator error is more likely because there are more components (valves and actuators) which may fail or be improperly operated.

### 3.2.6 Activation

Activation has many of the same advantages as maintainability/operability. In general, it was judged that activating four beamlines at a time provided scheduling flexibility that would decrease the total activation time required. After the first beam bundle is activated, procedures and techniques will have been optimized and workers trained. This will benefit the activation of the remaining 188 beams. The learning curve with the baseline design will be much slower.

For the amplifier and some of the other optical assemblies there is significantly less in-situ work required. The amplifier FAU is completely assembled and cleaned in an off-line facility and then installed. Spatial filter lens modules can also be completely assembled prior to delivery to the laser bay. This will have high leverage to reduce the total activation time required.

### 3.2.7 Design flexibility

Beam expansion of the 1ω beam has been proposed as a method for reducing damage risk to downstream optics, the 3ω optics in particular. With the 2x2 design wedged spatial filter lenses can be located at the L3 position to cause a divergence of the four beams in the transport spatial. The divergence permits the beams to expand without interfering with each other. At the point down stream where the beam reaches the desired size, the L4 lens is located to recollimate the beam. Space is available in the 2x2 design to implement this concept if it is deemed necessary; it is impractical for the baseline design.

The 2x2 design can accommodate alternate amplifier and Pockels cell designs. If a side loading or top loading slab replacement concept can be demonstrated during the amplifier development program then the facility design could be implemented without additional facility floor area or change in the basic layout of the beamlines. Thus, a change in the amplifier design could be adopted late in the schedule. Also, a 1x2 Pockels cell could be implemented with minimal impact if it were to be successfully developed and proven to have reduced cost and performance risk.

The position of the 2x2 bundles in groups of four can be staggered in the direction of the beam. This provides the capability to adjust the optical path length from the output of the transport spatial filter to the target and can be used to equilibrate the path differences between the beams. As a result the image relay plane can be located more precisely on the frequency converter reducing beam modulation and the risk of laser damage.

The concept of staggering beamlines may be useful in other facility layout designs that may be considered during Advanced Conceptual Design Activities. One concept is an "in-line" laser facility which locates each laser bay on opposite sides of the target chamber rather than in the U-shape configuration proposed in the baseline. It has been proposed that this concept may reduce spatial filter length and cost. In this configuration staggering the beams can provide additional shortening of the optical path. The 2x2 design could take advantage of this potential change.

**Table 3-1**

### Comparison of the 2x2 Bundle Configuration to the Baseline 4x12 Design

Viewpoint: overall concept        Reviewer: Sawicki

| Issue | 2x2 Advantages | 2x2 Disadvantages |
|---|---|---|
| 1. Cost | Spatial filter can be fabricated as a simple round or square welded tube<br>Lower amplifier development costs: no in-situ cleaning, shorter lamps<br>1x2 Pockels cell development not required<br>Lower cost of in-vacuum components | Laser bays are 46 ft. wider and longer<br>Switchyard is 46 ft. wider; noble gas box longer<br>Amp is less efficient requiring 20% more pulse power<br>More amplifier hardware components<br>More than 2x number of flashlamps<br>More pulsers required for Pockels cell |
| 2. Schedule | Amplifier development schedule is less critical<br>First beam bundle (first-off unit) can be brought on-line sooner<br>Added construction flexibility due to smaller module size | Time is required to advance design to CDR level |
| 3. Performance risk | Small technology step from Beamlet experience<br>Side flashlamp reflectors may improve gain uniformity in the slab<br>Can use a 1x1 Pockels cell<br>Personnel do not enter spatial filter, reduced cleanliness risk | |
| 4. Maintenance and operational ease | No in-situ cleaning required of the amplifier<br>Design is highly modular with simpler installation/removal procedures for all assemblies<br>Only 2 amplifier slabs removed per maintenance operation<br>Side access permits easy inspection and in-situ maintenance<br>Modules are half as tall and are easier to handle<br>Personnel do not have to enter spatial filters<br>Possible to locate motors/mechanisms outside spatial filter<br>Less expensive to achieve more rapid pump-down of spatial filter<br>Increased availability with bundle loss due to smaller size<br>Much easier LM3/polarizer maintenance<br>Significantly improved availability from firing different subset of beams<br>Reduced cost exposure to operator error<br>Bundle size improves availability on laser during maintenance of power power conditioning & spatial filters<br>Fewer lenses exposed to possible contamination during venting | More components to manage (amp, gas handling & vacuum system) |
| 5. Hardware failure exposure | Only 4 beamlines are exposed to vacuum or flashlamp failure | Potentially more opportunity for failure due to more subsystems |
| 6. Activation | Can activate 4 beamlines at a time<br>Learning curve is more rapid; easier to train personnel<br>Less in-situ assembly required for system components<br>Scheduling is potentially simpler for installation/testing<br>(plus almost all of the same issues as #4) | 2 x number of slab insertions |
| 7. Design Flexibility | Accommodates beam expansion with wedged spatial filter windows<br>Pockels cell can be either 1x1 or 1x2 module<br>Accommodates bottom loading and side loading amp slabs<br>Laser bundles can be staggered to compensate for optical path differences | |

## 4.0 4x4 Bundle Concept

### 4.1 4x4 Bundle Description

The 4x4 bundle configuration, utilizing the 4x1 bottom loading cassette design for the amplifiers, represents a minimal departure from the baseline 4x12. This configuration simply divides each 4x12 bundle into three 4x4s, and adds aisles (≤6ft) between the 4x4 bundles. The aisles between bundles incorporate an inexpensive raised floor (e.g., aluminum grating) which provides for personnel access at equipment level. The plan view of the system is shown in Figure 4-1. As in the 4x12 baseline, the amplifier units are suspended from overhead I-beams and serviced from the bottom. The spatial filters are built of smaller rectangular sections.

For the purpose of this bundle size study, we took the minimum departure approach. However, if the baseline is changed to the 4x4, other design options for ease of operations and maintenance (especially for the amplifiers) could be considered. In addition, the 4x4 transport spatial filter could be designed to provide beam expansion using wedged lenses, if needed.

One major advantage to the 4x4 bundle design is in system constructability. Reducing the bundle size from 4x12 to 4x4 provides the advantage of fabricating system components which are of a more manageable size for installation (especially the spatial filters), thus allowing most major components to be completely fabricated, painted, and cleaned before being installed. This provides greater schedule flexibility and lower risk during construction. This feature alone is a strong reason for considering the 4x4 even if the aisle width is minimized to keep down the added cost of the building.

Another advantage is that in the event of one amplifier or spatial filter unit being down for service (16 beamlines), only 8.3% of the beams would be out of commission for a target shot (as opposed to 25% for the 4x12).

**Amplifiers:** The 4x4 amplifier design is identical to the baseline 4x12, using the post-CDR cassette design, with the exception that it is 1/3 the width. This results in having 8% additional flashlamps and power conditioning, because two of the central eight lamp arrays in the 4x12 become four end lamp arrays with six lamps each. The basic mechanical design of the amplifier unit remains the same as the 4x12 baseline. Figure 4-2 shows the 4x4 amplifiers as they are suspended in the overhead structure, which uses concrete buttresses and a large I-beam across the span. Enhancements could be made to the amplifier frame design to improve the stiffness and/or optimize for improved assembly, but for the purpose of this study the only cost increase is for the end flashlamp arrays.

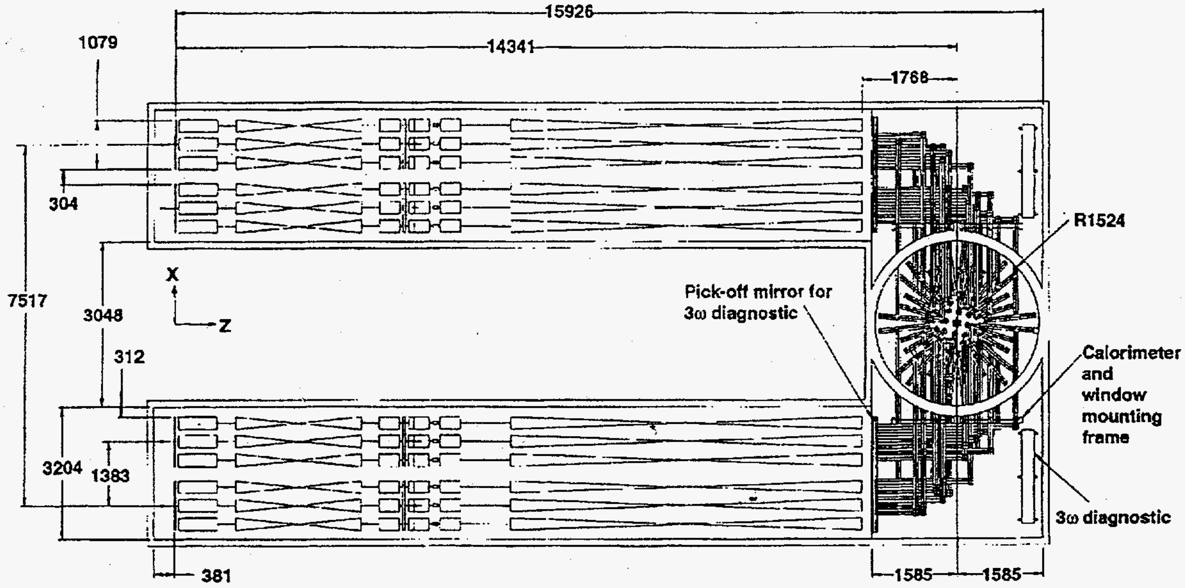


Figure 4-1 4x4 Bundle with 6 ft. Aisle Ways (1,532 cm increase in width)

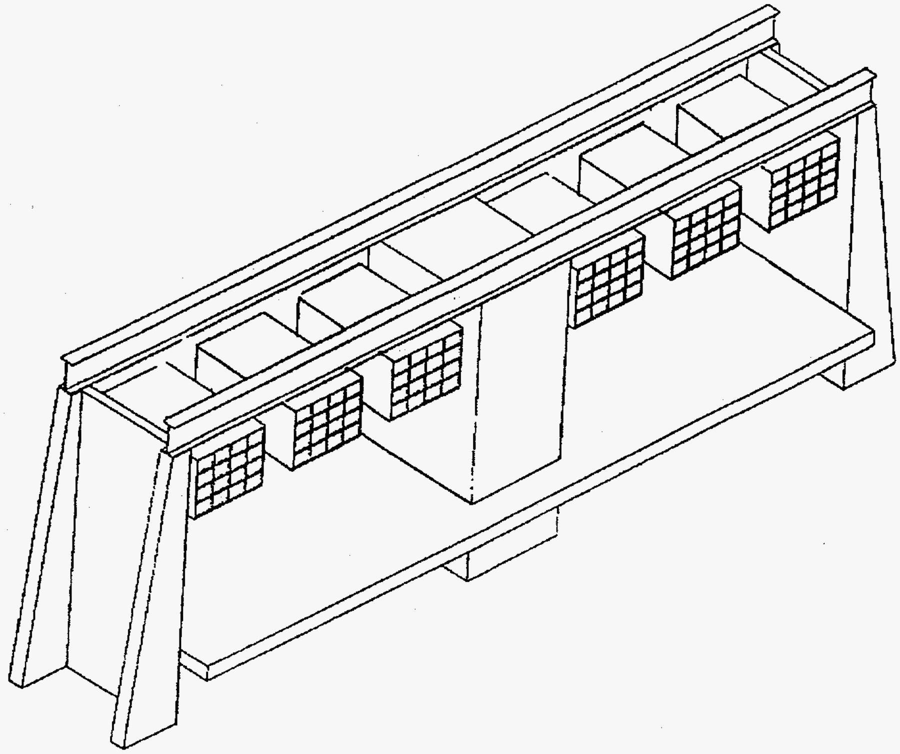


Figure 4-2 Amplifiers for the 4x4 Bundle Suspended From an Overhead Structure as in the Baseline

**Spatial Filters:** The 4x4 spatial filters are of similar conceptual design to the 4x12 baseline, using a rectangular vacuum chamber with external stiffeners, except they have 1/3 the horizontal cross section. This change results in improved manufacturability of the filters, because they could be fabricated in 20-50 ft. long sections (as shown in Figure 4-3) which can be trucked to the site and bolted together, thus saving the cost (and mess) of on-site welding. Eliminating on-site welding also will provide greater flexibility in the construction plan for the spatial filters, because the installation process would be cleaner. The size (72"x90") of the 4x4 rectangular cross section also preserves the option of personnel entry into the filter for servicing of equipment if necessary. One of the concerns of the spatial filter for the 4x4 bundle compared to the 2x2 or 4x2 is that it is simply larger, which makes access more time consuming due to the greater vent/pump times. The spatial filter concept presented here has the advantage that it could be constructed with an internal septa running longitudinally, which would cut the volume in half and create a spatial filter similar to the 4x2 (although access would only be from one side). It is not clear whether venting half of a 4x4 spatial filter would affect alignment or other operation in the other half, however. The cost of this modification would be a modest increment to the 4x4 spatial filter concept.

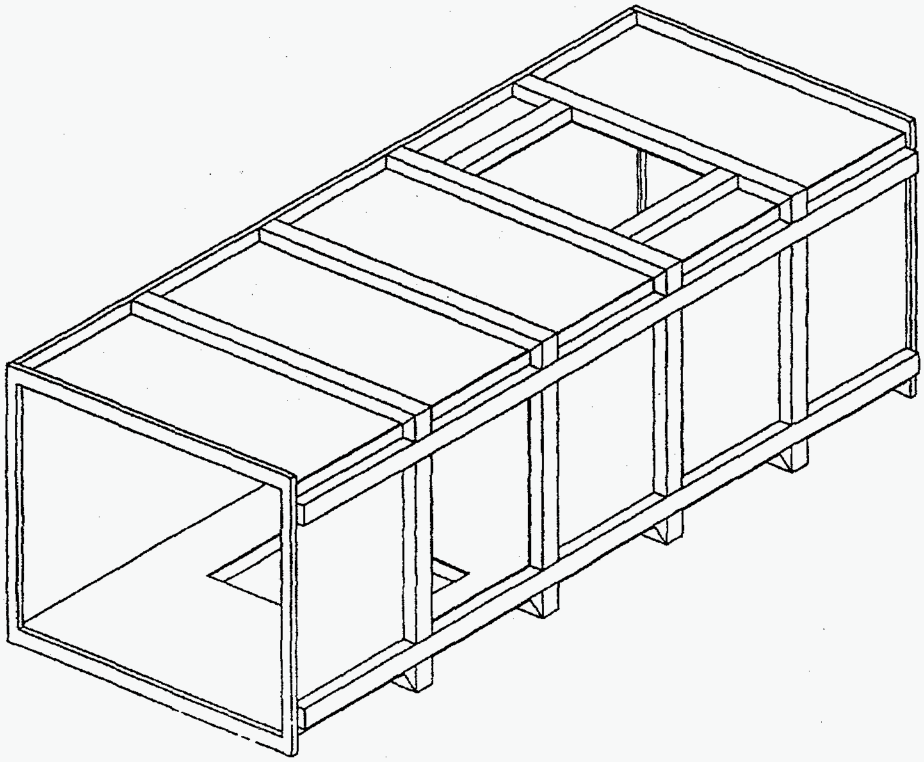


Figure 4-3 Spatial Filter Module for 4x4 Bundle

**Other Laser Bay Components:** For the purpose of this study, the basic design of all other laser components remains the same as the 4x12 baseline design. The only difference is that the 4x4 the structural support frames for the mirrors, polarizers, and Pockels cells would be modified to support 4x4 arrays, thus adding a little more steel to the cost. However, there is a real advantage in having structural units that are 1/3 the size of the 4x12, because they are now small enough to be completely fabricated in vendor shops.

**Building:** The laser bays and switchyard bays become ≤24ft. wider than the baseline to accommodate the ≤6ft aisles between the bundles. This is the major cost driver in the design. (However, the building cost could be minimized if all components were serviced from below, then the aisles could be reduced to the minimum width that would accommodate 2X areal beam expansion.)

**Switchyard Structures:** The design of the switchyard structures remains nearly identical to the 4x12 baseline, with the exception that the width in the X-direction increases corresponding to the added 6 ft. aisle spacing, totaling ≤24ft for each of the two bays. (This also could be reduced in cost by minimizing aisle width.)

**Design Flexibility:** The 4x4 bundle configuration provides added flexibility in the NIF system design which could improve the maintainability and ease of operations, and could allow for beam expansion in the transport spatial filter. These features are not costed in the study, but should be mentioned under the category of design flexibility. The following are design options which could be investigated:

- **Beam Expansion:** The 4x4 bundle configuration is probably the practical upper limit for which beam expansion could be done in the transport spatial filter by using wedged lenses. This method is certainly feasible for either the 2x2 or 4x2, but would be exceptionally difficult with the 4x12. Figure 4-4 shows the placement of beams, with the output overlaid on the input, for an areal expansion of 2X. Beam expansion by this method would require precise manufacturing control of four different wedge magnitudes and rotational angles for both the input and output lenses of the filter. However, if done correctly, it would be an efficient method of producing expanded collimated beams of lower fluence going into the frequency converters. Beam expansion could be accomplished by either preserving f# or overall spatial filter length. Since the baseline transport filter is f/85, increasing the speed to f/68 to maintain the 65m length would not affect the spherical aberration.

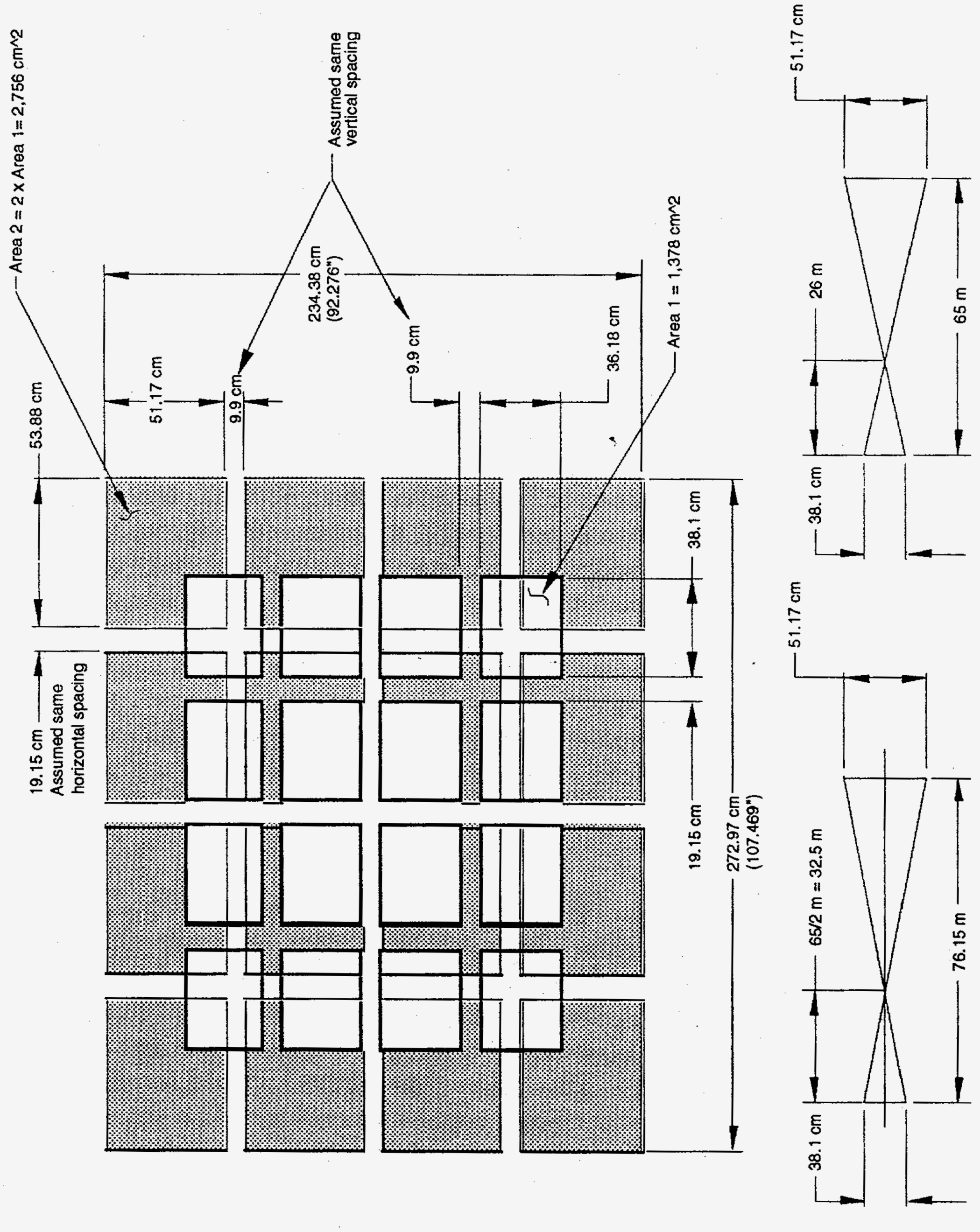


Figure 4-4 4x4 Beams Shown with 2x Beam Expansion

- **4x4 "Slice-of-Bread":** Reduction of the bundle size to 4x4 provides the flexibility to consider alternate schemes for servicing the amplifier units. The amplifier concept presented in the 4x12 baseline design (also assumed for the 4x4) appears viable and offers significant operational advantages since only four slabs must be removed at a time. One alternate amplifier concept is the 4x4 "slice-of-bread" serviced from below. This concept would require that the lower floor area directly beneath the amplifiers be a class ≤100 clean room. In this configuration (see Figure 4-5) the amplifier structural frame is equipped with two pairs of vertical rails that can be positioned at each 4x4 slice along the beamline. Any of the slices could be individually picked from the unit (e.g., by engaging pins) and lowered down to the first floor for inspection or maintenance. The flashlamp cassettes are bottom loaded (similar to the 4x12 baseline) and are independently removable from the 4x4 slices. The maintenance personnel would have the option of removing all flashlamp cassettes prior to lowering a 4x4 slice or having the cassettes come down with the complete slice. One drawback to this concept is that 16 slabs must be removed at a time, which would be less desirable from an operational standpoint.

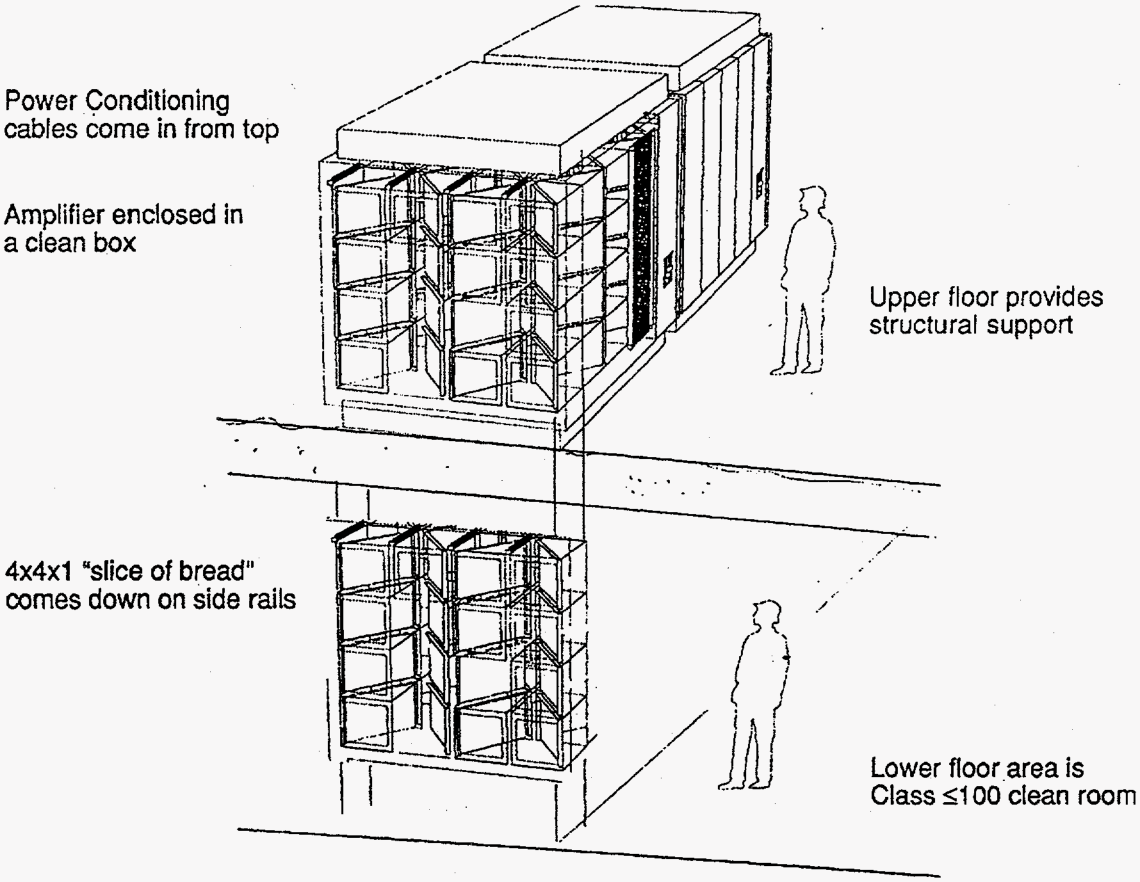


Figure 4-5 Alternate 4x4 Amplifier Concept with a "Slice of Bread" Bottom Loading System

## 4.2 4x4 Bundle Comparison

Table 4-1 gives the comparison of the 4x4 bundle configuration to the 4x12 baseline in terms of the seven comparison issues. The advantages and disadvantages listed were derived from a consensus of the committee. It was generally agreed that the 4x4 bundle design provides the cost and technological advantages of the 4x12 baseline along with vastly improved constructability and a significant improvement in operability.

The main driver for the cost increase is the increased width of the laser bays and switchyard due to the 6 ft. aisles. By including 6 ft. aisles between the bundles, with a raised deck, there is an improvement in system access which significantly helps with system operability and maintainability. Planning for aisles also provides for the option of beam expansion without impacting building design, if that decision is made in the future. However, if cost of the building became prohibitive, the width of the aisles could be reduced to the minimum required for beam expansion, and all equipment could be serviced from below (although perhaps not as easily).

The secondary cost driver is from the increased number of end flashlamp arrays, which causes an 8% increase in flashlamps and attendant power conditioning. There is also a minor increase in cost due to the extra mechanical components for the end arrays.

A major benefit of the 4x4 is schedule flexibility during system construction. Reduction in the size of major components, such as spatial filters and mirror structures, allows the hardware to be built, finished (i.e., painted), and tested by outside fabricators. This provides flexibility for choice of contractors, start of fabrication, and installation time. It also reduces the risk of mistakes that could occur during on-site fabrication, and provides for a cleaner facility. The only minor schedule downside to going to the 4x4 (from the baseline) is the slight schedule delay incurred early in Title I to rework the design.

The 4x4 bundle configuration provides for more design options for servicing the critical optical components other than the amplifiers. Mirrors and polarizers could be accessed from the side, and an entire 4x4 spatial filter lens array could be serviced from below by lowering it down. In addition, when servicing an amplifier or spatial filter, only 8.3% of the beams are down, as opposed to 25% with a 4x12. If the 4x4 spatial filter is divided internally, vent/pump times would be halved, which would assist maintenance tasks.

In the event of a catastrophic failure of a spatial filter or amplifier, only 16 beams are at risk of collateral damage. This is a significant improvement over the 4x12.

During activation the 4x4 provides the advantage of isolating 16 beams from the others so as to begin early activation. This provides for a more rapid learning curve, and a reduction in early risk to the hardware.

By reducing the bundle size to 4x4 there is an improvement in design flexibility for amplifier, spatial filter lens array, and mirror/polarizer servicing methods. The spatial filter could be constructed with an internal septa to improve maintenance. The 4x4 is the maximum feasible bundle size for beam expansion, which may be required. It is recommended that the system design provide for this option early on in the building design, so that it can be accommodated if necessary.

## Table 4-1

### Comparison of the 4x4 Bundle Configuration to the Baseline 4x12 Design

Viewpoint: overall concept

Reviewer: S.A. Kumpan

| Issue | 4x4 Advantages | 4x4 Disadvantages |
|---|---|---|
| 1. Cost | – Spatial filters are easier to fabricate and install<br>– Other major components are more modular (potentially less costly) | – 8% increase in flashlamps and power conditioning<br>– Laser bays and switchyard are ≤24ft wider |
| 2. Schedule | – Spatial filter sections are easier and quicker to fabricate<br>– Spatial filters will be easier and cleaner to install<br>– Smaller module size should improve overall fab/installation time<br>– Side flashlamp reflectors may improve gain uniformity in 1/2 the slabs<br>– Smaller bundle will increase schedule flexibility during construction<br>– Structural modules are easier to fabricate and install | – Slight delay to advance the design to CDR level |
| 3. Performance risk | – System performance risk slightly reduced<br>– Amplifier bundle could be prototyped for ≤1/3 cost of 4x12 | – None |
| 4. Maintenance and operational ease | – More options for servicing components (4x4 spatial filter lens array)<br>– Aisles between bundles permit side access to critical components<br>– Only 8.3% of the beams are lost when servicing any one bundle<br>– Less expensive to achieve more rapid pump-down of spatial filter<br>– Reduced cost exposure to operator error<br>– Moderate improvement in system availability by firing different subset of beams<br>– Easier LM3/polarizer maintenance<br>– Fewer lenses exposed to possible contamination during venting<br>– Spatial filter can be constructed with an internal septa | – More components to manage (amp, gas handling & vacuum system) |
| 5. Hardware failure exposure | – Design limits collateral damage from a spatial filter lens failure to 16 beams (or from another problem) | – None |
| 6. Activation | – Can activate a complete bundle of 16 beams while isolated from others<br>– Potentially easier to activate the first beam line during construction<br>– Learning curve is more rapid; easier to train personnel<br>– Less in-situ assembly required for major system components<br>– Scheduling is potentially more flexible for installation/testing<br>– (plus almost all of the same issues as #4) | – None |
| 7. Design flexibility | – Maximum array size that allows beam expansion with wedged lenses<br>– More amplifier designs could be considered if desired<br>– Aisle width can be reduced to lower the building cost<br>– Easier to upgrade system during operational lifetime<br>– Laser bundles can be staggered to compensate for optical path differences | – None |

# 5.0 4x2 Bundle Concept

## 5.1 4x2 Bundle Description

### 5.1.1 Overview

It is generally perceived that smaller bundle sizes are easier to activate, prototype, and maintain than larger bundle sizes. On the other hand, cost modeling performed for the NIF CDR shows that grouping more beams together leads to significant cost savings, by reducing building size, decreasing the number of laser parts, and increasing amplifier efficiency. Thus, there is a tradeoff between cost on the one hand, and operability and maintainbility on the other. The 2x2 and 4x4 bundle groupings described in sections 3.0 and 4.0 are significantly smaller than the baseline 4x12 grouping and illustrate these tradeoffs. The 4x2 bundle grouping represents an intermediate choice between the 4x4 and 2x2 designs.

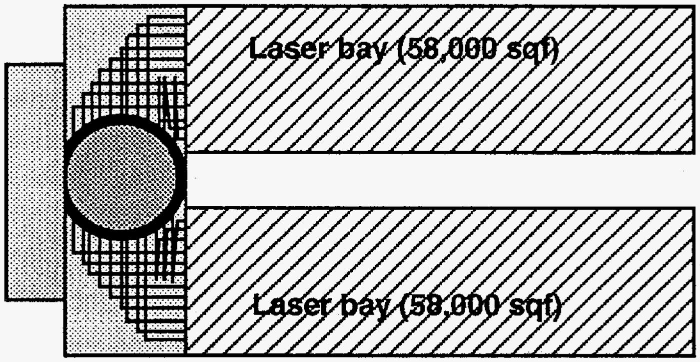
A major advantage of the 4x2 grouping relative to the 4x12 and 4x4 groupings is direct, side access to all beamlines. Side access offers the freedom to perform essential maintenance operations in either of two ways: 1) with robotics techniques, which remain to be developed; or 2) with more traditional methods, used previously on Beamlet and Nova. With the 4x12 and 4x4 designs (as presented), there is no choice -- robotics are required. Although the robotics-based methods seem feasibile, there is some concern among committee members that robotics may prove to be more difficult to develop than currently envisioned. Thus, the 4x2 design has lower risks for development problems and schedule slips. At the same time, however, the 4x2 design does not preclude taking advantage of robotics techniques once they have been developed. Potential advantages of robotics are more rapid and less labor-intensive operations, and improved cleanliness.

Other major advantages of the 4x2 design relative to the 4x12 and 4x4 designs are: 1) a larger fraction of the beamlines remain operable when an entire beamline is disabled (95.8%, compared with 75% for the baseline); 2) it will be easier to prototype or activate the first-off beamline, since it represents a smaller fraction of the system; and 3) there is greater schedule flexibility and lower risk of schedule slips during construction and activation. In this regard, the 2x2 design offers even greater advantages, but at significantly higher cost.

The 4x2 design presented here is not as mature as the 2x2 and 4x4 designs. As discussed in Section 8.0, it seems likely that costs of a 4x2 design could be reduced by putting the beamlines on two floors and by using a vertical switchyard arrangement.

### 5.1.2 Facility Layout

Like the baseline design, this 4x2 design uses a U-shaped Laser and Target Area Building (LTAB) with two laser bays (see Figure 5-1). However, the laser bays are wider, and the space between the laser bays is smaller, leaving less room for the master oscillator room, offices, and other utilities located in this space. It is not clear whether there is sufficient space in the switchyards to redirect the inner beams as shown. To reduce the footprint of the LTAB, this design uses an LTAB with three floor levels (see Figure 5-2). The first floor supports the pulsed-power system and an area for staging spares. The second floor supports the laser cavity, the preamplifier modules, and the injection optics. The third floor supports the transport spatial filter. Figure 5-3 shows a side view of the LTAB and laser system.



LTAB with 4 x 2 amplifier bundles

Figure 5-1 The 4x2 Design Uses a U-Shaped LTAB

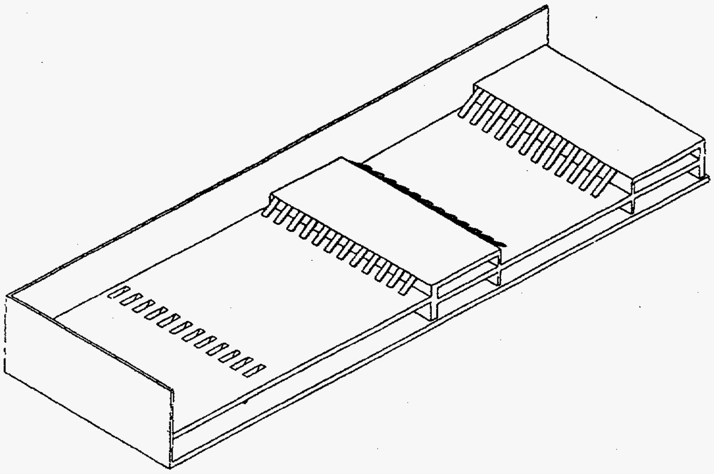


Figure 5-2 The LTAB for 4x2 Design has Three Floor Levels

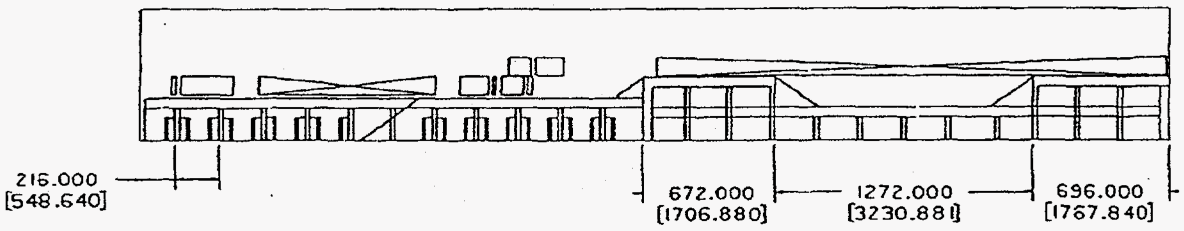


Figure 5-3 A Side View of the Laser and Target Area Building
Shows Three Floor Levels

Figure 5-4 shows a plan view of the concrete ground floor for one of the two laser bays. The ground floor has a total area of 58,156 sq ft. (134 ft. x 434 ft.), of which approximately one-half is occupied by the pulsed power system. The pulsed power resides directly below the amplifiers to minimize pulsed-power cable lengths. Air flows freely over the pulsed-power system, for cooling. The other half of the ground floor, located under the transport spatial filters, could be used for storage space or for staging spares. The cost of this staging area could be kept relatively low by placing the spares in protective carts, to eliminate the need for HEPA filtering. Some 200 columns support the second floor, located 18 feet above the ground floor.

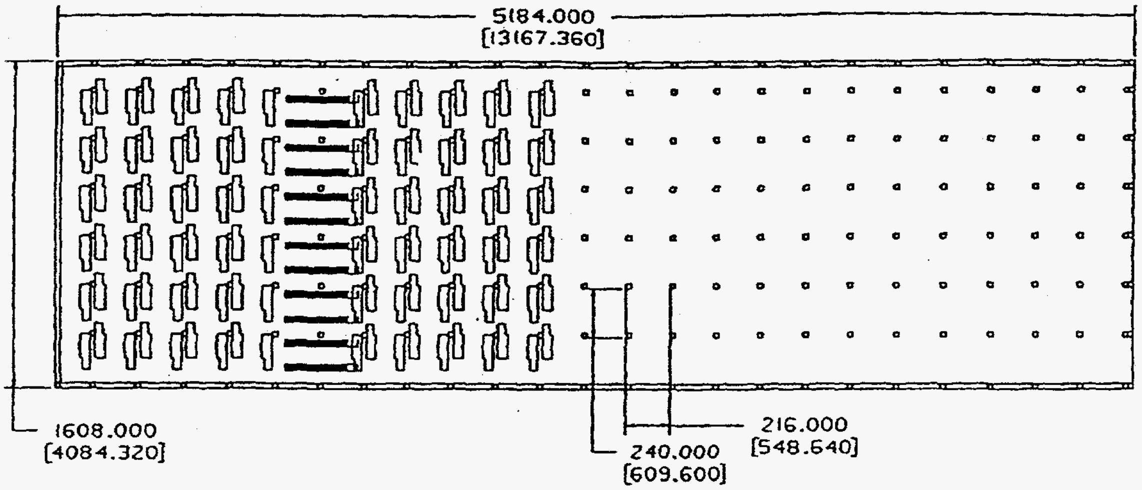


Figure 5-4 A Plan View of the Ground Floor
The Wide Black Lines are Stairwells

The second floor supports twelve 4x2 beam bundles, with 6-ft.-wide aisles between bundles for side access to laser components (see Figure 5-5). This bundle arrangement requires a laser bay that is 134 ft. wide, 54 ft. wider than the baseline design. The second floor is made of 4-ft.-thick concrete, to ensure stable support for optical components. Components are mounted to large I-beams which run across the top of the floor. As shown in Figures 5-3 and 5-4, stairwells running between the ground floor and second floor permit transverse movement of personnel between beamlines. The 3- ft.-wide stairwells do not block the 6-ft. wide hallways. There is free flow of air over the beamlines.

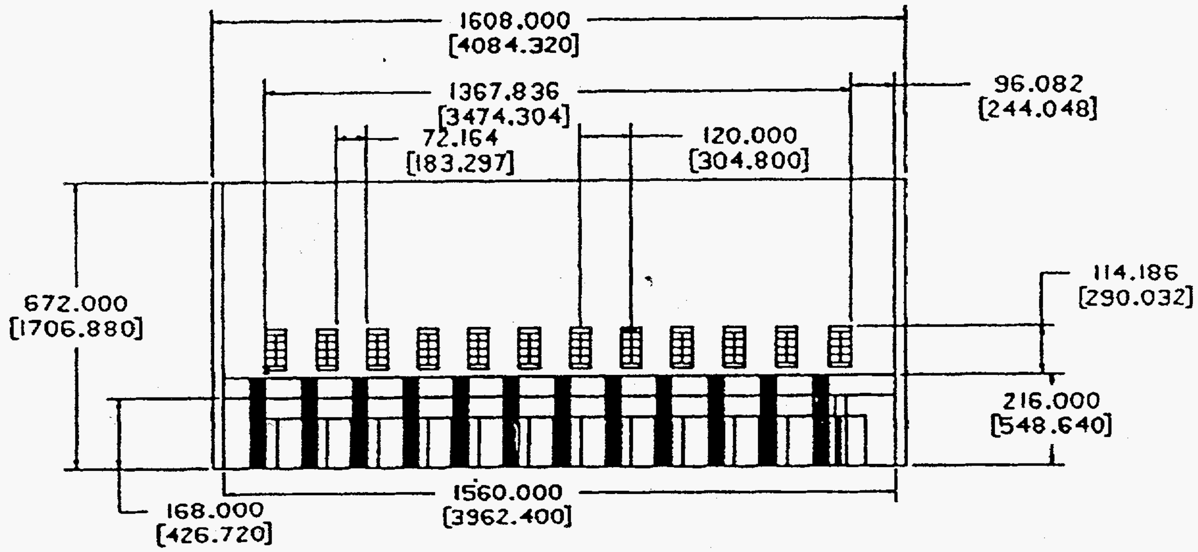


Figure 5-5 And End View of One Laser Bay
The Wide Black Lines are Stairwells

After the beam is switched out of the main laser cavity, the beam propagates through a booster amplifier located 8 feet higher than the cavity amplifiers. This vertical jog in beam height occurs by virtue of using the same Pockels cell-polarizer combination as was used in the baseline design for switching the beam out of the cavity. The booster amplifiers are mounted on a concrete support system (not shown), which was included in the cost estimates.

The third floor is divided into two parts, with each part supporting one end of the transport spatial filter (see Figures 5-2 and 5-3). As in the baseline design, the preamplifier section and the beam-injection optics are mounted under the middle of the transport spatial filter. They are supported by the second floor. To leave sufficient space for these components, the second floor is two feet lower under the transport spatial filter than it is under the laser cavity.

### 5.1.3 Amplifiers

The amplifiers have eight apertures arranged in a 4x2 matrix. The major design features that affect pump-cavity performance remain the same as for the NIF baseline design:

- 40 cm x 40 cm hard apertures
- 4.3-cm-bore x 180-cm-arc length Xe flashlamps

- Eight flashlamps per central lamp cassette
- Six flashlamps per side flashlamp cassette
- LG-750 or LG-770 laser glass, with 4.2% Nd doping concentration
- 3.36-cm-thick laser slabs
- 360 ms flashlamp pulselength
- Lamps operated at 20% of their single-shot explosion energy (in air)
- 9-slab-long main cavity amplifiers (A1)
- 5-slab-long switch amplifiers (A2)
- 5-slab-long booster amplifiers (A3)

Due to the use of narrower beam bundles, the 4x2 design uses more side flashlamp cassettes than the baseline design. As a result, there are 20% more flashlamps and 20% more pulsed power. However, within our ability to predict, optical performance will be the same.

To reduce development risks, the 4x2 amplifier design uses assembly techniques similar to those used for the Beamlet amplifiers. However, to improve cleanliness, sliding guillotines have been added. Figure 5-6 illustrates the concept. The amplifiers are installed as slab cassette modules (SCMs) that are one slab long, one slab wide, and four slabs high. Each SCM consists of an aluminum frame which supports a slab holder (with four slabs) and top and bottom silver reflectors. To protect the laser slabs from contamination, each SCM has glass blastshields mounted on the sides and guillotines inserted at the ends. The SCMs are assembled in a clean room, double-bagged in clean-room plastic, and placed on a transport cart.

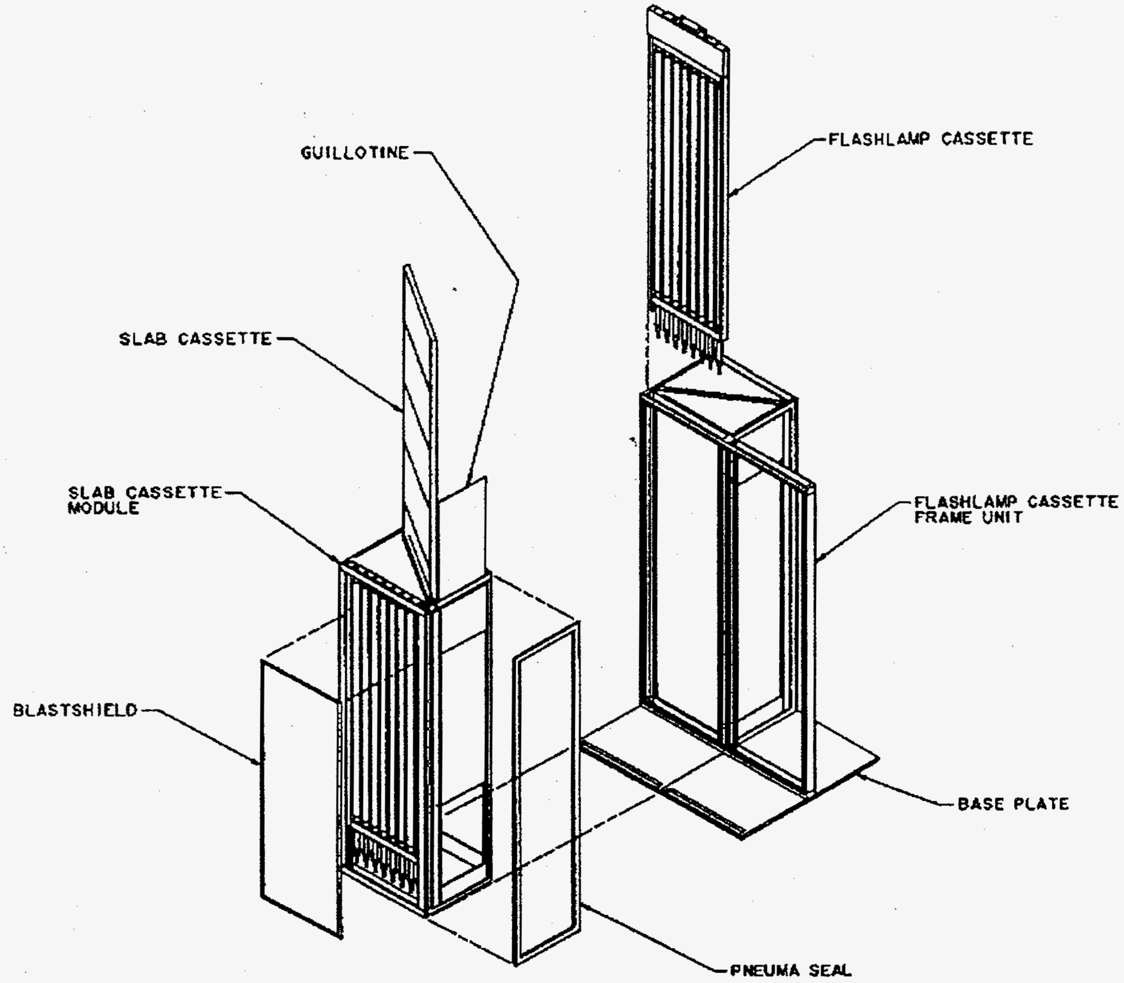


Figure 5-6 4x2 Amplifiers are Assembled Using 1-Slab-Wide, 4-Slab-High, 1-Slab-Long Slab Cassette Modulos (SCMS)

In the laser bay, the SCM is moved under a portable HEPA-filter unit that has been placed over the work area. There, the clean-room bagging is removed and the cart lifts the SCM into place in the beamline. The SCMs rest on baseplates, which may have kinematic mounts for precise positioning. To seal adjacent SCMs together, pneumo-seals located at the end of each SCM are inflated. These seals are needed to protect the slabs from particle contamination in the laser bay. After the pneumo-seals are inflated, a crane is used to remove the guillotines and install the flashlamp cassettes (see Figure 5-7). Finally, the portable HEPA filter unit protecting the work area is removed.

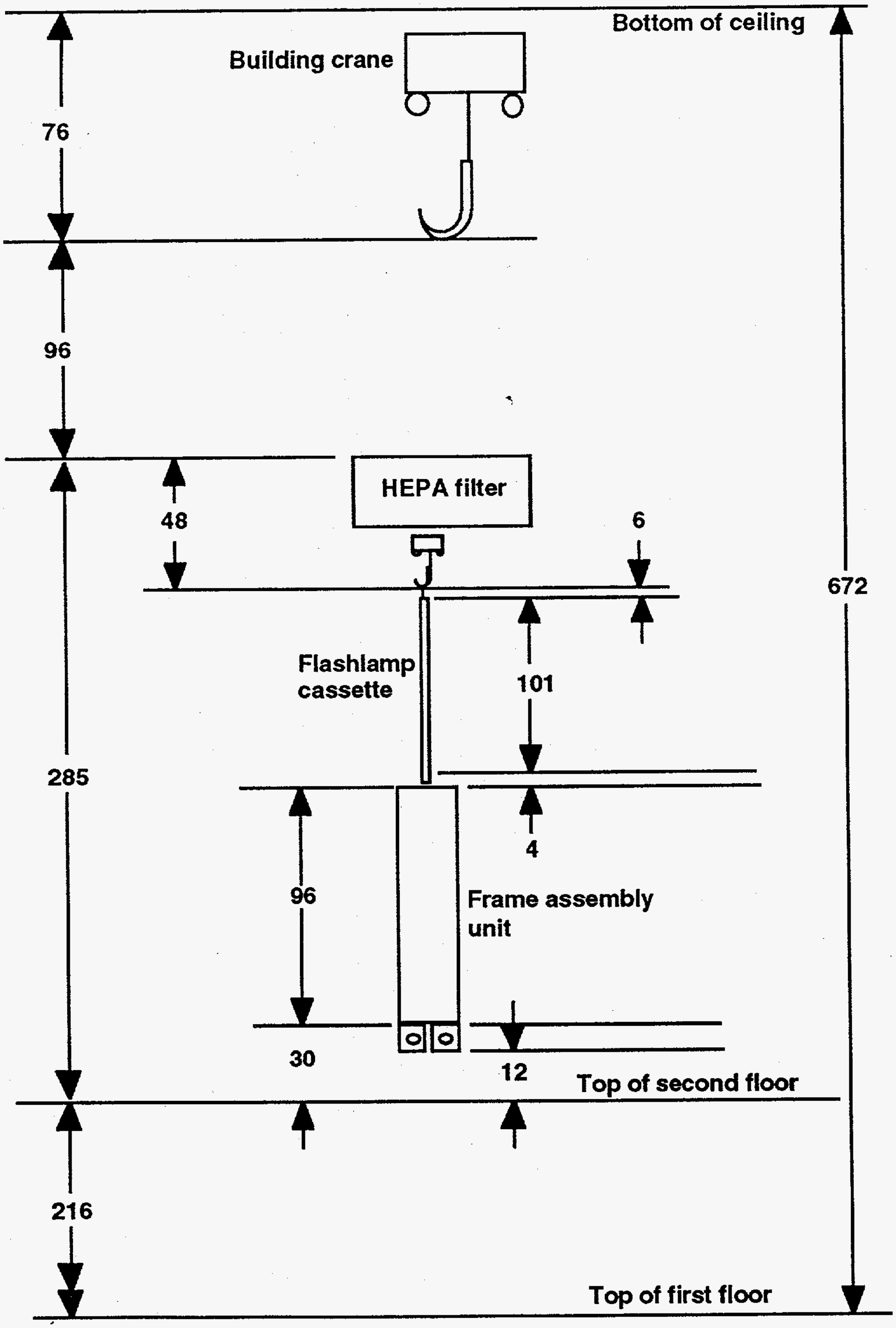


Figure 5-7 A Small Crane Located Under a Portable HEPA Filter Unit is Used to Remove and Replace Flashlamp Cassettes and Guillotines

Figure 5-8 shows a top view of two SCMs, side by side. This design has approximately the same slab-to-slab and lamp-to-slab separations as the 4x12 baseline amplifier design. Only the separation between the central flashlamp cassette and the laser slabs is greater, by 5 mm. Ray-trace modeling shows that this increased separation reduces slab pumping rates by about 1%.

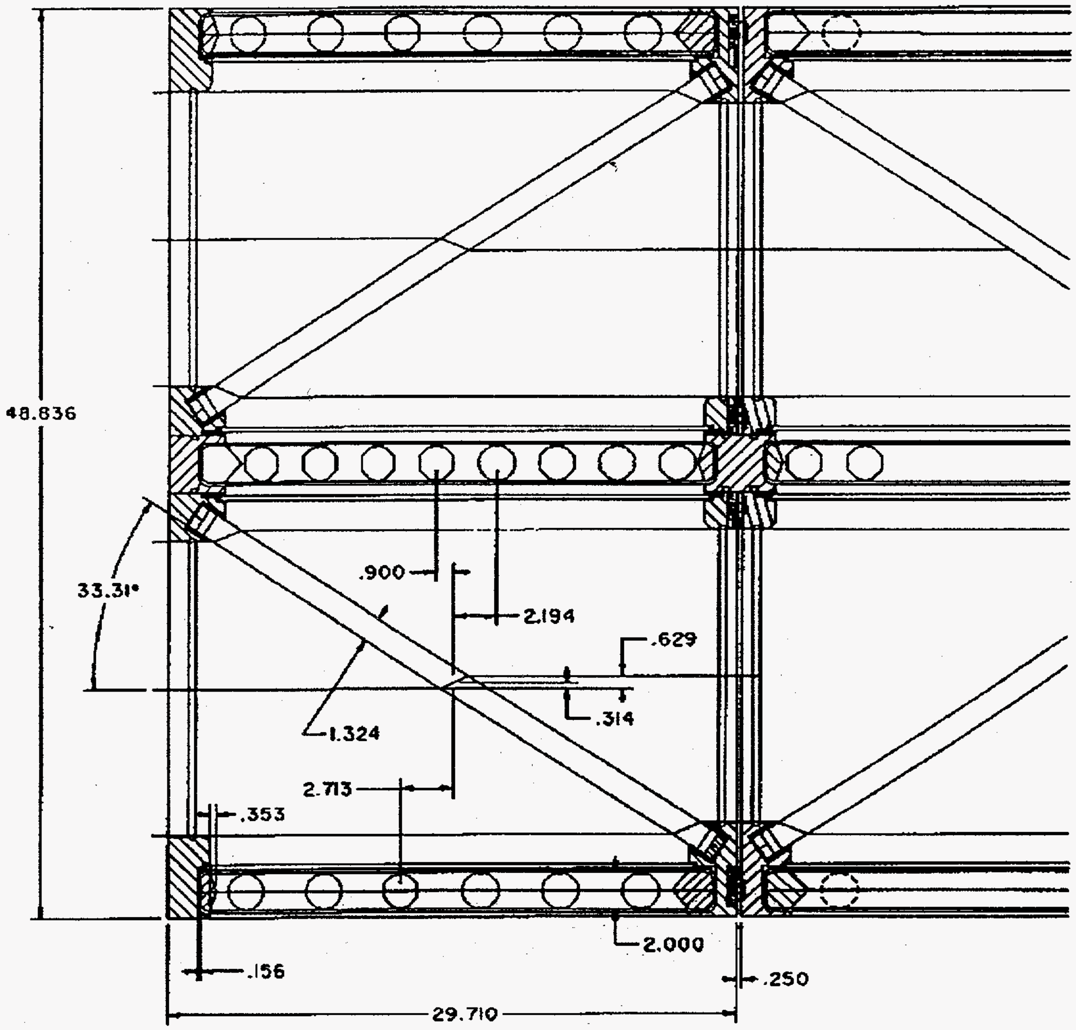


Figure 5-8 The 4x2 Amplifiers Use a Compact, Efficient Design

Flashlamp cassettes are nearly identical to those used in the baseline design. The only signficant differences are that the flashlamp cassettes are inserted from the top of the amplifiers rather than from the bottom, while the electrical and gas connections are made at the bottom rather than at the top. The same electrical and gas connections are used in the baseline design.

### 5.1.4 Spatial Filters

The 4x2 spatial filters will have a rectuangular cross section and may use side ribbing to increase strength. Like the 2x2 spatial filters, the 4x2 spatial filters are probably small enough to be fabricated, painted, cleaned, and otherwise prepared for installation in an off-line facility. Installation activities are facilitated by minimizing the amount of work performed by on-line crews.

Side access eliminates the need for personnel to enter spatical filters for servicing equipment. All equipment is accessible through side doors.

It should be possible to mount some components, such as stepping motors, outside the vacuum chamber. This would eliminate the vacuum compatibility requirement for the motors and reduce contamination risk. Also, it would allow replacement of the motors without venting the vessel.

### 5.1.5 Preamplifier Modules and Output Sensors

As in the other designs, preampliifer modules and beam-injection optics are located underneath the transport spatial filters. The output sensor packages are located above the transport spatial filter. However, to improve access, either of these packages could be re-located to the sides of the transport spatial filter. If the 4x2 design is chosen, this needs to be worked out.

### 5.1.6 Other Optical Components (Spatial Filter Lenses, Pockels Cells, Mirrors, Polarizers)

All optical components (with the exception of the central flashlamp cassettes in the amplifiers) can be installed and removed from the side using special equipment. For contamination protection, components would be installed, removed, or replaced only with portable HEPA filter units installed over the work area. For additional contamination protection, each optical component would have sliding guillotines mounted at its ends. Section 3.1.3.4 describes how such guillotines would be used.

## 5.2 4x2 Bundle Comparison

Table 5-1 summarizes the advantages and disadvantages of this 4x2 bundle design relative to the baseline 4x12 design. This table represents the evaluations and consensus of the committee.

The advantages of the 4x2 design spring from two factors, which are shared with the 2x2 design. These two factors are: 1) smaller bundle size; and 2) side access to all components. Thus, for the most part, the two designs (4x2 and 2x2) have advantages that vary only in degree.

### 5.2.1 Cost

The committee's estimates for 4x2 project costs (PACE) are greater than for the baseline design. The largest contributing factor is the increased size of the building. Each laser bay is 54 feet wider and 54 feet longer than the baseline design. A wider building is needed since the 4x2 design splits the beam bundles into smaller units and separates them by 6-ft. aisles. This also moves the outermost beams farther away from the target area, thereby increasing the length of the transport spatial filters (and the building) which image relay the beams to the frequency converters. It may be possible to reduce the size of the building, by putting beamlines on both the ground floor and on the second floor.

The second largest cost driver is the structural supports. This particular 4x2 design supports the beamlines on elevated floors. Floors cover a larger area and are more expensive than the overhead support sturctures used in the baseline design.

Cost increases for the pulsed power system and the amplifiers result from using narrower amplifiers which require a larger number of side arrays. This increases both the number of flashlamps and the size of the pusled power system by 20%. However, if theoretically-possible efficiency improvements in the side reflectors are realized, this cost difference could be signficantly reduced.

The spatial filters cost less than for the baseline design, due to improved manufacturability of smaller units.

This 4x2 design has lower development costs than the baseline design. Two aspects of development were eliminated: in-situ $CO_2$ spray-cleaning for amplifiers and 1x2 Pockels cells. These savings in development costs may be underestimated, however, since some committee members believe that the development of advanced robotics for the baseline design may turn out to be more difficult than envisioned. The 4x2 design does not require robotics, since essential maintenance operations can be performed using methods developed previously for Nova and Beamlet. (However, robotics could be used, once they are developed.) Thus, the 4x2 design appears to have lower development risks.

### 5.2.2 Other Factors (Schedule, Performance Risk, Maintainability and Operability, Hardware Failure Exposure, and Activation)

For these factors, the 4x2 design has nearly the same advantages and disadvantages as the 2x2 design. Therefore, the comments made in sections 3.2.2 through 3.2.7 on the 2x2 design apply to the 4x2 design as well.

However, one comment made regarding the 2x2 design does not apply to the 4x2 design. Section 3.2.4 states: It has been estimated that sufficient uniformity on target can be achieved, even with the loss of one beam.

**Table 5-1**

### Comparison of the 4x2 Bundle Configuration to the Baseline 4x12 Design

| Issue | 4x2 Advantages | 4x2 Disadvantages |
|---|---|---|
| 1. Cost | Spatial filter is easier to fabricate and install<br>Lower amplifier development costs: no *in-situ* cleaning<br>1x2 Pockels cell development not required<br>Fewer in-vacuum components<br>Capacitors under floor shorten pulsed power cables | Laser bays are 54 ft. wider and 50 ft. longer<br>Switchyard is 54 ft. wider, noble gas box longer<br>Amp is less efficient requiring 20% more pulse power<br>More amplifier hardware components<br>Approximately 20% more flashlamps required<br>More pulsers required for Pockels cell |
| 2. Schedule | Amplifier development schedule is less critical<br>First beam bundle (first-off unit) can be bought on-line sooner<br>Added construction flexibility due to smaller module size | Time is required to advance design to CDR level |
| 3. Performance risk | Small technology step from Beamlet experience<br>Side flashlamp reflectors may improve gain uniformity in the slab<br>Can use a 1x1 Pockels cell<br>*Personnel do not enter spatial filter, reduced cleanliness risk* | None |
| 4. Maintenance and operational ease | No in-situ cleaning required of the amplifier<br>Design is highly modular with simpler installation/removal procedures for all assemblies<br>Side access permits easy inspection and in-situ maintenance<br>*Personnel do not have to enter spatial filters*<br>Possible to locate motors/mechanisms outside spatial filter<br>Less expensive to achieve more rapid pump-down of spatial filter<br>Increased availability with bundle loss due to smaller size<br>Much easier LM3/polarizer maintenance<br>Moderate improvement in availability from firing different subset of beams<br>Reduced cost exposure to operator error<br>Bundle size improves availability on laser during maintenance of power conditioning and spatial filters<br>Fewer lenses exposed to possible contamination during venting | More components to manage (amp, gas handling and vacuum system) |
| 5. Hardware failure exposure | Only 8 beamlines are exposed to vacuum or flashlamp failure | Potentially more opportunity for failure due to more subsystems |
| 6. Activation | Can activate 8 beamlines at a time<br>Learning curve is more rapid; easier to train personnel<br>Less in-situ assembly required for system components<br>Scheduling is potentially simpler for installation/testing<br>*(Plus almost all of the same issues as #4)* | None |
| 7. Design flexibility | Accommodates beam expansion and wedged spatial filter windows<br>Pockels cell can be either 1x1 or 1x2 module<br>Accommodates top loading and side loading amp slabs<br>Laser bundles can be staggered to compensate for optical path differences<br>More amplifier designs could be considered if desired<br>Easier to upgrade system during operational lifetime | None |

This is not true for the 4x2 design, since twice as many beams (4%) would be lost.

## 6.0 Bundle Evaluation

We compared each bundle to the baseline 4x12 concept against the seven committee issues listed in the comparison charts and attempted to make evaluations on an objective basis where possible. We developed differences in project costs and CS&T costs for each of the three bundles (1st committee issue), and estimates of project schedule delay due to a change in the baseline design (2nd committee issue). The effect on laser performance (3rd committee issue) was a subjective evaluation, but was ranked numerically according to a defined scale. Maintenance and operational ease (4th committee issue) was also a subjective evaluation, but we gave different weights to a number of maintenance and operational issues for each different WBS element, to obtain a better overall evaluation. We evaluated operational risk (5th committee issue) by considering cost to recover from two catastrophes (spatial filter lens implosion and flashlamp explosion), which produced results that are somewhat objective. Evaluation for activation risk (6th committee issue) was subjective, but was weighted in a similar manner as was done for maintenance and operational ease. Design flexibility (7th committee issue) was also more subjective. The evaluations for the seven committee issues were used along with the bundle comparison charts to help guide us to a final bundle change recommendation.

### 6.1 Cost relative to baseline (committee issue #1)

We compared the cost differences of the different bundle configurations to the baseline in two areas: Plant and Capital Equipment (PACE) costs for the NIF project, and Core Science and Technology (CS&T) development costs.

### 6.1.1 PACE cost

The CDR baseline cost for the 4x12 design is $583M without escalation or contingency. This includes $372M for laser and control components, $114M for facilities (building), $43M for the target area, and $27M for the project office. For this exercise, the last two costs were assumed to be unchanged. The estimated cost differences for the different bundle sizes are listed in Table 6-1. The 2x2 bundle is estimated to cost $78M more than the baseline design, the 4x2 $56M more, and the 4x4 $22M more.

### 6.1.1.1 Facility cost

Smaller bundle sizes have less densely packed beams, and this increases the volume of the laser and target area building (LTAB). The laser arrays also become wider, increasing the size of the switchyard area and the length of beam propagation paths, which will increase the length of the transport spatial filter. An increase in the length of the transport spatial filter was included, which increased the length of the building and hence its cost. The CDR-estimated cost of the building is about $700 per square foot on average, so larger buildings can be a serious cost penalty. The building cost estimates for this exercise were not a simple square footage charge, as discussed in Appendix A. We estimate that the factor of 1.6 increase in floor space for the 2x2 bundle size increases the cost of the LTAB by about $42M. A smaller increase in laser bay width costs about $15M extra for the 4x4 design. This cost is fairly accurate since it was derived from the building cost for the 240-beam laser proposed in the CDR. The laser bays for the 240-beam case are almost the same size as for the 4x4 configuration we reviewed. The 4x2 costed here has an additional building cost of abour $34M

Some members of the committee feel that the cost estimates of the building for the other two configurations may be high and can be reduced. In addition, the cost per square foot of the building enclosing long spatial filters should be much less than the cost of sensitive areas around laser components and pinhole planes. These cost reductions have not been estimated here. Such reductions also apply to the baseline 4x12 design.

#### 6.1.1.2 Laser hardware cost

The laser hardware cost increases over the $372M baseline cost are $44M for the 2x2, $22M for the 4x2, and $7M for the 4x4. Table 6-1 shows the distribution among the laser components. In summary, smaller amplifier and other component arrays have more parts and, therefore, cost more. The structural support cost rises with less dense packing of hardware because of increased width of the switchyard and amplifier support structures. Side flashlamp arrays are less efficient, so the cost of the pulsed power system goes up about 20% for a 2-wide array or 8% for a 4-wide array when compared to the 12-wide baseline. The Pockels cell cost goes up for the two-wide arrays since it is assumed that the cells are separate 1x1 modules rather than 1x2 arrays, so the cost of electrical hardware and connections rises. The pulse generation system is slighly cheaper for the two-wide designs because some small spatial filters are estimated. Optical component costs are unchanged since all array sizes use the same components. The 4x2 amplifier costed is a Beamlet-like top-loading 4x2 which helps reduce development costs. The dual-level deck system in the 4x2 concept (not present in other concepts) is costed as a structural support similar to the concrete portion of a switchyard (i.e., designed to the same stability requirements).

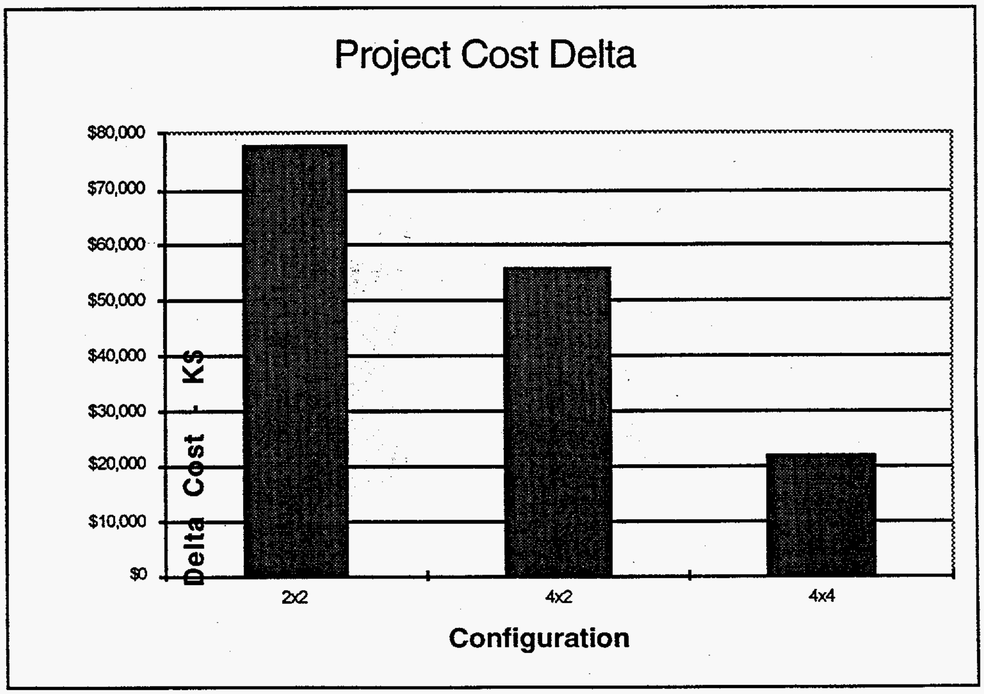
Note that the cost of the spatial filters for the smaller arrays is listed as less than for the baseline system. A reanalysis of those costs suggests that there will be some cost savings from fabricating large components such as the spatial filters in small, truckable sections rather than having on-site fabrication and assembly. The baseline design cannot use this advantage since the 12-wide width severely limits length and increases the number of pieces that must be welded together on site.

**Table 6-1. Estimate of difference in PACE cost with bundle size.**

Cost Delta Relative to Baseline - PACE

| WBS | Description | Estimator | Delta K$ | | | CDR cost |
|---|---|---|---|---|---|---|
| | | | 2x2 | 4x2 | 4x4 | 4x12 |
| 1 | Project | | $77,715 | $55,722 | $21,861 | |
| 1.1 | Project Office | none | | | | |
| 1.2 | Facility | Foley | $41,742 | $34,119 | $14,676 | 123656 |
| 1.3 | Laser | | | | | |
| 1.3.1 | Pulse generation | Larson | ($600) | ($500) | $200 | 49964 |
| 1.3.2 | Amplifier | Erlandson | $17,122 | $3,580 | $1,465 | 35398 |
| 1.3.3 | Spatial filter | Horvath | ($3,071) | ($4,131) | ($4,382) | 29791 |
| 1.3.4 | Cavity mirror mounts | Horvath | $399 | $330 | $261 | 5171 |
| 1.3.5 | Transport mirror mnts | Horvath | $390 | $314 | $238 | 18628 |
| 1.3.6 | Pockels cell | Larson | $2,530 | $2,530 | $0 | 10060 |
| 1.3.7 | Polarizer mount assy | Horvath | $265 | $220 | $175 | 2952 |
| 1.3.8 | Interstage hardware | Horvath | $639 | $420 | $551 | 3971 |
| 1.3.9 | Final optics | none | | | | 7061 |
| 1.3.10 | Structural supports | Horvath | $9,169 | $11,618 | $4,417 | 12637 |
| 1.3.11 | Auxiliary systems | Hackel | $0 | $0 | $0 | 2830 |
| 1.3.12 | Power conditioning | Larson | $8,930 | $7,122 | $4,210 | 35567 |
| 1.3.13 | Beam control | Hackel | $200 | $100 | $50 | 39243 |
| 1.4 | Target area | none | $0 | $0 | $0 | 43212 |
| 1.5 | Computer control | Tietbohl | $0 | $0 | $0 | 14817 |
| 1.6 | Optical components | Murray | $0 | $0 | $0 | 103875 |

Rating parameter: Total cost differential in FY 94 dollars. No contingency. No escalation.



## 6.1.2 CS&T development costs

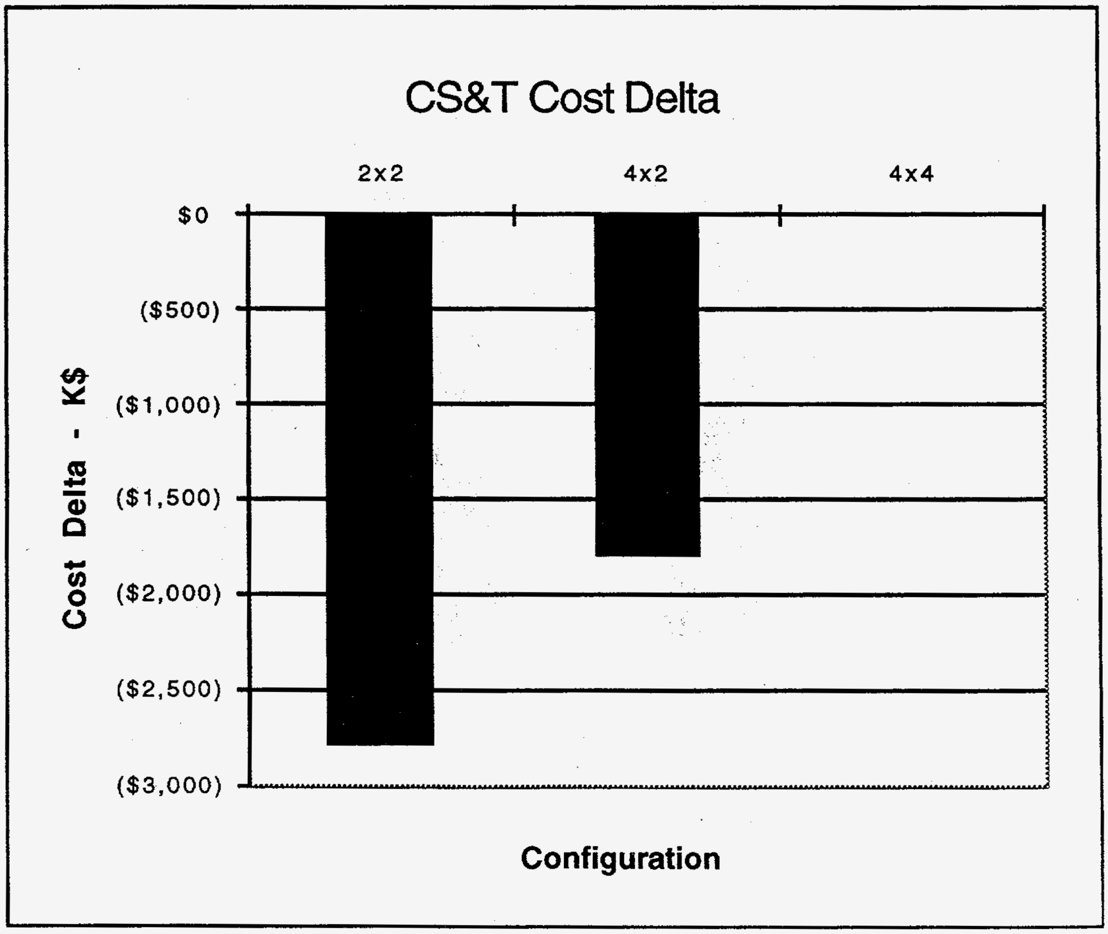
As shown in Table 6-2, the CS&T development costs are about $2.8M less for the 2x2 and $1.3M less for the 4x2. Most of this cost is in amplifier development, and assumes that we do not need to develop techniques for clean assembly in place for these two choices. There is an estimated $0.5M savings for the two-wide arrays from the use of single-beamlet Pockels cells so that two-wide cells do not need to be developed. The 4x4 uses the same concepts as the baseline and has essentially the same development cost.

**Table 6-2. Estimate of difference in PACE cost with bundle size.**

Cost Delta Relative to Baseline -CS&T

| WBS | Description | Estimator | Delta K$ | | |
|---|---|---|---|---|---|
| | | | 2x2 | 4x2 | 4x4 |
| 1 | CS&T | | ($2,785) | ($1,800) | $0 |
| 1.3.1 | Pulse generation | Larson | $0 | $0 | $0 |
| 1.3.2 | Amplifier | Erlandson | ($2,285) | ($1,300) | $0 |
| 1.3.6 | Pockels cell | Larson | ($500) | ($500) | $0 |
| 1.3.12 | Power conditioning | Larson | $0 | $0 | $0 |
| 1.3.13 | Beam control/laser diag. | Hackel | $0 | $0 | $0 |
| 1.6 | Optical components | Murray | $0 | $0 | $0 |

Rating parameter: Total cost differential relative to baseline
CS&T baseline plan.
FY 94 dollars. No contingency. No escalation.



## 6.2 Schedule impact relative to baseline (committee issue #2)

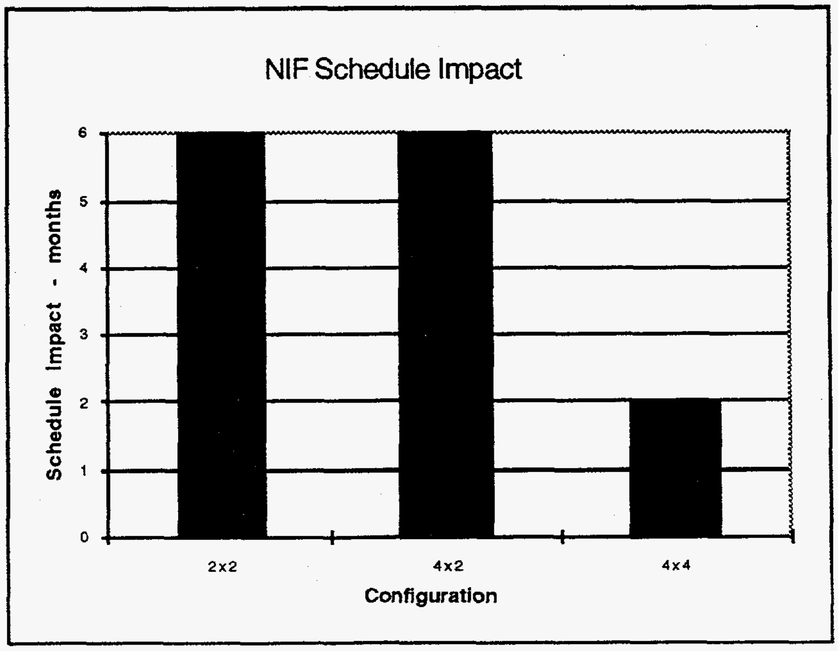
The two-wide concepts cause an overall NIF project schedule slip of about six months, as shown in Table 6-3, which is the time required to bring these concepts up to the level of detail for the 4x12 concept analyzed in the CDR. This schedule impact could be recovered by adding resources at the start of the project at some cost, which was not estimated. Note that the individual entries in the table are each less than six months, but some of these activities are sequential. The 4x4 requires some re-analysis and reworking of drawings, but the difference is much less and could be considered part of the normal advanced conceptual design already envisioned for the baseline.

**Table 6-3. Estimate of NIF project schedule impact with bundle size.**

NIF Schedule Impact Relative to Baseline - calendar months

| WBS | Description | Estimator | Delta months | | |
|---|---|---|---|---|---|
| | | | 2x2 | 4x2 | 4x4 |
| 1 | Project | | 6 | 6 | 2 |
| 1.1 | *Project Office* | | | | |
| 1.2 | Facility | Foley | 3 | 3 | 1 |
| 1.3 | Laser | | | | |
| 1.3.1 | Pulse generation | Larson | 1 | 1 | 0 |
| 1.3.2 | Amplifier | Erlandson | 3 | 2 | 1 |
| 1.3.3 | Spatial filter | Horvath | 3 | 3 | 1 |
| 1.3.4 | Cavity mirror mounts | Horvath | 2 | 2 | 1 |
| 1.3.5 | Transport mirror mnts | Horvath | 2 | 2 | 1 |
| 1.3.6 | Pockels cell | Larson | 1 | 1 | 0 |
| 1.3.7 | Polarizer mount assy | Horvath | 2 | 2 | 1 |
| 1.3.8 | Interstage hardware | Horvath | 0 | 0 | 0 |
| 1.3.9 | Final optics | none | 0 | 0 | 0 |
| 1.3.10 | Structural supports | Horvath | 3 | 3 | 1 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 0 |
| 1.3.12 | Power conditioning | Larson | 1 | 1 | 1 |
| 1.3.13 | Beam control | Hackel | 1 | 0 | 0 |
| 1.4 | Target area | none | 0 | 0 | 0 |
| 1.5 | Computer control | *Tietbohl* | 0 | 0 | 0 |
| 1.6 | Optical components | Murray | 0 | 0 | 0 |

Rating parameter: Time required to advance concept to CDR level of design maturity



### 6.3 Performance risk relative to baseline (committee issue #3)

Smaller arrays are closer to current experience, so the performance risk is assumed to be lower for them. Table 6-4 shows the committee's judgment on where these risks lie. The overall change in performance risk is small relative to the baseline for all of the smaller bundles, although individual components are more strongly affected. The 2x2 arrays have substantially lower risk in the amplifier and Pockels cell, since units have already been tested that are very similar to the hardware proposed. There is somewhat lower risk in other component arrays and the spatial filter since these are closer in size and design to hardware with which we are familiar, and the two-wide arrays do not require as many components to operate inside the spatial filter vacuum.

# Table 6-4. Estimate of change in performance risk with bundle size.

Performance Risk Relative to Baseline

| WBS | Description | Estimator | Weighting | Risk Factor | | | Weighted Performance risk | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 2x2 | 4x2 | 4x4 | 2x2 | 4x2 | 4x4 |
| | Weighted average | | | | | | 0.7 | 0.7 | 0.3 |
| | Standard Deviation | | | 0.9 | 0.9 | 0.5 | | | |
| 1.2 | Facility | Foley | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.3.1 | Pulse generation | Larson | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.3.2 | Amplifier* | Erlandson | 3 | 2 | 2 | 1 | 6 | 6 | 3 |
| 1.3.3 | Spatial filter | Horvath | 3 | 1 | 1 | 1 | 3 | 3 | 3 |
| 1.3.4 | Cavity mirror mounts | Horvath | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1.3.5 | Transport mirror mnts | Horvath | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1.3.6 | Pockels cell | Larson | 2 | 3 | 3 | 0 | 6 | 6 | 0 |
| 1.3.7 | Polarizer mount assy | Horvath | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1.3.8 | Interstage hardware | Horvath | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.3.9 | Final optics | none | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.3.10 | Structural supports | Horvath | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.3.11 | Auxiliary systems | Hackel | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.3.12 | Power conditioning | Larson | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.3.13 | Beam control | Hackel | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.4 | Target area | none | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.5 | Computer control | Tietbohl | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.6 | Optical components | Murray | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Sum | 27 | | | | | | |

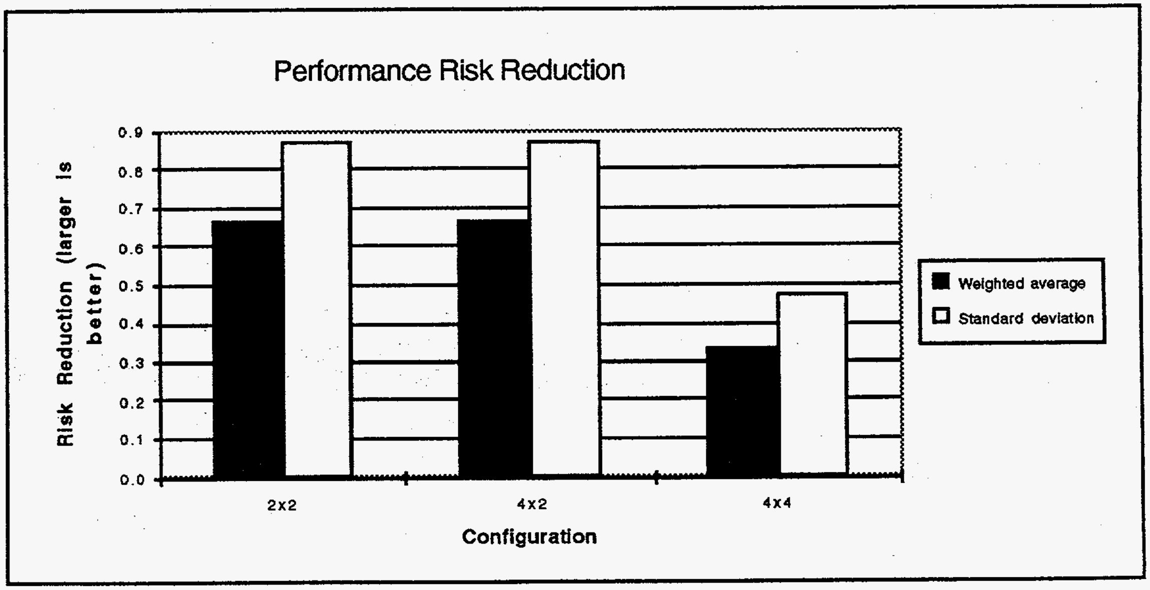
Rating parameter: Relative risk in achieving NIF Primary criteria Functional Requirements

1.8 MJ/500TW
600 micron spot size
50 micron beam stability on target
etc.

Ranking Scale

| | |
|---|---|
| Significant risk reduction | 5 |
| | 4 |
| Moderate risk reduction | 3 |
| | 2 |
| Slight risk reduction | 1 |
| No impact | 0 |
| Slight risk increase | -1 |
| | -2 |
| Moderate risk increase | -3 |
| | -4 |
| Unacceptable risk | -5 |

* performance will vary from design to design depending on relative performance of side and central flashlamp cassettes. Further development is required to quantify difference.



## 6.4 Maintainability/Operability (committee issue #4)

### 6.4.1 Operations and Maintenance

We evaluated operability and maintainability subjectively rather than using cost analysis. We chose several criteria to rank in relation to the WBS elements, which is included in Appendix E. These criteria included safety, ease & efficiency, availability, flexibility, risk of contamination, and consequence of a mistake. In order to provide consistent evaluations among all members of the group we provided definitions for each criteria. The criteria, definition, and brief examples are provided below.

### 6.4.2 Safety

Ability to provide a safe work environment and low risk to components while doing maintenance and operations. The ability to service the components of a spatial filter without actually entering the filter and minimizing the use of ladders and climbing was rated higher.

### 6.4.3 Ease & Efficiency

Issues associated with numbers of personnel and special equipment required for maintenance, ability to reach components for adjustment and troubleshooting, time required to perform a given task, etc. Options that allowed side access to components for in-situ inspection and adjustment and that minimized the number of components handled during servicing were rated higher. Options that simply made it easier to do a given task were rated higher.

### 6.4.4 Availability

Ability to complete maintenance between shots, ability to continue significant experiments/operations on remaining active bundles during maintenance or repair, ability to continue with significant operations after system failure prior to and during repair. Options that had higher potential to allow maintenance to be completed between shots were rated higher. Options that minimized the number of beams effected by maintenance or a failure prior to maintenance, were rated higher. The baseline design could cause a loss of up to 25% of the system during maintenance activities, due to the large spatial filters. Venting a large filter requires a longer time and affects more beams than a smaller unit. Servicing mirrors or polarizes on larger bundles affects more beams than smaller bundles.

ICF experimenters indicate that availability will be a significant issue relative to experiments planned to demonstrate ignition.

To assess the NIF amplifier bundle issue as it affects targets physics, we refer to Table 3.5-2: "Summary of the experimental plan for NIF" in the NIF CDR[2]. This target physics plan calls for 1600 shots to demonstrate ignition. The shots are broken down into four categories: Startup experiments, Hohlraum symmetry experiments, Cryogenic and pre-ignition experiments and Ignition shots.

With a 4x4 bundle if one bundle were to go down, we would loose 16/192 = 8% of the beams, namely, loss of 8% of the energy and power. The current state of our understanding indicates that to achieve ignition each beam must achieve a power balance of ~8% rms with respect to a reference value.[2] Though we do not know the exact correlation between loss of some percent of the beams and loss of overall power balance, we suspect that most shots requiring good symmetry would be dropped with the loss of 8% of the beams. It is our estimation that most of the startup experiments would proceed. We also think subsets of the category "Hohlraum symmetry" would proceed (square pulse hohlraums, square pulse implosions, tuning: filling, tuning: instabilities). Half of the subsets, Tuning: $T_r$ vs. time, Tuning: shock timing would not proceed with loss of one 4x4 bundle. None of subsets Tuning: time average symmetry, Tuning: time dependent symmetry, High convergence, sub-ignition, Ignition experiments, or Parameterization of ignition would proceed. The total loss of shots would be 625 out of the required 1600 needed for demonstration of ignition. Therefore, loss of one 4x4 bundle means loss of 40% of the shots required for demonstration of ignition.

We would predict that loss of a 2x4 bundle (4% of the beams) would have similar implications, i.e., loss of 40% of the required shots, whereas most shots would proceed with loss of a single 2x2 bundle (2% of the beams).

Concerning 4x12 bundles, loss of a single bundle (25% of the beams) would have more serious consequences. In addition to the above, it is estimated that all of the square pulse categories (hohlraums, implosions), at least half of the tuning categories (filling, instabilities) and all of the High yield and activation check category would not proceed if 25% of the beams were missing. This implies at least 50% of the required shots for demonstration of ignition could not be done if one 4x12 bundle were lost. The downtime for repair presumably is considerably longer as well.

Table 6-5 summarizes our estimate of the impact on required NIF shots from loss of a single bundle.

Table 6-5

| Array Type Lost | Percent of 1600 Shots Impacted | Downtime |
|---|---|---|
| 2x2 | None | None |
| 2x4 | 40% | Short |
| 4x4 | 40% | Moderate |
| 4x12 | 50% | Long |

### 6.4.5 Flexibility

Ability to fire a fraction of the system alternately for useful experiments, thereby increasing the shot rate. Options that provided a more uniform distribution of beams on target when firing a fraction of the system were rated higher. The ability to fire 25% to 50% of the system alternately has the potential to increase shot rate. The beam distribution on target as the result of using a fraction of the system would have to be sufficiently uniform to yield a credible target experiment. Smaller bundles could provide a sufficient number of beams to allow for such a distribution. These issues were not fully evaluated during this review although target experimenters indicate that 20% to 50% of the total annual shots plan for the NIF could use this type of scenario.

We note that non-ICF users of NIF, such as Weapons Physics and Scientific/University research, will generally have far less stringent requirements on beam uniformity and energy. NIF would be a very useful facility for many of these experiments even if several 4x12 bundles were unavailable. However, since we will be unable to plan for downtime of a bundle, except in the case of routine maintenance, scheduling experiments to efficiently use the laser in this configuration would be impractical if not impossible. Target and diagnostic configuration, along with personnel schedules, will clearly constrain the flexibility of the NIF, making it difficult to respond to rapid changes in experimental schedule.

### 6.4.6 Risk of Contamination

The risk of contaminating optical components or systems during maintenance and system operation. The inherent risk of contamination during maintenance was evaluated. Options that allowed servicing of components without entering enclosures such as spatial filters, mirror boxes, and polarizer enclosures were given higher ratings.

### 6.4.7 Consequence of a Mistake

The effect (magnitude and extent) of a personnel mistake during maintenance and operations. Options that minimized the number of components handled, the number of components personnel were exposed to, and the number of components that were interconnected were given a higher rating. Examples of mistakes include accidental contamination, dropping or mishandling components, dropping something onto components, and failure of handling fixtures.

In addition to rating the criteria, we used a weighting system to apply a higher value to those criteria that we felt were more significant to the evaluation (Appendix E). An example of this is that the risk of contamination of an amplifier is weighted heavier than the ease and efficiency issues associated with interstage hardware.

### 6.4.8 Maintainability/Operability Summary

As mentioned earlier, the maintainability/operability estimates were derived from weighting six different criteria for each bundle. The weighted ranking numbers are shown in Table 6-6; the detailed backup analysis is included in Appendix E. Smaller arrays have easier access to parts, more options for access to parts, and less risk that a failure will cause loss of a large number of adjacent beamlets, as shown in the relative ranking of Table 6-6. The larger arrays (4x4 and 4x12) assume assembly and maintenance techniques that have not been tested on existing systems, while the 2-wide arrays could be serviced in much the same way as is now done on Nova and Beamlet. The 4x4 configuration with aisles between bundles allows access to certain components that is not practical with the 4x12 array (such as side access to polarizers, Pockels cells, and elbow mirrors). Almost all typical target shots could proceed with a single 2x2 bundle out of operation (e.g., with the spatial filter open for maintenance), while the number that could proceed for the two intermediate sizes is ~60% and for the baseline is ~50%. There are more options for firing selected sets of fewer beams with the smaller arrays. Even with the 4x4 design, it is much more likely than in the baseline to allow replacement of components (even spatial filter lenses) between shots.

# Table 6-6. Estimate of change in maintainability/operability with bundle size.

Maintainability/operability Relative to Baseline

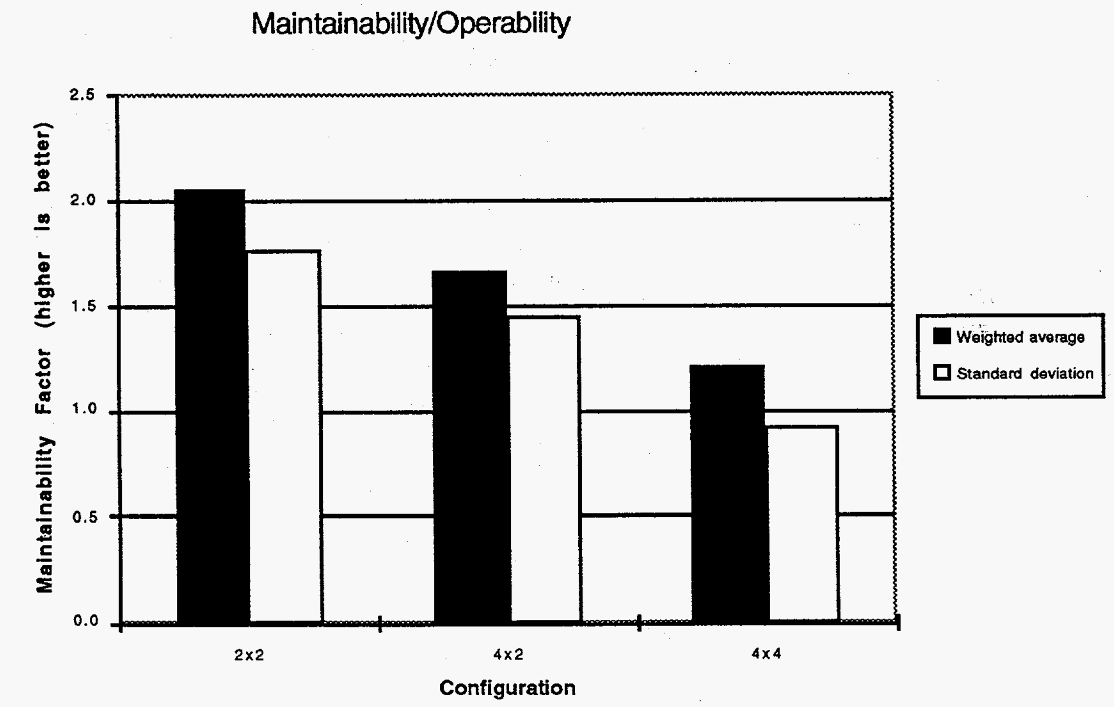
| WBS | Description | Estimator | Maintainability/operability | | |
|---|---|---|---|---|---|
| | | | 2x2 | 4x2 | 4x4 |
| | Weighted average | | 2.0 | 1.7 | 1.2 |
| | Standard Deviation | | 1.8 | 1.4 | 0.9 |
| 1.1 | Project Office | none | 0.0 | 0.0 | 0.0 |
| 1.2 | Facility | Foley | 0.0 | 0.0 | 1.0 |
| 1.3 | Laser | | 0.0 | 0.0 | 0.0 |
| 1.3.1 | Pulse generation | Larson | -0.9 | 0.5 | 0.4 |
| 1.3.2 | Amplifier | Erlandson | 1.9 | 0.4 | 0.5 |
| 1.3.3 | Spatial filter | Horvath | 4.8 | 4.2 | 2.3 |
| 1.3.4 | Cavity mirror mounts | Horvath | 2.6 | 2.1 | 1.7 |
| 1.3.5 | Transport mirror mnts | Horvath | 0.0 | 0.0 | 2.1 |
| 1.3.6 | Pockels cell | Larson | 1.2 | 1.2 | 0.0 |
| 1.3.7 | Polarizer mount assy | Horvath | 3.9 | 3.4 | 2.4 |
| 1.3.8 | Interstage hardware | Horvath | 4.7 | 4.0 | 2.2 |
| 1.3.9 | Final optics | none | 0.0 | 0.0 | 0.0 |
| 1.3.10 | Structural supports | Horvath | 0.0 | 0.0 | 0.0 |
| 1.3.11 | Auxiliary systems | Hackel | 0.8 | 0.8 | 0.5 |
| 1.3.12 | Power conditioning | Larson | 1.4 | 0.8 | 0.4 |
| 1.3.13 | Beam control | Hackel | 2.6 | 2.6 | 1.6 |
| 1.4 | Target area | none | 0.0 | 0.0 | 0.0 |
| 1.5 | Computer control | Tietbohl | 3.0 | 2.0 | 1.0 |
| 1.6 | Optical components | Murray | 0.0 | 0.0 | 0.0 |

Ranking Scale

| | |
|---|---|
| Significant risk reduction | 5 |
| | 4 |
| Moderate risk reduction | 3 |
| | 2 |
| Slight risk reduction | 1 |
| No impact | 0 |
| Slight risk increase | -1 |
| | -2 |
| Moderate risk increase | -3 |
| | -4 |
| Unacceptable risk | -5 |

Rating parameter: Capability to maintain all systems operating.
Ease of repair. Risk to equipment during routine repair.
Cleanliness risk. Cost of operating off-line facilities

availability = 72%
shots/year = 616
reliability - 80% of shots within specification



## 6.5 Operational Risk (committee issue #5)

Larger arrays allow more components to be damaged or contaminated in a failure. The worst laser system failure considered by the committee was an implosion of a single input transport spatial filter lens L3. The costs associated with recovering from this type of failure is shown in Table 6-7. It was assumed that this failure will contaminate all lenses in that spatial filter so that they must be removed and cleaned, with some fraction of them refinished. It is assumed that mechanical design features prevent the fracture of any other lens. All of the final amplifier slabs in the adjacent booster amplifier will also be removed and cleaned, with a fraction refinished. Some other amplifier and pinhole-plane components will be replaced, including about $10K of alignment and diagnostics components per beamlet in the bundle. The repair estimates are likely low due to insufficiently detailed lists of damaged components which would make all costs higher.

The baseline has the most expensive catastrophic failure at $1.3M. Smaller bundles have less costly failures, by a ratio slightly less than linear in the total number of beamlets exposed (because beamlets remotely located from the failure in a large array are somewhat less likely to be damaged than those nearby). The 2x2 array has a catastrophic failure potential of about $130K, or ~$1.16M less than the baseline. The 4x2 configuration is ~$1.0M less and the 4x4 is ~$0.8M less.

A flashlamp explosion at the input side of the booster amplifier was also analyzed, since this failure could contaminate a large number of mirrors, polarizers, and Pockels cells. It was judged to cause considerably less damage, or about $634K for the baseline 4x12 configuration. This is primarily a result of the reduction in number of optics that would need to be refinished. The 2x2 array has a catastrophic failure potential of about $475K less than the baseline. The 4x2 configuration is ~$272K less and the 4x4 is ~$84K less.

Details of the cost estimates for these two catastrophic failures is included in Appendix F.

It should be noted that the most serious catastrophic failure in the system was not considered, since the risk of that failure is independent of bundle size. That failure is the implosion of a target chamber focus lens.

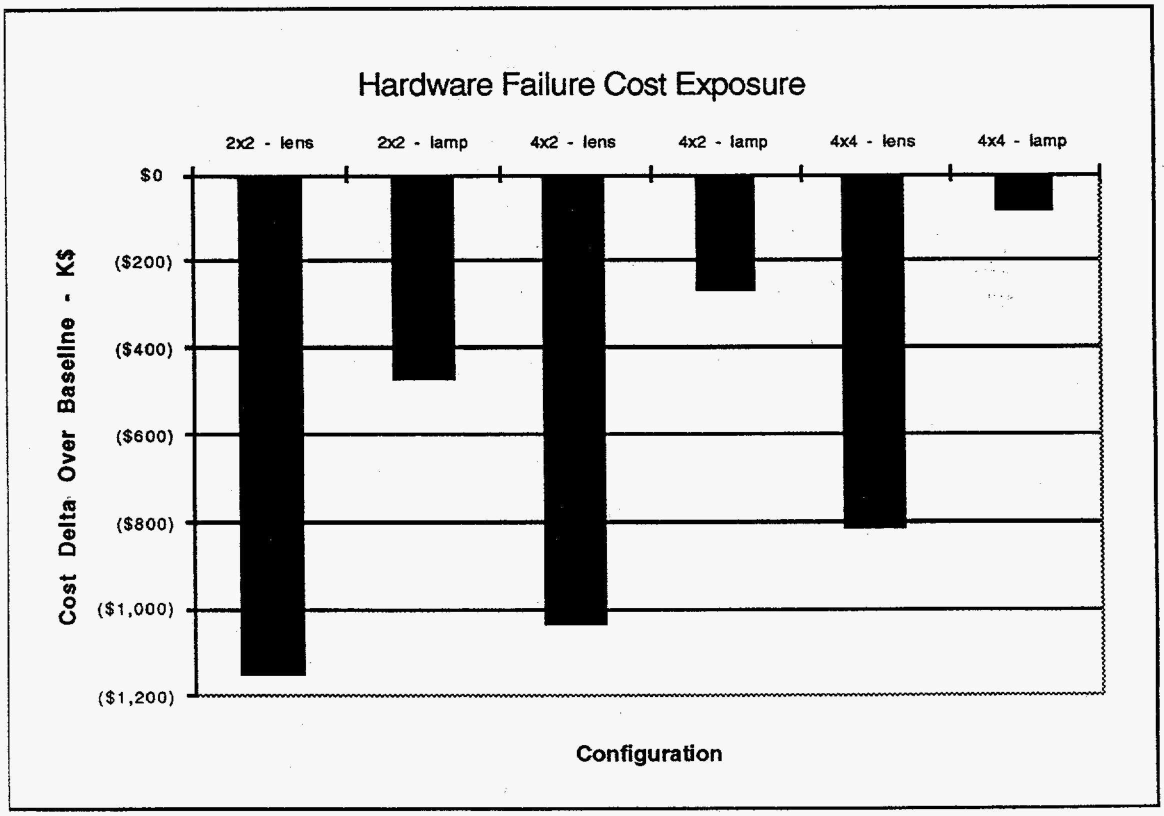
**Table 6-7. Estimate of difference in cost to recover from a catastrophe with bundle size.**

Hardware Failure Cost Exposure Relative to Baseline

| WBS | Description | Estimator | Hardware exposure - K$ | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 2x2 - lens | 2x2 - lamp | 4x2 - lens | 4x2 - lamp | 4x4 - lens | 4x4 - lamp |
| | | | 1 | 2 | 1 | 2 | 1 | 2 |
| | Total | | ($1,155) | ($475) | ($1,039) | ($272) | ($819) | ($84) |
| 1.1 | Project Office | none | | $0 | | $0 | | $0 |
| 1.2 | Facility | Foley | | | | | | |
| 1.3 | Laser | | | | | | | |
| 1.3.1 | Pulse generation | Larson | | | | | | |
| 1.3.2 | Amplifier | Erlandson | ($132) | ($13) | ($120) | ($12) | ($96) | ($10) |
| 1.3.3 | Spatial filter | Horvath | ($55) | | ($47) | | ($37) | |
| 1.3.4 | Cavity mirror mounts | Horvath | | ($20) | | ($18) | | ($15) |
| 1.3.5 | Transport mirror mnts | Horvath | | ($20) | | ($18) | | ($15) |
| 1.3.6 | Pockels cell | Larson | | ($13) | | ($12) | | ($10) |
| 1.3.7 | Polarizer mount assy | Horvath | | ($13) | | ($12) | | ($10) |
| 1.3.8 | Interstage hardware | Horvath | ($9) | ($36) | ($8) | ($30) | ($6) | ($24) |
| 1.3.9 | Final optics | none | | | | | | |
| 1.3.10 | Structural supports | Horvath | ($1) | | ($1) | | ($1) | |
| 1.3.11 | Auxiliary systems | Hackel | | | | | | |
| 1.3.12 | Power conditioning | Larson | | | | | | |
| 1.3.13 | Beam control | Hackel | ($493) | | ($448) | | ($359) | |
| 1.4 | Target area | none | | | | | | |
| 1.5 | Computer control | Tietbohl | | | | | | |
| 1.6 | Optical components | Murray | ($465) | ($360) | ($415) | ($170) | ($320) | $0 |

Rating parameter: Cost exposure (K$) (labor and material repair costs)
to worst case failure scenario. Downtime caused by failure.

**1) Spatial filter lens implosion ($1283K repair cost for baseline)**
**2) Flashlamp/debris shield failure ($634K repair cost for baseline)**



## 6.6 Activation Risk (committee issue #6)

Activation costs are a small part of the total system costs and thus activation is not a strong factor if one is only trying to minimize the construction costs. However, minimizing construction cost should not be the only criterion in choosing a design. Operability, maintenance, and lifetime project costs are among the other factors that should be considered. Because they have many common requirements, designs that make activation easier are also easier and less expensive to operate and maintain, and may have lower total project cost.

Whether any design has significant advantages during activation is an issue that depends on the details of each of the designs, the thoroughness with which the assembly, installation, alignment, and test procedures are thought out during the design phase, and the tools that are supplied. Some of these items have been considered in the baseline design but most have not to the detail required for a meaningful comparison. In the limited time available we did not have the time or resources to consider the procedures and tools required for each of the designs considered. Therefore, we made our conclusions from subjective judgments of the top level issues. These issues were; (1) system cleanliness, (2) personnel and equipment safety, (3) access for installation, adjustments, and testing, (4) system alignment, (5) activation staging, and (6) ability to do early operational testing (see Appendix D for details of this evaluation). All of these issues lead one to choose the smaller bundle sizes with the nx2 sizes the most preferred. The discussion of each of the issues that follows will briefly attempt to justify this conclusion.

### 6.6.1 Cleanliness

The initial stages of construction of the system are inherently dirty; welding or bolting large structures together, pulling and terminating cables, installing utilities, etc. After these tasks are complete one must begin cleaning the facility and transition to clean room status, at least in local areas, before installing optics and amplifier components. This involves cleaning the interior of structures like amplifier frames, spatial filter tanks, and mirror towers, and keeping them in a class 10 clean condition until the optical components are installed and they can be enclosed by covers and/or beam tubes. In Beamlet this was done by precleaning the local area where an optic was to be installed, placing a portable clean module over the area, doing a more thorough cleaning, installing the optic or component that had been cleaned and assembled in a clean room, and finally attaching clean covers and/or beamtubes before the clean module is removed. Such a procedure becomes more and more difficult as the structures get larger. One would probably try to clean a 4x12 structure a small section at a time but is faced with the problem of preventing recontamination from the still dirty portion. One could envision installing internal baffles in spatial filters and mirror towers and sectioning beam tubes to solve this problem but these measures further restrict access to difficult to reach parts. It seems clear that designs with smaller modular units that can be separately converted to temporary clean areas is the most reasonable solution to this problem.

### 6.6.2 Personnel and equipment safety

Safety concerns increase significantly when one enters a structure such as a spatial filter vacuum chamber, a nitrogen filled beam tube, or a crowded and perhaps nitrogen filled mirror tower to do installation, adjustment, or modifications. When one enters such a structure there is a need for safety interlocks and assurances, ventilation and lighting, and one must be fully suited to protect the clean environment. There is the danger of inadvertently bumping equipment in the crowded areas causing misalignment or breakage. Concerns about the implosion of spatial filter lenses and possible oxygen deficiency in areas open to the amplifier increase as the size of the module grows. A design that provides access to all components without having to enter the structure is a much preferred design from a safety standpoint.

### 6.6.3 Access

Side access from an aisle is a very desirable feature. It allows access to individual components for installation, adjustment, inspection, and replacement. It allows one to view the alignment beam at many places along the beamline to check alignment, and to inspect individual components for dirt, damage, burn marks, etc. These are activities that we have not yet found an adequate replacement for and are of value during both the activation and operational periods. Side access also allows installation of special diagnostic as required to troubleshoot problems. During their operational phase all system we have built have required continuous monitoring and maintenance to keep them capable of top performance. Again side access will make these tasks much easier. The larger and more integrated the structure becomes and the more access to individual components becomes restricted the harder it is going to be to make the assessments and to do the adjustments necessary to make the system operate properly.

### 6.6.4 System Alignment

The largest bundle sizes we are considering require large structures to be built in precise alignment; not an impossible task but one that adds to the difficulty during construction. The smaller bundle designs could provide limited x, y adjustment of spatial filters as well as mirrors, Pockels cells, and polarizers which will relax these initial alignment requirements. Side access would make the centering operation easy. Other alignment activities such as acquiring the input beam from the preamplifier, doing the initial pointing of the beam through the system, setting the length of the spatial filters to collimate the beam, and acquiring the beam in the diagnostic and alignment sensors are facilitated by the side access.

### 6.6.5 Activation Staging

Small bundle units allow bundles to be completed and tested in sequence one or more at a time. Bundles can be completed and sealed with beam tubes while the assembly and alignment of adjacent bundles continues. Such an assembly and activation sequence has many advantages. It is easier to establish and maintain cleanliness of the smaller assemblies, manpower can be divided into small teams and scheduled more efficiently (different tasks on different bundles simultaneously), component assembly and installation can be coordinated more effectively thus minimizing the need for clean storage space, experience gained in assembling the first few bundles can be applied to later ones, and it fits better with our past experience. Test firing of completed bundles can be done as other bundles are being assembled. This could be done in alternate shifts as we did on Nova.

### 6.6.6 Ability to do Early Operational Testing

A small bundle unit might allow a full bundle prototype to be built that could provide early data to check and refine the design. If we do not have the resources to do this, the possibility still exists of building one bundle in the facility early with prototype or first off production components. Such tests would be invaluable in checking all of the subsystems and how well they work together. They would provide the opportunity to do operation testing of the control system, a critical element in making the system operational and one that is likely to require extensive debugging. They would also give us experience during which we could develop activation procedures and train personnel who would become the leaders when full system activation begins. Although it has been proposed, testing of a subsection of a 4x12 module would require that much more hardware be installed, would require special partitions and hardware, and would be of less value because it would necessarily occur later in the construction schedule.

### 6.6.7 Activation Summary

The NIF is a much larger and more complex facility than any of our previous ICF lasers. In considering beam bundles one should not lose sight of the fact that each aperture in a bundle will have to be aligned, monitored and maintained; by present count 192 in all. None of us can predict how easy or difficult it is going to be to activate and maintain 192 beams but with only a few of our usual problems it can become a monumental task. It is important in optimizing the facility that features that make activation, operation, and maintenance easy be seriously considered. We want to build a facility that can soon begin shooting a few shots per day and not one that will take years to make operate properly or is down continuously for maintenance. For this reason we should place a premium on issues like the ability to establish and maintain clean optics, a safe working environment, and easy access to components. The ability to do single bundle tests as early as possible is important to uncover the problems we are going to encounter with the full machine to give ourselves as much time as possible to solve them. All of these factors lead to the smaller bundle sizes we are considering. Side access for adjustments and maintenance is a particularly attractive feature that can be easily incorporated into both the 2x2 and 4x2 designs.

Activation risk was estimated in a similar fashion to operability/maintainability with weighting applied to six criteria. The weighted ranking numbers are shown in Table 6-8, with the backup material included in Appendix D. Smaller arrays have several advantages during activation. The smaller bundle size permits a first production unit to be installed and activated early. From this exercise, one can refine the activation procedures, train personnel who will later lead the activation teams, and do operational testing of a bundle unit. The smaller bundle sizes will be assembled and activated in smaller units making it easier to establish and maintain cleanliness, efficiently schedule component assembly and installation, and use manpower efficiently (different tasks can be carried out on different beamlines simultaneously). The improved access to individual components simplifies the installation, adjustment, and testing steps. As individual bundles are completed, they would be sealed with beam tubes to maintain cleanliness and could be test fired as other bundles are being assembled. This permits a phased activation of the facility as was done with Nova.

# Table 6-8. Estimate of the change in activation risk with bundle size.

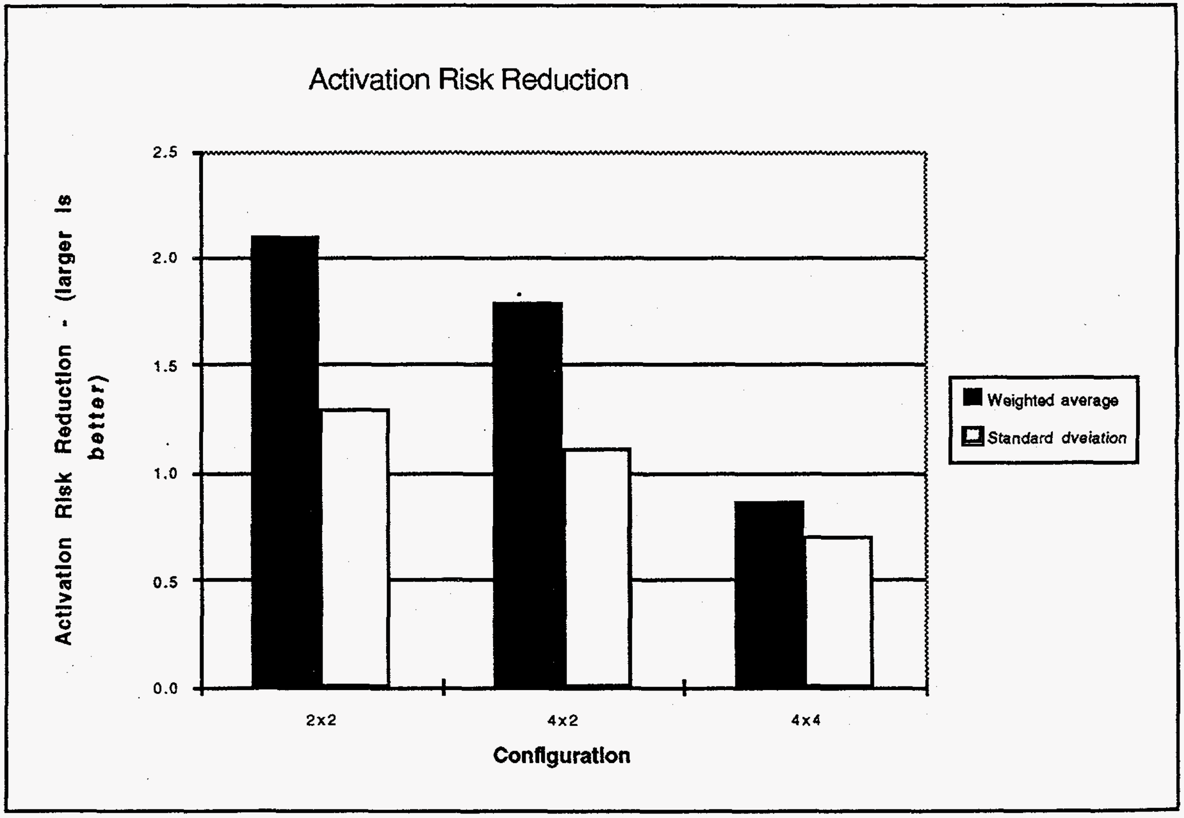
Activation risk

| WBS | Description | Estimator | Activation risk | | |
|---|---|---|---|---|---|
| | | | 2x2 | 4x2 | 4x4 |
| | Weighted average | | 2.1 | 1.8 | 0.9 |
| | Standard Deviation | | 1.3 | 1.1 | 0.7 |
| 1.1 | Project Office | none | 0.0 | 0.0 | 0.0 |
| 1.2 | Facility | Foley | 0.0 | 0.0 | 0.0 |
| 1.3 | Laser | | 0.0 | 0.0 | 0.0 |
| 1.3.1 | Pulse generation | Larson | 2.3 | 2.3 | 0.4 |
| 1.3.2 | Amplifier | Erlandson | 1.9 | 1.2 | 0.6 |
| 1.3.3 | Spatial filter | Horvath | 3.8 | 3.3 | 2.0 |
| 1.3.4 | Cavity mirror mounts | Horvath | 2.1 | 1.7 | 1.3 |
| 1.3.5 | *Transport mirror mnts* | Horvath | 2.8 | 2.1 | 1.5 |
| 1.3.6 | Pockels cell | Larson | 1.8 | 1.8 | 0.2 |
| 1.3.7 | Polarizer mount assy | Horvath | 2.8 | 2.1 | 1.5 |
| 1.3.8 | Interstage hardware | Horvath | 3.6 | 2.9 | 1.3 |
| 1.3.9 | Final optics | none | 0.0 | 0.0 | 0.0 |
| 1.3.10 | Structural supports | Horvath | 0.0 | 0.0 | 0.0 |
| 1.3.11 | Auxiliary systems | Hackel | 0.5 | 0.5 | 0.0 |
| 1.3.12 | Power conditioning | Larson | 1.8 | 1.6 | 0.0 |
| 1.3.13 | Beam control | Hackel | 2.4 | 2.4 | 1.5 |
| 1.4 | Target area | none | 0.0 | 0.0 | 0.0 |
| 1.5 | Computer control | Tietbohl | 1.8 | 1.8 | 1.2 |
| 1.6 | Optical components | Murray | 1.1 | 0.7 | 0.4 |

Ranking Scale

| | |
|---|---|
| *Significant risk reduction* | 5 |
| | 4 |
| Moderate risk reduction | 3 |
| | 2 |
| Slight risk reduction | 1 |
| No impact | 0 |
| Slight risk increase | -1 |
| | -2 |
| Moderate risk increase | -3 |
| | -4 |
| Unacceptable risk | -5 |

Rating parameter: Risk associated with installing and activating hardware relative to baseline



## 6.7 Design Flexibility (committee issue #7)

We compared the change in design flexibility with bundle size for a number of issues, which is shown in Table 6-9. Smaller arrays have increased potential to accommodate design features we might wish to add later in the design process after the basic size of the building is frozen, such as beam expansion. Smaller arrays are also more compatible with staggering the position of beamlines to optimize the distances to the target chamber. A second target chamber that might use only a smaller subset of the beams is more easily accommodated. Smaller unit assemblies that can be constructed off-site and trucked in a more finished state will make final assembly of the system easier and possibly cheaper, as discussed previously.

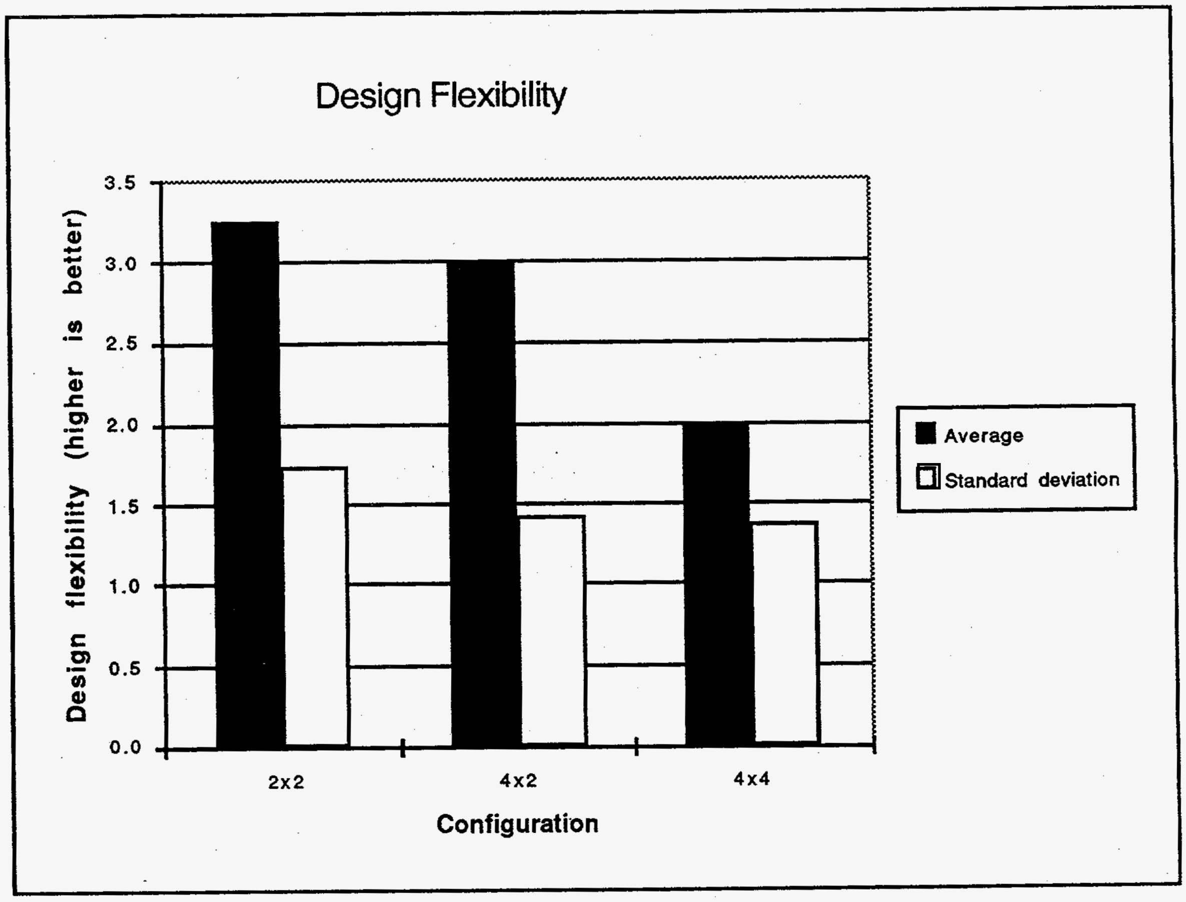
We estimated that the 2x2 and the 4x2 configurations have much better design flexibility than the baseline, and the 4x4 bundle is also better but to a lesser degree.

## Table 6-9. Estimate of the change in design flexibility with bundle size.

Design Flexibility Relative to Baseline

| WBS | Description | Estimator | Design flexibility | | |
|---|---|---|---|---|---|
| | | | 2x2 | 4x2 | 4x4 |
| | Average | | 3.3 | 3.0 | 2.0 |
| | Standard Deviation | | 1.7 | 1.4 | 1.4 |
| 1.3 | Beam Expansion | all | 5 | 4 | 3 |
| 1.3 | Direct Drive | all | 2 | 1 | 0 |
| 1.3 | Spatial filter length | all | 0 | 0 | 0 |
| 1.3 | Constructability | all | 3 | 3 | 3 |
| 1.3 | Second chamber | all | 2 | 2 | 1 |
| 1.3 | Beamline staggering | all | 1 | 2 | 1 |

Rating parameter: Flexibility to adapt to changes to requirements and potential technology advances.



## 7.0 Recommendations

### 7.1 Majority Recommendations: Change to a 4x4

The committee agreed in general that smaller is better for many reasons when considering bundle size. However, when considering the cost of a smaller bundle versus benefits obtained, the committee was somewhat divided. The majority of the committee (~80%) felt that there are sufficiently compelling reasons to change the NIF CDR baseline design to the 4x4 bundle configuration. The increase in PACE costs is small (~$22M, no escalation, no contingency) in comparison to the total project cost ($583M, same basis), which seemed reasonable in light of the various improvements that would be realized. These improvements include:

- Easier installation of many components due to a module size that is fabricatable in vendor shops, more easily handled, and requires less fabrication in-situ.

- Better access along the beamline for improved maintenance, operation, and activation due to the added aisles. This allows sideways removal of polarizers, Pockels cells, mirrors, and possibly pinhole positioners in 1x2 modules. These operations for the baseline design are more difficult.

- A slight reduction in perceived system performance risk due to the smaller module size compared to the baseline.

- Minimal effect on changing the present NIF project schedule due to the relatively small change from the baseline design. Effort needed to reach the post-CDR design status for this alternate bundle concept is small.

- Significantly reduced exposure to hardware failure due to the smaller spatial filter volume. Reducing bundle components by 1/3 significantly reduces the cost of recovering from an unexpected catastrophe.

- Easier access for maintenance on spatial filter lenses, which are the largest potential maintenance items in the baseline design.

- Quicker vent/pump cycle on spatial filters due to the smaller volume. It may be possible to replace spatial filter lenses within a shot cycle due to the smaller spatial filter volume. If not, the system beam loss due to a complete bundle loss is ~8%, which is 1/3 of the baseline loss and is a more desirable amount from a target-shooting viewpoint. Replacement of a spatial filter lens in the baseline design will likely cause a lost shot due to the length of time to vent/pump the spatial filter volume. It should be noted that the baseline spatial filter could be segmented to achieve the same vent/pump advantage.

- An increase in the ability to expand the beams using wedged lenses. This is significantly more difficult in the baseline design.

It should be noted that the committee felt that the bottom loading amplifier concept as presented in the CDR is a reasonable and viable design. The successful demonstration of this concept for maintenance will save significant operational manpower in the long-term. Reducing the baseline bundle size to a 4x4 size still allows this concept to be utilized.

### 7.2 Minority Recommendations: Change to a 4x2 or 2x2

Based on our evaluations it is clear that smaller bundle size is more desirable from all aspects except for cost. Since this review was predicated on evaluating three fixed options, the optimum choice was not necessarily presented as an option. Although the 4x4 bundle provides a percentage of the majority of issues that are considered improvements it appears that further reduction of bundle size would provide significant additional benefits.

Additional reduction in the size of the spatial filters could significantly improve beam availability. Considering that the spatial filters will contain significant numbers of actuators, position sensors, injection optics, diagnostic pickoff optics, transmission windows, and high fluence optics, they may be one of the highest maintenance items on the system with a large impact on availability. Smaller filters that do not require personnel entry (such a 4x2 with side access) reduces the risk of contamination and improves safety and possibly reduces time and manpower associated with confined space procedures and permits. Reducing the need of this type of maintenance is highly desirable.

Based on input from target experimentalists, any system failure or maintenance activity that takes down 4% of the beams or more may have a significant impact on certain target experiments (see Section 6.4.4 Availability). It will likely be very difficult to simply change to a different type of experiment. It may take up to several days to configure the system for a specific type of experiment. The system should be designed to provide for maximum availability. Outside users paying for experiments will demand high availability having invested significant time and expense in their preparation for NIF time.

Smaller bundles also reduce the extent and impact of mistakes during maintenance and operations. When servicing a mirror, polarizer, or Pockels cell assembly limiting exposure to neighboring components is highly desirable in the event of failure of a maintenance fixture, mishandling of components, etc. Contamination due to beam misalignment and clipping is also further limited with smaller bundles.

Interacting with smaller groups of support assemblies for mirrors, polarizes, etc. during maintenance reduces the effect on other beamlines from disruption of noble gas enclosures, vibrations and movement incurred during maintenance. Servicing one item of a large array may require realignment of the entire array.

Another area that was not fully evaluated is the ability to fire fractions of the system thereby increasing shot rate. Input from the target experimenters indicates that 20% to 50% of the total annual target experiments could benefit from firing a fraction of the system (25% to 50% of the beams) with improved turn around time. With smaller bundles the distribution of beams on target could be more uniform. These types of shots could be useful for anything that does not require 1.8 MJ of balanced power on target, such as timing, diagnostic tests and calibrations, and a host of others. This may also be useful for laser diagnostic calibrations.

## 7.3 Minority Recommendations: Remain with the Baseline Design

Smaller bundles have lower risk, greater flexibility, easier access, and less uncertainty than larger bundles: there is general agreement on these conclusions. They extend down even to 1x1 designs. Any disagreements arise in the evaluation whether the disadvantages of large bundles are so severe that they justify the increased cost of small bundles, the evaluation of whether those additional funds are available, and some judgment whether the increased funding (if available) should be applied to reducing bundle size or applied elsewhere.

Table 7-1 shows an example of a different choice of where additional funds might be applied compared to the increased costs of the smaller bundles we considered. The 240-beamlet CDR design, compared using the same cost numbers as used here (bare hardware and facility unescalated, no contingency, no activation or project office, etc.) is about $63M more expensive than the 192-beam baseline, therefore, roughly the same cost as a 192-beam 4x2 system and measurably less than a 2x2. The 240-beamlet system gives a 25% increase in laser system capability or a corresponding decrease in the severity of laser operating conditions for the same net energy on target, which could be much more valuable than the advantages of the smaller arrays.

**Table 7-1. Comparison of cost deltas between baseline 192-beam configuration presented in the CDR and other laser options.**

| | 192 CDR baseline | 2x2 | 4x2 | 4x4 | 240 CDR baseline |
|---|---|---|---|---|---|
| | (base PACE cost) | (+D from 192-beamlet base cost) | | | |
| Facility | $114M | $42M | $34M | $15M | $14M |
| Laser | $372M | $36M | $22M | $ 7M | $49M |
| Total D | $ 0M | $78M | $56M | $22M | $63M |

There are significant design and development tasks that must be completed for the large arrays before the perceptions of high risk will dissipate that are the cause of the concern with the baseline design. These include:

- Demonstration of clean assembly in place for the amplifier. A fairly detailed concept exists, but there remain many questions about its success since it has not yet been proven in practice.

- Detailing and demonstration of techniques to install and service other components, such as Pockels cells, polarizers, and mirrors. There has been much less work on concepts for these components. It is easy to see how these components could be serviced in the smaller arrays (even in the 4x4 bundle). In the absence of these concepts, people may favor the small arrays because the uncertainties are much smaller.

- Elimination of the risk of catastrophic failures that damage an entire bundle. A lens implosion is the obvious example. Probably the only acceptable solution for this type of failure is to eliminate the risk by reducing the stress on the lens and instituting operational safeguards that do not allow the critical crack size to be exceeded, so this will not be a problem in the final system (although it may cause a significant increment in operating cost and a decrease in laser performance). Less serious failures, such as the flashlamp explosion, could be limited by subdividing beam tubes and spatial filters to reduce the number of beamlets that can interact with each other. This will cause a minor cost increase and might impede certain kinds of component access, but will probably be necessary.

- Reduction of the perceived uncertainties in the operability of large arrays. If a large array takes much longer to service, has much worse cross-contamination or other interactions between beamlets, and takes down a quarter of the system for every minor problem that occurs, then there will be a significant and probably unacceptable impact on operations. There is considerable disagreement whether these perceived liabilities are real, but no agreement at present on how to resolve the issue.

The 4x4 concept evaluated here is not a large change from the monolithic 4x12 baseline design and should be considered to be an evaluation, as part of advanced conceptual design, of the most cost-effective and efficient way to subdivide and activate the 4x12 rather than a "change in the baseline." If it is cheaper and more convenient to fabricate large 4x4x9 amplifier frame arrays or 4x4 sections of spatial filter vessel off-site rather than assembling them in place (as in the CDR design), then those changes should be made.

## 8.0 Alternate Beam Layout: In-Line 4x2 Concept

Although the smaller bundle sizes (2x2 and 4x2) are notably more costly than the 4x4 bundle, they have distinct advantages over the 4x4 bundle with respect to constructability, activation, operability, and maintainability. The 4x2 concept also has the best component access along the length of the laser: any component can be removed laterally if desired in a one-component-deep assembly. In light of the general conclusion that smaller bundles are better, we felt compelled to review the NIF project costs (shown in Table 6-1) and determine whether they could be reduced to better justify a smaller bundle size (2x2 and 4x2) from a cost standpoint. The largest cost drivers are the building, amplifier, spatial filter, structural supports, and power conditioning. The amplifier and power conditioning cost estimates for the 2x2 and 4x2 concepts are essentially fixed with bundle size, but the other items are dependent on the bundle layout. The 4x2 amplifier estimate is ~$20M less than for the 2x2 (this cost difference will exist for any layout), which makes the 4x2 the more appealing low cost choice, providing the other cost drivers can be reduced.

As a result we developed another 4x2 bundle concept using an alternate beam layout in the building, which is shown in Figure 8-1. This is essentially the same in-line building concept that the French are considering for their LMJ laser. This concept allows a reduction in the length of the "switchyard" that the beams must traverse on the way to the target room, which allows a shortening of the transport spatial filters and hence a shortening of the laser bays. In addition, the 4x2 bundle configuration developed for the comparison included a multi-level floor design in the laser bay, which is a large cost increasing factor. We eliminated this concept for the alternate 4x2 bundle to reduce laser area structural support costs. The capacitor banks are thus located in the same location as in the baseline 4x12 building layout. Although not studied, this configuration allows staggering of the bundles if desired for improved beam path length adjustment. Beam path length equalization was not applied to the in-line system. Refinements in this regard may further increase switchyard and building costs.

The amplifier concept for this 4x2 arrangement is assumed to be one of three concepts: the same bottom loading concept as in the baseline 4x12 design, a top loading amplifier concept which is simply an upside-down version of the same concept, or a Beamlet-type side-access concept already discussed in Section 5.1. The cost estimates of these three amplifier concepts are approximately the same (within the error bars of this exercise), as well as the costs of the associated structural supports. The amplifiers would be located at approximately the same height above the concrete base slab as in the baseline design for all three configurations.

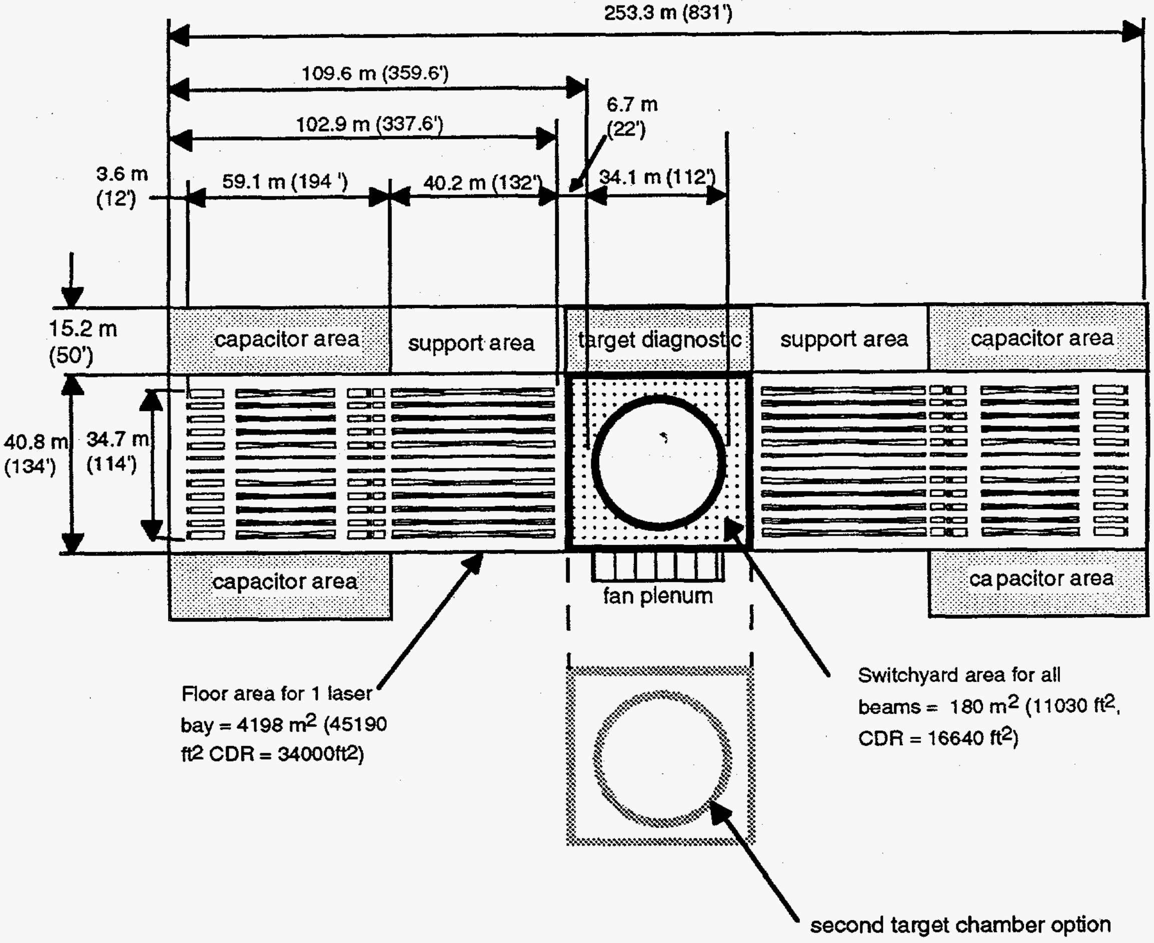


Figure 8-1 Plan layout of an in-line 4x2 bundle concept.

## 8.1 Alternate LTAB

The baseline LTAB configuration is a U-shaped facility with two laser bays, four capacitor bank areas, two switchyards, a cylindrical target area, a central facility support area, and a target diagnostic area. The alternate LTAB design that was evaluated is a linear configuration with laser bays at opposing ends of the target area, as shown in the figure. The following facility assumptions were used:

- Laser bays are increased in width from 80 to 134 feet.
- Laser bays are decreased in length from 425 to 338 feet.
- Laser bay heights remain the same.
- The central support areas which house control rooms, MOR, capacitor banks, and utilities are located along the length of the two laser bays, but with the same net area.
- The exterior capacitor bank areas remain the same.
- Switchyards change from two 80 by 100 foot rooms to a 156 by 134 foot room surrounding the target room cylinder.

- Switchyard has a lightweight truss/sheathing roof covering the entire target room cylinder.

A roof covering the target cylinder was not in the baseline building cost, but was identified as an item that may need to be added due to the concern about meeting optic stability requirements. This shielding from wind and solar loading allows a greater likelihood of meeting target area optic stability requirements and also allows the switchyard supports to use the target room walls for lateral support.

The modifications to the costs for this alternate LTAB are included in Table 8-1. Because this configuration is significantly different from the baseline design, construction details will vary and a more detailed evaluation will be required in order to validate these estimates.

**Table 8-1. Cost estimate of the difference in LTAB cost between the in-line 4x2 and the 4x12 baseline.**

| | Baseline 192 CDR K$ | 4×2 Configuration K$ | Cost Change K$ |
|---|---|---|---|
| Laser bays & support areas (width only) | 53,268 | 72,678 | 19,410 |
| Laser bays (length decrease 425 to 338) | — | (14,877) | (14,877) |
| Relocation of support areas (extra walls) | | 1,000 | 1,000 |
| Switchyard (target areas and diagnostics) | 36,546 | 34,116 | (2,430) |
| Sub Total | 89,814 | 92,917 | 3,103 |
| A-E | 10,780 | 11,150 | 370 |
| CM and integration | 13,230 | 13,658 | 428 |
| Total | 113,824 | 117,725 | 3,901 |

## 8.2 Spatial Filter

The in-line 4x2 spatial filter system is $6,002K less than the 4x12 baseline due to a reduction in length of spatial filters and the economies of assembly. This is based on the assumption that the cost of the vessel portion of the construction cost will be reduced by 40% of the difference in cost calculated by using a length ratio (i.e., cost is not proportional to 100% of the length difference). The spatial filter system is supported on its own structure from grade level in this calculation.

## 8.3 Structural Supports

The structural support system cost is increased by $5,408K over the 4x12 baseline. The differences between the U-shaped 4x2 and the in-line 4x2 structural systems lie mainly in the switchyard configuration and in the elimination of the concrete multi-deck structure in the laser bays. A structural system similar to the baseline is assumed in the laser bays. Its cost scales as laser system width as do the 4x4 and 2x2 systems. The switchyard cost is estimated by calculation of the total floor area of the single structure that is now substituted for the two switchyards in the 4x12. The single switchyard covers an area of 11,050 square feet. The two switchyards in the baseline covered 12,000 square feet. This produces an $875K savings. This is based on a conservative assumption of area to accommodate diagnostic systems and it does not account for the potential benefit of lighter structure due to the stiffening effect of linking to the target room cylindrical wall.

## 8.4 Total Cost Difference

The total cost differences between the in-line 4x2 concept and the 4x12 baseline design is shown in Table 8-2. The cost above the baseline for the original 4x2 concept discussed previously reduces from ~$56M to ~$20M for the in-line 4x2 concept. This is because the building cost reduces from ~$34M above the baseline in the original 4x2 concept to only ~$4M more, the spatial filter cost dropped from ~$3.5M less than the baseline to ~$6.0M less (more of a credit), and the laser structural supports reduces from about $12M more to about $5M more.

**Table 8-2. Cost difference between the in-line 4x2 concept and the 4x12 baseline.**

Cost Delta Relative to Baseline - PACE

| WBS | Description | Estimator | Delta K$ |
|---|---|---|---|
| | | | In-line 4x2 |
| 1 | Project | | $19,796 |
| 1.1 | Project Office | none | |
| 1.2 | Facility | Foley | $3,900 |
| 1.3 | Laser | | |
| 1.3.1 | Pulse generation | Larson | ($500) |
| 1.3.2 | Amplifier | Erlandson | $4,146 |
| 1.3.3 | Spatial filter | Horvath | ($6,002) |
| 1.3.4 | Cavity mirror mounts | Horvath | $330 |
| 1.3.5 | Transport mirror mnts | Horvath | $314 |
| 1.3.6 | Pockels cell | Larson | $2,530 |
| 1.3.7 | Polarizer mount assy | Horvath | $220 |
| 1.3.8 | Interstage hardware | Horvath | $420 |
| 1.3.9 | Final optics | none | |
| 1.3.10 | Structural supports | Horvath | $5,408 |
| 1.3.11 | Auxiliary systems | Hackel | $0 |
| 1.3.12 | Power conditioning | Larson | $8,930 |
| 1.3.13 | Beam control | Hackel | $100 |
| 1.4 | Target area | none | $0 |
| 1.5 | Computer control | Tietbohl | $0 |
| 1.6 | Optical components | Murray | $0 |

Rating parameter: Total cost differential in FY 94 dollars.
No contingency. No escalation.

There is a concern about whether there is sufficient space in the switchyard in the in-line 4x2 concept to accommodate beam redirection to the target chamber or to a second target chamber. Issues must be addressed in more detail such as maintaining beam polarization, verifying beam path lengths, and consideration of space for turning mirrors and relay transport spatial filters. An initial review (see Figure 8-2) indicates that the space to accommodate all of these issues may be too small, but this needs to be verified in a more detailed 3-D CAD study. If a larger switchyard is needed, the switchyard building would need to be larger, the required structural supports would increase, the spatial filter length could increase, and the laser bay length would increase. All of these are cost increasing factors, which would make this option more expensive than the $20M estimated.

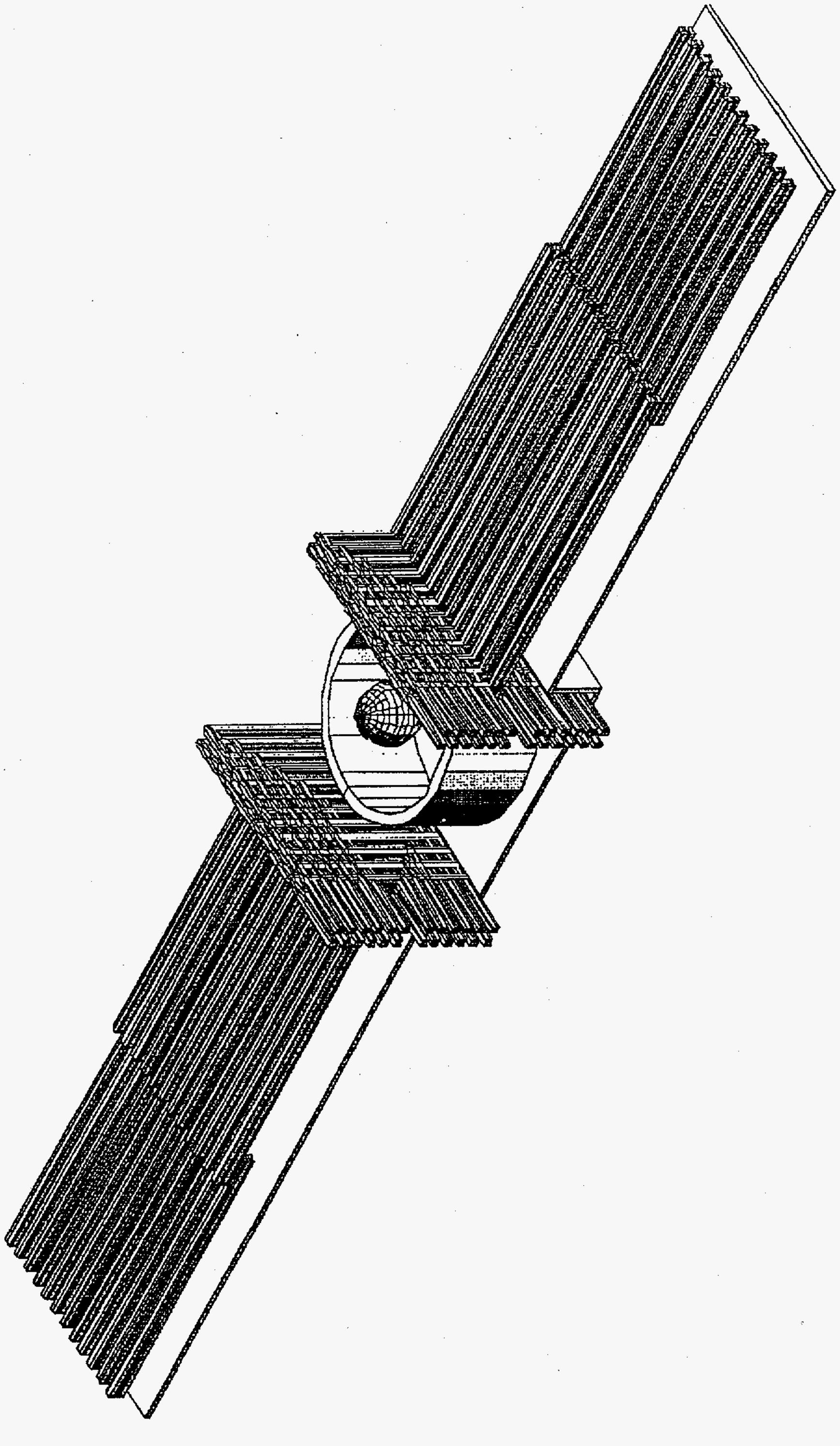


Figure 8-2 Preliminary In-line 4x2 Concept

## 8.5 Alternate Beam Layout Recommendation

Although review of the in-line building layout was not part of this committee's charter, investigation of this design alternative as a method of reducing the system cost seems attractive. The opinion of the committee is somewhat split with respect to the motivation for this additional work. Some members would use the potential cost savings to justify a change in the baseline bundle configuration to the smaller 4x2, rather than the previously recommended 4x4. The primary motivation for this change is the perception that the 4x2 has sufficiently greater operational advantages than the 4x4 (each beamline could be directly accessed by operations personnel). Others on the committee contend that much of the potential savings associated with the in-line design could also apply to the 4x4 or other bundles, and should simply represent a potential improvement to the previously recommended bundle design. In either case, a more detailed design and CAD model should be developed and a more thorough cost estimate completed to verify that this is a viable option. The magnitude of this effort is a small increment to the original bundle review effort, and could be completed well within the one month time frame allocated for a decision by the review committee.

## References

1. Kilkenny, J., Lindl, J., Paisner, J., Powell, H., "Review of NIF Laser and Target Area Baseline Design", ICF Program memo L-19578-1, May 26, 1995.

2. National Ignition Facility Conceptual Design Report, UCRL-PROP-117093, NIF-LLNL-94-113, L-169731, May, 1994.

3. "The National Ignition Facility Project," J.A. Paisner, E.M. Campbell, and W.J. Hogan, Fusion Technology 26, 755 (1994).

# Appendices

## Appendix A - Site and Conventional Facilities

The Laser and Target Areas Building (LTAB) baseline design consists of two laser bays—each bay being 80 feet wide by 425 feet long and 34 feet high at the base of the bridge crane. The two switchyards are each 80 feet wide by 100 feet long with a height of 84 feet. The facility also includes a target area, capacitor rooms, support areas and equipment space. The baseline cost for this facility included construction cost at $90M, A-E design ($10.8M), and Construction Management and Integration ($13M) for a total building cost of $114M (no escalation, no contingency). An assessment of the cost, schedule and operational variances from the baseline building configuration was made for each of the proposed amplifier bundle designs.

The cost estimates were based on the material and labor breakdown categories used in the 192-beam CDR cost data sheets. This method allows for cost estimates to be based on the increased materials, labor and construction complexity rather than using average square foot costs, which will vary greatly due to the wide variation in the quality of facility space.

### A.1 Evaluation Basis

The separate facility configurations were evaluated, and compared to the baseline 192 beam CDR LTAB. The evaluations were based on the following assumptions for each configuration:

The 4×4 amplifier bundle:
- Each laser bay was increased in width from 80 feet to 96 feet, with the length and height remaining the same.
- The switchyards were also increased in width from 80 feet to 96 feet.
- Open grate platforms were installed in the aisles between the amplifier and spatial filters.

The 2×2 amplifier bundle:
- Laser bays were increased in width from 80 feet to 126 feet
- Laser bay lengths were increased from 425 feet to 474 feet.
- Laser bay height remained the same.
- Switchyard width was increased from 80 feet to 126 feet.

The 4×2 amplifier bundle:
- Laser bays were increased in width from 80 feet to 134 feet
- Laser bay lengths were increased from 425 feet to 474 feet.
- Laser bay height remained the same.
- Capacitor bank areas outside of the laser bays were deleted.

- Additional floor levels were added.
- Switchyard widths were increased from 80 feet to 116 feet.
- Support areas between the laser bays were decreased in width from 100 feet to 66 feet.
- Additional utility space was added for mechanical and electrical equipment

The LTAB facilities costs do not include additional shear walls or floors that are used as structural support for the special equipment (amplifiers, etc.). These costs and discussions are included in Section 2.2.10.

### A.1.2 Assessment of LTAB Modification

#### A.1.2.1 4x4 Amplifier Bundle

The LTAB facility modifications required for this configuration are virtually the same as those studied for the CDR 240 beam case, which required the laser bays and switchyard to be 100 feet wide. The HVAC, structural, electrical and architectural equipment, material and labor have been previously costed. The only additional cost added was for the grated platforms in the aisles between the amplifiers and spatial filter. Table A-1 summarizes this cost and provides a comparison with the baseline.

**Table A-1**

| | Baseline 192 CDR K$ | 4×4 240 Beam CDR K$ | Cost Change K$ |
|---|---|---|---|
| Laser bays & support areas | 53,268 | 60,457 | 7,189 |
| Switchyard (target areas and diagnostics) | 36,546 | 40,509 | 3,963 |
| Platforms | — | 850 | 850 |
| A-E | 10,780 | 12,116 | 1,336 |
| CM and integration | 13,230 | 14,336 | 1,106 |
| Total | 113,824 | 128,268 | 14,444 |

The complexity of the construction for this configuration will be slightly less than for the baseline design because of the improved airflow paths created by the aisles separating the bundles. This will improve the thermal stability and constructability of the LTAB. The schedule will not be affected by this configuration.

### A.1.2.2 2x2 Amplifier Bundle

In addition to the added area to the laser bays from the increased width and length, the size and number of HVAC units and corresponding electrical equipment will increase, thus requiring additional utility space. The openness of this design will provide significant improvements in the ability to achieve air flow distribution for improving the cleanliness and temperature stability. The constructability and installation scheduling are improved by the modularity of the special equipment. The LTAB cost impact of the configuration is presented in Table A-2.

**Table A-2**

| | Baseline 192 CDR K$ | 2×2 Configuration K$ | Cost Change K$ |
|---|---|---|---|
| Laser bays & support areas (width only) | 53,268 | 69,802 | 16,534 |
| Laser bays (length increase) | — | 8,016 | 8,016 |
| Switchyard (target areas and diagnostics) | 36,546 | 45,660 | 9,114 |
| A-E | 10,780 | 14,817 | 4,037 |
| CM and integration | 13,230 | 18,151 | 4,921 |
| Total | 113,824 | 156,446 | 42,622 |

### A.1.2.3 4x2 Amplifier Bundle

This configuration will require extensive modifications to the baseline LTAB. Additional area has been included in the laser bays by increasing the width and length and the switchyard by an increase in the width.

The addition of floor structures for support to the laser components has increased the complexity of the HVAC ducting network, required additional elevators for equipment movement and stairwells. The capacitor banks have been moved to the lower level of the laser bays which eliminates some lower cost areas in the baseline design. The support space between the laser bays has also been reduced in width. This reduction has the effect of decreasing floor space but also creates difficulty with the placement of mechanical and electrical equipment which is located on the mezzanine level above this central area. To accommodate the mechanical and electrical equipment requirements, additional utility space has been included.

The thermal stability will probably be increased over the baseline by the additional HVAC ducting. However, to achieve the required vibrational stability, a significant amount of design and construction inspection effort will be required to eliminate vibration sources from the HVAC and increased structure.

The LTAB constructability, schedule and integration will be effected by this more complex structure. The net schedule increase is estimated at two months.

The LTAB cost impacts for this configuration are included in Table A-3.

**Table A-3**

| | Baseline 192 CDR $K | 4×2 Configuration $K | Cost Change $K |
|---|---|---|---|
| Laser bays & support areas (width only) | 53,268 | 72,678 | 19,410 |
| Laser bays (length increase) | — | 8,525 | 8,525 |
| Capacitor bank (delete) | ---- | (3500) | (3500) |
| Central support (reduced) | --- | (2890) | (2890) |
| Utility support space | --- | 1445 | 1445 |
| Switchyard (target areas and diagnostics) | 36,546 | 40,509 | 3,963 |
| A-E | 10,780 | 14,012 | 3,232 |
| CM and integration | 13,230 | 17,164 | 3,934 |
| Total | 113,824 | 147,774 | 34,119 |

## Appendix B Laser Components

### B.1 Optical Pulse Generation

Following is the basis for the cost deltas and other grades summarized in the evaluation and comparison charts.

**2x2**

- A credit of $5K was given for each of the 96 PAM beam transport spatial filters eliminated by the 2x2 layout for a total of $500K
- A $100K credit was given for the simpler PAM support structure relative to the baseline
- A -5 rating was given in operability chart due to the reduced access to the PAM in the 2x2 design

**4x2**

- A credit of $5K was given for each of the PAM beam transport 96 spatial filters eliminated by the 4x2 layout for a total of $500K

- The support frame is wider but shorter so no cost delta is assumed
- The layout provides slightly better access to the PAMs than the other designs so a score of +3 was given on the operability chart

**4x4**

- A $200K additional cost was assumed to provide a wider support frame for the PAMs.
- A +2 rating was given in operability for the slightly improved access due to the aisles between bundles

## B.2 Amplifier Segments

The following chart summarizes hardware costs for the 4x12, 4x4, 4x2, and 2x2 amplifiers. These costs include procurement costs for mechanical hardware and flashlamps and manpower to design and install parts. They do not include the procurement costs for the laser slabs, which are included under optics.

| Design | Cost ($K) | Cost delta relative to baseline ($K) |
|---|---|---|
| 4x12 | 35,398 | 0 |
| 4x4 | 36,863 | 1,465 ($1,097/lamp) |
| 4x2 | 38,978 | 3,580 ($1,097/lamp) |
| 2x2 | 52,520 | 17,122 ($ 700/lamp) |

The following three charts break down the cost of the amplifiers by manpower and parts.

**4x12**

| | | Cost ($K) | |
|---|---|---|---|
| | cost/part | # of parts | total cost |
| Side lamp cassette | 11.0 | 152 | 1,680 |
| Central lamp cassette | 12.5 | 836 | 10,450 |
| Slab cassette | 7.6 | 912 | 6,931 |
| Frame assembly unit | 8.7 | 912 | 7,934 |
| Assembly hardware | 1,200 | set | 1,200 |
| Manpower | | | 7,203 |
| TOTAL | | | 35,398 |

**4x4**

| | | Cost ($K) | |
|---|---|---|---|
| | cost/part | # of parts | total cost |
| Side lamp cassette | 11.0 | 456 | 5,041 |
| Central lamp cassette | 12.5 | 684 | 8,550 |
| Slab cassette | 7.6 | 912 | 6,931 |
| Frame assembly unit | 8.7 | 912 | 7,934 |
| Assembly hardware | 1,200 | set | 1,200 |
| Manpower | | | 7,207 |
| TOTAL | | | 36,863 |

**4x2**

| | | Cost ($K) | |
|---|---|---|---|
| | cost/part | # of parts | total cost |
| Side lamp cassette | 11.0 | 912 | 10,082 |
| Central lamp cassette | 12.5 | 456 | 5,700 |
| Slab cassette | 6.4 | 912 | 5,836 |
| Frame assembly unit | 9.7 | 912 | 8,846 |
| Assembly hardware | 1,200 | set | 1,200 |
| Manpower | | | 7,314 |
| TOTAL | | | 38,978 |

**2x2**

| | | Cost ($K) | |
|---|---|---|---|
| | cost/part | # of parts | total cost |
| Aide lamp cassette | 8.2 | 1,824 | 15,000 |
| Central lamp cassette | 9.3 | 912 | 8,390 |
| Slab cassette | 5.7 | 1,824 | 10,397 |
| Frame assembly unit | 58.6 | 192 | 11,251 |
| Assembly hardware | 1,000 | set | 1,000 |
| Manpower | | | 6,482 |
| TOTAL | | | 52,520 |

## B.3 Spatial Filters

The following chart lists the WBS 1.3.3 spatial filter costs broken down into categories.

| | | Cost ($K) | | |
|---|---|---|---|---|
| Category | (4x12) | (2x2) | (4x4) | (4x2) |
| Manpower | 5,974 | 5,257 | 4,779 | 4,779 |
| Vessels | 14,127 | 13,703 | 12,290 | 13,279 |
| Mechanisms | 8,435 | 6,326 | 7,170 | 6,326 |
| Pumping Systems | 1,231 | 1,194 | 1,182 | 1,108 |
| Installation Equip. | 5,000 | 5,000 | 5,000 | 5,000 |
| Vessel Supports | 717 | 933 | 682 | 861 |
| TOTALS | 35,484.3 | 32,413.1 | 31,102.6 | 31,353.5 |

## B.4 Cavity Mirror Assemblies

The following chart lists the WBS 1.3.4 cavity mirror assembly costs showing the distribution of fixed cost and bundle-sensitive costs. The fixed portion relates to Title I, II and III engineering and component-level fabrication and installation. The bundle-sensitive portion relates to array frame fabrication and installation.

| | Cost ($K) | | | |
|---|---|---|---|---|
| Cost Component | (4x12) | (2x2) | (4x4) | (4x2) |
| Fixed Portion | 1,424.00 | 1,424.00 | 1,424.00 | 1,424.00 |
| Variable Portion | 3,974.40 | 4,373.76 | 4,235.52 | 4,304.64 |
| TOTALS | 5,398.40 | 5,797.76 | 5,659.52 | 5,728.64 |

## B.5 Transport Turning Mirrors

The following chart lists the WBS 1.3.5 transport turning mirror mount costs showing the distribution of fixed cost and bundle-sensitive costs. The fixed portion relates to Title I, II and III engineering and component-level fabrication and installation. The bundle-sensitive portion relates to array frame fabrication and installation.

| | Cost ($K) | | | |
|---|---|---|---|---|
| Cost Component | (4x12) | (2x2) | (4x4) | (4x2) |
| Fixed Portion | 4,085.00 | 4,085.00 | 4,085.00 | 4,085.00 |
| Variable Portion | 15,463.68 | 15,853.44 | 15,701.76 | 15,777.60 |
| TOTALS | 19,548.68 | 19,938.44 | 19,786.76 | 19,862.60 |

## B.6 Pockels Cell Assemblies

Following is the basis for the cost deltas and other grades summarized in the evaluation and comparison charts:

**2x2 and 4x2**

- The recurring costs of the vacuum system, switch pulsers and plasma pulsers were added from the CDR. The cost delta for the 1x1 cell was calculated by assuming that the required double number of pulsers and vacuum systems required could be purchased and installed for only 1.5 times the cost of the baseline, since they would require lower capacity.
- These bundle designs received higher maintainability and operability scores since the 1x1 cells are expected to be easier to maintain and align.
- A $500K reduction in the cost of the PEPC CS&T program is assumed since a 1x2 cell would not have to be developed. The savings is lower than one might

expect, however, nearly all of the tasks in the existing development plan are still necessary, though the risk is lower with a 1x1 cell.

**4x4**

No difference is assumed relative to the baseline 4x12 bundle design.

### B.7 Polarizer Assembly

The following chart lists the WBS 1.3.7 polarizer mount assembly costs showing the distribution of fixed cost and bundle-sensitive costs. The fixed portion relates to Title I, II and III engineering and component-level fabrication and installation. The bundle-sensitive portion relates to array frame fabrication and installation.

| | **Cost ($K)** | | | |
|---|---|---|---|---|
| Cost Component | (4x12) | (2x2) | (4x4) | (4x2) |
| Fixed Portion | 886.00 | 886.00 | 886.00 | 886.00 |
| Variable Portion | 2,160.00 | 2,424.96 | 2,334.72 | 2,379.84 |
| TOTALS | 3,046.00 | 3,310.96 | 3,220.72 | 3,265.84 |

### B.8 Interstage and Beam Transport Hardware

The following chart lists the WBS 1.3.8 interstage and beam transport system costs broken into material and manpower components.

| | **Cost ($K)** | | | |
|---|---|---|---|---|
| Cost Component | (4x12) | (2x2) | (4x4) | (4x2) |
| Material | 3,070 | 3,438 | 3,531 | 3,377 |
| Manpower | 901 | 1,171 | 991 | 1,014 |
| TOTALS | 3,971 | 4,610 | 4,522 | 4,391 |

### B.9 Final Optics System

**(Not considered in this review.)**

### B.10 Structural Support System

### B.10.1 Costs

The following chart lists the WBS 1.3.10 structural support system costs itemized by structure type for each bundle size.

| | Cost ($K) | | | |
|---|---|---|---|---|
| Structure Moniker | (4x12) | (2x2) | (4x4) | (4x2) |
| LM1 | 165.36 | 307.91 | 234.02 | 225.96 |
| A1 Amps | 1,377.60 | 2,565.19 | 1,949.62 | 2,520.58 |
| A2 Amps/S | 1,068.88 | 2,023.85 | 1,538.19 | 2,035.65 |
| PL/LM2/LM3 | 508.64 | 947.12 | 719.84 | 525.26 |
| A3 Amps | 982.48 | 1,829.45 | 1,390.44 | 1,740.82 |
| Switchyard | 6,515.54 | 12,132.39 | 9,220.99 | 12,806.41 |
| Concrete Decks | 0.00 | 0.00 | 0.00 | 2,400.00 |
| Title I, II, III Eng. | 4,156.23 | 4,156.23 | 4,156.23 | 4,156.23 |
| TOTALS | 14,792.73 | 23,962.13 | 19,209.33 | 26,410.90 |

The scaling algorithm for structural concrete decks in the 4x2 implementation is based on the assumption that concrete multi-deck structures that meet the same stiffness requirements have the same cost per unit volume of enclosed volume. The cost calculation for the concrete decks in the 4x2 array implementation is calculated as follows:

The enclosed volume of the concrete lower portion of a baseline switchyard structure is 332,900 cubic feet. The weight of that concrete is 3,159,000 lb. Therefore, approximately 9.5 lb. of concrete are required for each cubic foot of enclosed switchyard volume.

The enclosed volume of the deck system in one bay of the 4x2 laser is 1,134,600 cubic feet. The "switchyard-like" deck system weight per bay would be 10,779,000 lb.

Assuming a $300/cubic yard construction cost, the concrete deck system would cost $1.2M per bay or $2.4M total. This construction cost is about $1.06 per cubic foot of enclosed volume.

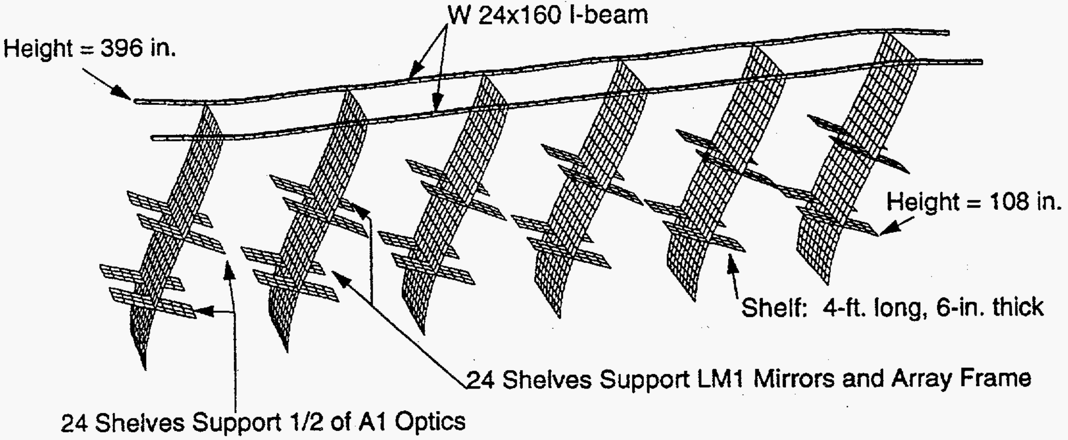
### B.10.2 Finite Element Analyses

The cost of construction for the 2x2 laser support system was based on the assumption that the overall cost would scale with the width of the enclosed laser beam system. The 2x2 conceptual design was analyzed in the LM1 cavity mirror region to ascertain the degree of difference in structural efficiency of the support concept and to estimate the ramifications of required upgrades to structures in portions of the laser chain other than the LM1 region.

The following finite element analyses illustrate the sensitivity of the first fundamental frequency of the LM1 region structure to the assumed height above grade. The 4x12 baseline structural system that was shown to meet stability requirements for optics had first mode frequencies around 10Hz. The three iterations verify that additional modifications to the member sizes as presented are needed to bring the 2x2 structures in into the same stiffness category, hence the scaling of baseline costs with system width is justified.

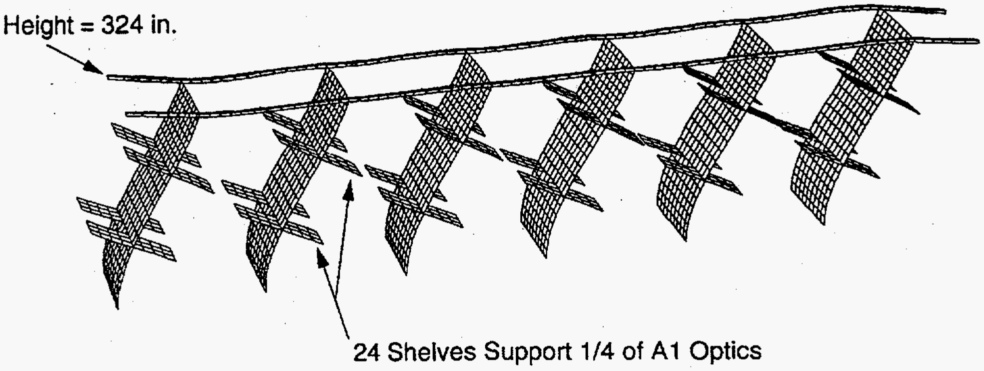
The first iteration uses LM1-region dimensions as presented in the original 2x2 concept sketches. A first mode frequency of 3.28Hz is observed.

- Fundamental Mode - 3.28 Hertz



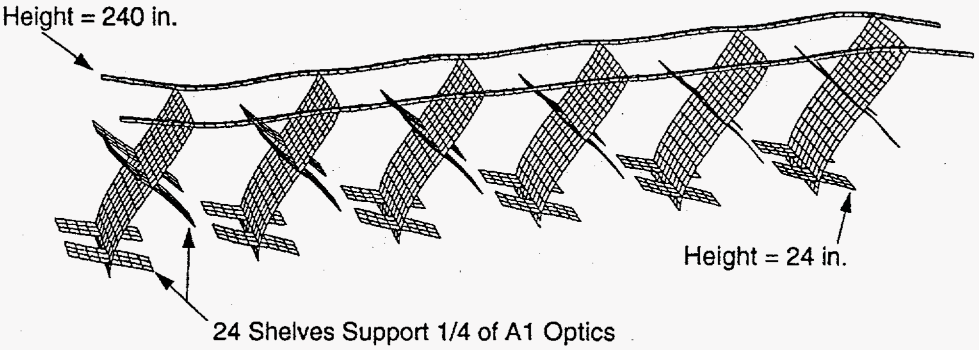
Modifications to system height dimensions relative to grade bring the first mode up to 4.51Hz in the second iteration.

- Fundamental Mode - 4.51 Hertz



Additional changes to the system height dimensions relative to grade bring the first mode of the LM1 region up to 7.82Hz.

- Fundamental Mode - 7.82 Hertz



Similar variations of other parameters as well as a verification of the impact on facility costs of excavating a deeper target area building to accommodate the lowering of system height above grade are needed (refer to Appendix B.10). This is accounted for in the schedule delay for bringing the 2x2 and 4x2 concepts up to the degree of development as the baseline prior to Title I engineering.

## B.11 Laser Auxiliary System

## B.12 Power Conditioning System

Following is the basis for the cost deltas and other grades summarized in the evaluation and comparison charts.

### 2x2

- Additional power conditioning cost is charged to the 2x2 design since the total flashlamp load is greater. The additional stored energy is calculated directly from the ratio of flashlamps in the new design relative to the baseline, divided by 2 since each of the lamps in the 2x2 is half as long. The resulting increase is 20%. The cost of the added bank is calculated by multiplying the additional energy required by the recurring cost of power conditioning from the baseline estimate. This recurring cost is estimated at $0.1/Joule stored. Therefore, the resulting cost delta for the additional energy is $0.1/J x .2 x 320 MJ = $6.4M.

- There is an additional cost penalty for smaller bundle sizes due to the lower utilization of the bank modules. The utilization cost is calculated from: (Total bank energy) x (1-utilization factor normalized to baseline) x (fixed portion of the bank module cost). The "fixed" module costs are those costs not dependent on the number of lamps powered by the module, e.g., the enclosure, switch, charging supply, etc. These are estimated at 30% of the $0.1/J recurring cost. The utilization factor for the 2x2 is 75% (78% normalized to the baseline), and the cost of the lower utilization is estimated at $2.53M. This cost is added to the energy cost in 1 above.

- The 2x2 design receives higher scores than the baseline in operability and activation, due to the improved correlation of bank modules to amplifier bundles. This improved correlation allows activation or operation of a smaller number of beams without firing additional bank modules.

**4x2**

The cost calculations and operability scores described above for the 2x2 apply as well to the 4x2 bundle design. The additional energy requirements and utilization factors are the same in both cases.

- The 4x2 receives a cost credit, relative to the baseline, since the layout results in significantly shorter transmission lines. It is estimated that roughly half of the \$3271K in the baseline estimate for procurement and installation of the T-lines could be saved. A small additional savings is realized since the shorter lines would improve the transfer efficiency from the bank to the flashlamps. This small improvement is calculated by assuming that 10% of the 15% of the energy lost in the baseline would be saved. This fraction, multiplied by the total energy and capacitor cost (\$.03/J) yields an estimated additional savings of \$173K for the 4x2 design. Thus, the shorter T-line runs associated with the 4x2 bundle are estimated to save \$1808K of the project costs.

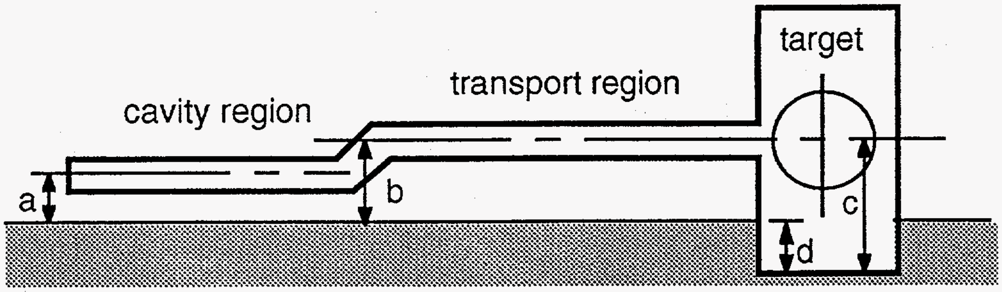
**4x4**

- The 4x4 design requires an additional 8% stored energy to drive the larger number of lamps. Repeating the analysis above yields a cost penalty of \$2.56M.
- The module utilization of the 4x4 design is 81% (84% normalized to the baseline), yielding a utilization cost of \$1.65M.
- The 4x4 design received higher marks than the baseline in operability and activation for the same reasons as the 4x2 and 2x2 designs, but to a lesser extent.

## B.13 Beam Control and Laser Diagnostic

## B.14 Laser Integration

The following figures show the system elevations intrinsic in the bundle implementations:



|  | Value (inches) |  |  |  |
|---|---|---|---|---|
| Dimension | (4x12) | (2x2) | (4x4) | (4x2) |
| a = Beam system centerline elevation in cavity region | 180.0 | 189.6 | 180.0 | 282.5 |
| b = Beam system centerline elevation in transport region | 275.1 | 249.6 | 275.1 | 378.5 |
| c = Target elevation above switchyard bay floor | 492.0 | 492.0 | 492.0 | 492.0 |
| d = Depth of switchyard bay | 216.9 | 242.4 | 216.9 | 113.5 |

# Appendix C Laser Performance

## Weighting factors for activation

Committee issue 6

| WBS | Description | Estimator | Cleanliness | Safety | Accessability | Alignment | Activation staging | Startup | Sum wts |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | | | | | | | |
| 1.2 | Facility | Foley | | | | | | | |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 3 | 3 | 3 | 3 | 3 | 1 | 14 |
| 1.3.2 | Amplifier | Erlandson | 3 | 3 | 3 | 3 | 3 | 2 | 17 |
| 1.3.3 | Spatial filter | Horvath | 3 | 3 | 3 | 3 | 3 | 3 | 18 |
| 1.3.4 | Cavitiy mirror mounts | Horvath | 2 | 2 | 3 | 3 | 2 | 2 | 14 |
| 1.3.5 | Transport mirror mnts | Horvath | 2 | 2 | 3 | 3 | 2 | 2 | 14 |
| 1.3.6 | Pockels cell | Larson | 3 | 3 | 3 | 3 | 3 | 2 | 17 |
| 1.3.7 | Polarizer mount assy | Horvath | 2 | 2 | 3 | 3 | 2 | 2 | 14 |
| 1.3.8 | Interstage hardware | Horvath | 2 | 1 | 2 | 1 | 1 | 1 | 8 |
| 1.3.9 | Final optics | none | | | | | | | |
| 1.3.10 | Structural supports | Horvath | 1 | 1 | 0 | 2 | 2 | 3 | 9 |
| 1.3.11 | Auxiliary systems | Hackel | 1 | 3 | 2 | 0 | 1 | 1 | 8 |
| 1.3.12 | Power conditioning | Larson | 1 | 3 | 3 | 0 | 3 | 3 | 13 |
| 1.3.13 | Beam control | Hackel | 2 | 2 | 2 | 3 | 3 | 3 | 15 |
| 1.4 | Target area | none | | | | | | | |
| 1.5 | Computer control | Tietbohl | 0 | 1 | 1 | 2 | 3 | 3 | 10 |
| 1.6 | Optical components | Murray | 3 | 2 | 3 | 3 | 3 | 3 | 17 |
| Sum wts | | | 28 | 31 | 34 | 32 | 34 | 31 | |

## Activation

**Committee Issue 6**

## 4 x 4 amplifier bundle

| WBS | Description | Estimator | Cleanliness | Safety | Accessability | Alignment | Activation staging | Startup | Wtd ave |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | 0 | 0 | 0 | 0 | 0 | 0 | |
| 1.2 | Facility | Foley | 0 | 0 | 3 | 0 | 2 | 0 | |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 0 | 0 | 1 | 0 | 0 | 2 | 0.36 |
| 1.3.2 | Amplifier | Erlandson | 0 | 0 | 0 | 0 | 2 | 2 | 0.59 |
| 1.3.3 | Spatial filter | Horvath | 2 | 0 | 3 | 1 | 3 | 3 | 2.00 |
| 1.3.4 | Cavitiy mirror mounts | Horvath | 3 | 0 | 0 | 0 | 3 | 3 | 1.29 |
| 1.3.5 | Transport mirror mnts | Horvath | 3 | 0 | 1 | 0 | 3 | 3 | 1.50 |
| 1.3.6 | Pockels cell | Larson | 0 | 0 | 0 | 0 | 1 | 0 | 0.18 |
| 1.3.7 | Polarizer mount assy | Horvath | 3 | 0 | 1 | 0 | 3 | 3 | 1.50 |
| 1.3.8 | Interstage hardware | Horvath | 1 | 0 | 1 | 0 | 3 | 3 | 1.25 |
| 1.3.9 | Final optics | none | 0 | 0 | 0 | 0 | 0 | 0 | |
| 1.3.10 | Structural supports | Horvath | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.12 | Power conditioning | Larson | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.13 | Beam control | Hackel | 0 | 2 | 2 | 1 | 2 | 2 | 1.53 |
| 1.4 | Target area | none | 0 | 0 | 0 | 0 | 0 | 0 | |
| 1.5 | Computer control | Tietbohl | 0 | 0 | 0 | 0 | 2 | 2 | 1.20 |
| 1.6 | Optical components | Murray | 0 | 0 | 0 | 0 | 1 | 1 | 0.35 |
| Wtd ave | | | 0.93 | 0.13 | 0.71 | 0.19 | 1.59 | 1.65 | 0.86 |

## Activation

**Committee issue 6**

## 4 x 2 amplifier bundle

| WBS | Description | Estimator | Cleanliness | Safety | Accessability | Alignment | Activation staging | Startup | Wtd ave |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | | | | | | | |
| 1.2 | Facility | Foley | | | | | | | |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 0 | 3 | 3 | 4 | 0 | 2 | 2.29 |
| 1.3.2 | Amplifier | Erlandson | 2 | -1 | 0 | 1 | 3 | 3 | 1.24 |
| 1.3.3 | Spatial filter | Horvath | 3 | 5 | 4 | 0 | 4 | 4 | 3.33 |
| 1.3.4 | Cavitiy mirror mounts | Horvath | 4 | 0 | 0 | 0 | 4 | 4 | 1.71 |
| 1.3.5 | Transport mirror mnts | Horvath | 4 | 0 | 2 | 0 | 4 | 4 | 2.14 |
| 1.3.6 | Pockels cell | Larson | 0 | 0 | 4 | 3 | 2 | 2 | 1.82 |
| 1.3.7 | Polarizer mount assy | Horvath | 4 | 0 | 2 | 0 | 4 | 4 | 2.14 |
| 1.3.8 | Interstage hardware | Horvath | 4 | 3 | 2 | 0 | 4 | 4 | 2.88 |
| 1.3.9 | Final optics | none | | | | | | | |
| 1.3.10 | Structural supports | Horvath | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 0 | 0 | 2 | 2 | 0.50 |
| 1.3.12 | Power conditioning | Larson | 0 | 0 | 0 | 0 | 4 | 3 | 1.62 |
| 1.3.13 | Beam control | Hackel | 0 | 3 | 3 | 2 | 3 | 3 | 2.40 |
| 1.4 | Target area | none | | | | | | | |
| 1.5 | Computer control | Tietbohl | 0 | 0 | 0 | 0 | 3 | 3 | 1.80 |
| 1.6 | Optical components | Murray | 0 | 0 | 0 | 0 | 2 | 2 | 0.71 |
| Wtd ave | | | 1.68 | 0.97 | 1.62 | 0.94 | 2.74 | 2.81 | 1.79 |

## Activation

**Committee issue 6**

## 2 x 2 amplifier bundle

| WBS | Description | Estimator | Cleanliness | Safety | Accessability | Alignment | Activation staging | Startup | Wtd ave |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | | | | | | | |
| 1.2 | Facility | Foley | | | | | | | |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 0 | 3 | 3 | 4 | 0 | 2 | 2.29 |
| 1.3.2 | Amplifier | Erlandson | 2 | 0 | 1 | 1 | 4 | 4 | 1.88 |
| 1.3.3 | Spatial filter | Horvath | 3 | 5 | 5 | 0 | 5 | 5 | 3.83 |
| 1.3.4 | Cavitiy mirror mounts | Horvath | 5 | 0 | 0 | 0 | 5 | 5 | 2.14 |
| 1.3.5 | Transport mirror mnts | Horvath | 5 | 0 | 3 | 0 | 5 | 5 | 2.79 |
| 1.3.6 | Pockels cell | Larson | 0 | 0 | 4 | 3 | 2 | 2 | 1.82 |
| 1.3.7 | Polarizer mount assy | Horvath | 5 | 0 | 3 | 0 | 5 | 5 | 2.79 |
| 1.3.8 | Interstage hardware | Horvath | 5 | 3 | 3 | 0 | 5 | 5 | 3.63 |
| 1.3.9 | Final optics | none | | | | | | | |
| 1.3.10 | Structural supports | Horvath | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 0 | 0 | 2 | 2 | 0.50 |
| 1.3.12 | Power conditioning | Larson | 0 | 0 | 0 | 0 | 4 | 4 | 1.85 |
| 1.3.13 | Beam control | Hackel | 0 | 3 | 3 | 2 | 3 | 3 | 2.40 |
| 1.4 | Target area | none | | | | | | | |
| 1.5 | Computer control | Tietbohl | 0 | 0 | 0 | 0 | 3 | 3 | 1.80 |
| 1.6 | Optical components | Murray | 0 | 0 | 0 | 0 | 3 | 3 | 1.06 |
| Wtd ave | | | 1.96 | 1.06 | 2.03 | 0.94 | 3.21 | 3.39 | 2.10 |

Ranking Scale

| | |
|---|---|
| Significantly improved over baseline | 5 |
| | 4 |
| Moderate improvement | 3 |
| | 2 |
| Slight improvement | 1 |
| No impact | 0 |
| Slight diminishment | -1 |
| | -2 |
| Moderate diminishment | -3 |
| | -4 |
| Significantly diminished over baseline | -5 |

**Criteria to be ranked**

| | | |
|---|---|---|
| 1 | Cleanliness | Ability to establish and maintain cleanliness of amplifier cavity and beamline optics |
| 2 | Safety | Ability to provide a safe work environment and low risk to components while doing installation and activation tasks |
| 3 | accessability | Ability to reach components for installation, adjustment, and troubleshooting |
| 4 | Alignment | Ability to establish and maintain component and beam alignment |
| 5 | Activation staging | Ability to schedule installation, alignment, and test firing activities |
| 6 | Startup | Ability to do early activation and operational tests of a first off beamline |

## NIF Bundle Size Review: Operability and Maintainability

### Ranking Scale

| | |
|---|---|
| Significantly improved over baseline | 5 |
| | 4 |
| Moderate improvement | 3 |
| | 2 |
| Slight improvement | 1 |
| No impact | 0 |
| Slight diminishment | -1 |
| | -2 |
| Moderate diminishment | -3 |
| | -4 |
| Significantly diminished over baseline | -5 |

### Criteria to be Ranked

| Criteria Numb | Criteria Description | Criteria Definition |
|---|---|---|
| 1 | Safety | Ability to provide a safe work environment and low risk to components while doing maintenance and operations. |
| 2 | Ease/Efficiency | Issues associated with numbers of personnel and special equipment required for maintenance, ability to reach components for adjustment and troubleshooting, time required to perform a given task, etc. |
| 3 | Availability | Ability to complete maintenance between shots, ability to continue significant experiments/operations on remaining active bundles during maintenance or repair, ability to continue with significant operations after system failure prior to and during repair. |
| 4 | Flexibility | Ability to fire a fraction of the system alternately for useful experiments, thereby increasing the shot rate. |
| 5 | Risk of Contamination | The risk of contaminating optical components or systems during maintenance and system operation. |
| 6 | Consequence of Mistake | The effect (magnitude and extent) of a personnel mistake during maintenance and operations. |

## Weighting factors for Operability and Maintainability

| WBS | Description | Estimator | Safety | Ease/Efficiency | Availability | Flexibility | Risk of Contamination | Consequence of Mistake | Sum wts |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | | | | | | | |
| 1.2 | Facility | Foley | 1 | 2 | 2 | 0 | 0 | 0 | 5 |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 2 | 2 | 1 | 3 | 0 | 3 | 11 |
| 1.3.2 | Amplifier | Erlandson | 3 | 3 | 2 | 3 | 3 | 3 | 17 |
| 1.3.3 | Spatial filter | Patton | 3 | 3 | 3 | 3 | 3 | 3 | 18 |
| 1.3.4 | Cavitiy mirror mounts | Horvath | 3 | 2 | 2 | 2 | 3 | 2 | 14 |
| 1.3.5 | Transport mirror mnts | Horvath | 3 | 2 | 2 | 2 | 3 | 2 | 14 |
| 1.3.6 | Pockels cell | Larson | 3 | 2 | 2 | 2 | 3 | 3 | 15 |
| 1.3.7 | Polarizer mount assy | Horvath | 3 | 2 | 2 | 2 | 3 | 2 | 14 |
| 1.3.8 | Interstage hardware | Horvath | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| 1.3.9 | Final optics | none | | | | | | | |
| 1.3.10 | Structural supports | Horvath | 3 | 3 | 2 | 2 | 1 | 0 | 11 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 1 | 1 | 1 | 1 | 4 |
| 1.3.12 | Power conditioning | Larson | 3 | 2 | 2 | 2 | 0 | 1 | 10 |
| 1.3.13 | Beam control | Hackel | 1 | 1 | 2 | 3 | 0 | 0 | 7 |
| 1.4 | Target area | none | | | | | | | |
| 1.5 | Computer control | Tietbohl | 0 | 3 | 3 | 3 | 0 | 2 | 11 |
| 1.6 | Optical components | Murray | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sum wts | | | 29 | 28 | 27 | 29 | 21 | 23 | |

## Operability and Maintainability

## 4 x 4 amplifier bundle

| WBS | Description | Estimator | Safety | Ease/Efficiency | Availability | Flexibility | Risk of Contamination | Consequence of Mistake | Sum wts |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | | | | | | | |
| 1.2 | Facility | Foley | 1 | 1 | 1 | 1 | 1 | 1 | 1.00 |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 0 | 2 | 0 | 0 | 0 | 0 | 0.36 |
| 1.3.2 | Amplifier | Erlandson | 0 | 0 | 1 | 2 | 0 | 0 | 0.47 |
| 1.3.3 | Spatial filter | Patton | 0 | 3 | 3 | 3 | 2 | 3 | 2.33 |
| 1.3.4 | Cavitiy mirror mounts | Horvath | 0 | 0 | 3 | 3 | 2 | 3 | 1.71 |
| 1.3.5 | Transport mirror mnts | Horvath | 0 | 3 | 3 | 3 | 2 | 3 | 2.14 |
| 1.3.6 | Pockels cell | Larson | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.7 | Polarizer mount assy | Horvath | 0 | 3 | 3 | 3 | 3 | 3 | 2.36 |
| 1.3.8 | Interstage hardware | Horvath | 1 | 3 | 3 | 3 | 2 | 1 | 2.17 |
| 1.3.9 | Final optics | none | | | | | | | |
| 1.3.10 | Structural supports | Horvath | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 1 | 1 | -1 | 1 | 0.50 |
| 1.3.12 | Power conditioning | Larson | 0 | 0 | 0 | 2 | 0 | 0 | 0.40 |
| 1.3.13 | Beam control | Hackel | 2 | 2 | 2 | 1 | 0 | 0 | 1.57 |
| 1.4 | Target area | none | | | | | | | |
| 1.5 | Computer control | Tietbohl | 0 | 1 | 1 | 1 | 0 | 1 | 1.00 |
| 1.6 | Optical components | Murray | 0 | 0 | | 0 | 0 | 0 | 0.00 |
| Wtd ave | | | 0.14 | 1.25 | 1.56 | 1.62 | 1.33 | 1.35 | 1.21 |

## Operability and Maintainability

## 4 x 2 amplifier bundle

| WBS | Description | Estimator | Safety | Ease/Efficiency | Availability | Flexibility | Risk of Contamination | Consequence of Mistake | Sum wts |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | | | | | | | |
| 1.2 | Facility | Foley | | | | | | | 0.00 |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 0 | 3 | 0 | 0 | 0 | 0 | 0.55 |
| 1.3.2 | Amplifier | Erlandson | -1 | -2 | 2 | 4 | -2 | 2 | 0.41 |
| 1.3.3 | Spatial filter | Patton | 4 | 4 | 4 | 4 | 5 | 4 | 4.17 |
| 1.3.4 | Cavitiy mirror mounts | Horvath | 0 | 0 | 4 | 4 | 2 | 4 | 2.14 |
| 1.3.5 | Transport mirror mnts | Horvath | | | | | | | 0.00 |
| 1.3.6 | Pockels cell | Larson | 0 | 4 | 0 | 2 | 0 | 2 | 1.20 |
| 1.3.7 | Polarizer mount assy | Horvath | 0 | 4 | 4 | 4 | 5 | 4 | 3.36 |
| 1.3.8 | Interstage hardware | Horvath | 3 | 4 | 4 | 4 | 5 | 4 | 4.00 |
| 1.3.9 | Final optics | none | | | | | | | |
| 1.3.10 | Structural supports | Horvath | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 2 | 1 | -2 | 2 | 0.75 |
| 1.3.12 | Power conditioning | Larson | 0 | 0 | 0 | 3 | 0 | 2 | 0.80 |
| 1.3.13 | Beam control | Hackel | 3 | 3 | 3 | 2 | 0 | 0 | 2.57 |
| 1.4 | Target area | none | | | | | | | |
| 1.5 | Computer control | Tietbohl | 0 | 2 | 2 | 2 | 0 | 2 | 2.00 |
| 1.6 | Optical components | Murray | 0 | 0 | | 0 | 0 | 0 | 0.00 |
| Wtd ave | | | 0.52 | 1.46 | 1.85 | 2.31 | 1.57 | 2.26 | 1.66 |

## Operability and Maintainability

### 2 x 2 amplifier bundle

| WBS | Description | Estimator | Safety | Ease/Efficiency | Availability | Flexibility | Risk of Contamination | Consequence of Mistake | Sum wts |
|---|---|---|---|---|---|---|---|---|---|
| 1.1 | Project Office | none | | | | | | | |
| 1.2 | Facility | Foley | | | | | | | 0.00 |
| 1.3 | Laser | | | | | | | | |
| 1.3.1 | Pulse generation | Larson | 0 | -5 | 0 | 0 | 0 | 0 | -0.91 |
| 1.3.2 | Amplifier | Erlandson | 0 | 0 | 3 | 4 | 2 | 3 | 1.94 |
| 1.3.3 | Spatial filter | Patton | 4 | 5 | 5 | 5 | 5 | 5 | 4.83 |
| 1.3.4 | Cavity mirror mounts | Horvath | 0 | 0 | 5 | 5 | 2 | 5 | 2.57 |
| 1.3.5 | Transport mirror mnts | Horvath | | | | | | | 0.00 |
| 1.3.6 | Pockels cell | Larson | 0 | 4 | 0 | 2 | 0 | 2 | 1.20 |
| 1.3.7 | Polarizer mount assy | Horvath | 0 | 5 | 5 | 5 | 5 | 5 | 3.93 |
| 1.3.8 | Interstage hardware | Horvath | 3 | 5 | 5 | 5 | 5 | 5 | 4.67 |
| 1.3.9 | Final optics | none | | | | | | | |
| 1.3.10 | Structural supports | Horvath | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 |
| 1.3.11 | Auxiliary systems | Hackel | 0 | 0 | 2 | 1 | -2 | 2 | 0.75 |
| 1.3.12 | Power conditioning | Larson | 0 | 0 | 3 | 3 | 0 | 2 | 1.40 |
| 1.3.13 | Beam control | Hackel | 3 | 3 | 3 | 2 | 0 | 0 | 2.57 |
| 1.4 | Target area | none | | | | | | | |
| 1.5 | Computer control | Tietbohl | 0 | 3 | 3 | 3 | 0 | 3 | 3.00 |
| 1.6 | Optical components | Murray | 0 | 0 | | 0 | 0 | 0 | 0.00 |
| Wtd ave | | | 0.62 | 1.43 | 2.56 | 2.69 | 2.14 | 2.83 | 2.04 |

# Appendix F Estimate of Recovery Costs From an Unexpected Catastrophe

## Spatial filter lens failure

assume failure occurs at input to transport SF
ignore replacement cost of blastshields & flashlamps (small delta)

| | Module | Slabs refinished | Cost per refinishing (K$) | Refinishing Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 9 | $5 | $45 | $0 |
| | 4x4 | 9 | $5 | $45 | $0 |
| (optics) | 4x2 | 6 | $5 | $30 | $15 |
| | 2x2 | 4 | $5 | $20 | $25 |

| | Module | Lenses refinished | Cost per refinishing (K$) | Refinishing Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 48 | $10 | $480 | $0 |
| | 4x4 | 16 | $10 | $160 | $320 |
| (optics) | 4x2 | 8 | $10 | $80 | $400 |
| | 2x2 | 4 | $10 | $40 | $440 |

| | Module | Lenses Removed, Cleaned, Installed | Cost per replacement ($) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 96 | $300 | $29 | $0 |
| | 4x4 | 32 | $300 | $10 | $19 |
| (SF) | 4x2 | 16 | $300 | $5 | $24 |
| | 2x2 | 4 | $300 | $1 | $28 |

| | Module | Pinhole repair time time (man-weeks) | Cost per man-week (K$) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 4 | $3 | $12 | $0 |
| | 4x4 | 2 | $3 | $6 | $6 |
| (SF) | 4x2 | 1.5 | $3 | $5 | $8 |
| | 2x2 | 1 | $3 | $3 | $9 |

| | Module | SF cleaning time (man-weeks) | Cost per man-week (K$) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 8 | $3 | $24 | $0 |
| | 4x4 | 4 | $3 | $12 | $12 |
| (SF) | 4x2 | 3 | $3 | $9 | $15 |
| | 2x2 | 2 | $3 | $6 | $18 |

| | Module | Slabs removed, Cleaned, Installed | Cost per replacement ($) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 48 | $300 | $144 | $0 |
| | 4x4 | 16 | $300 | $48 | $96 |
| (amp) | 4x2 | 8 | $300 | $24 | $120 |
| | 2x2 | 4 | $300 | $12 | $132 |

| | Module | Interstage cleaning time (man-weeks) | Cost per manweek (K$) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 4 | $3 | $12 | $0 |
| | 4x4 | 2 | $3 | $6 | $6 |
| (interstage) | 4x2 | 1.5 | $3 | $5 | $8 |
| | 2x2 | 1 | $3 | $3 | $9 |

| | Module | Beam Control Repair (man-weeks) | Cost per man-week (K$) | Hardware Cost (K$) | Repair Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|---|
| | 4x12 | 19 | $3 | $480 | $537 | $0 |
| | 4x4 | 6 | $3 | $160 | $178 | $359 |
| (beam control) | 4x2 | 3 | $3 | $80 | $89 | $448 |
| | 2x2 | 1.5 | $3 | $40 | $45 | $493 |

| **Bundle Size** | **Delta Repair Cost (K$)** | **NIF Baseline Cost (K$)** |
|---|---|---|
| **4x12** | **$0** | **$1,283** |
| **4x4** | **$818** | |
| **4x2** | **$1,037** | |
| **2x2** | **$1,153** | |

# Appendix F (cont.). Estimate of recovery costs from an unexpected catastrophe.

## Flashlamp & blastshield failure on A3

assume failure occurs on cavity end of A3 and showers debris toward LM3
ignore replacement cost of blastshields & flashlamps (small delta)

| | Module | Mirrors refinished | Cost per refinishing (K$) | Refinishing Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 4 | $25 | $100 | $0 |
| | 4x4 | 4 | $25 | $100 | $0 |
| (optics) | 4x2 | 2 | $25 | $50 | $50 |
| | 2x2 | 0 | $25 | $0 | $100 |

| | Module | Polarizers refinished | Cost per refinishing (K$) | Refinishing Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 12 | $30 | $360 | $0 |
| | 4x4 | 12 | $30 | $360 | $0 |
| (optics) | 4x2 | 8 | $30 | $240 | $120 |
| | 2x2 | 4 | $30 | $120 | $240 |

| | Module | Slabs refinished | Cost per refinishing (K$) | Refinishing Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 8 | $5 | $40 | $0 |
| | 4x4 | 8 | $5 | $40 | $0 |
| (optics) | 4x2 | 8 | $5 | $40 | $0 |
| | 2x2 | 4 | $5 | $20 | $20 |

| | Module | Mirrors Removed, Cleaned, Installed | Cost per replacement ($) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 96 | $450 | $43 | $0 |
| | 4x4 | 32 | $450 | $14 | $29 |
| (mirrors) | 4x2 | 16 | $450 | $7 | $36 |
| | 2x2 | 8 | $450 | $4 | $40 |

| | Module | Polarizers Removed, Cleaned, Installed | Cost per replacement ($) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 48 | $300 | $14 | $0 |
| | 4x4 | 16 | $300 | $5 | $10 |
| (polarizer) | 4x2 | 8 | $300 | $2 | $12 |
| | 2x2 | 4 | $300 | $1 | $13 |

| | Module | Pockels Cells Removed, Cleaned, Installed | Cost per replacement ($) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 48 | $300 | $14 | $0 |
| | 4x4 | 16 | $300 | $5 | $10 |
| (Pockels cell) | 4x2 | 8 | $300 | $2 | $12 |
| | 2x2 | 4 | $300 | $1 | $13 |

| | Module | Beamline cleaning time (man-weeks) | Cost per man-week (K$) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 16 | $3 | $48 | $0 |
| | 4x4 | 8 | $3 | $24 | $24 |
| (interstage) | 4x2 | 6 | $3 | $18 | $30 |
| | 2x2 | 4 | $3 | $12 | $36 |

| | Module | Slabs removed, Cleaned, Installed | Cost per replacement ($) | Cleaning Cost (K$) | Delta Cost to Baseline (K$) |
|---|---|---|---|---|---|
| | 4x12 | 48 | $300 | $14 | $0 |
| | 4x4 | 16 | $300 | $5 | $10 |
| (amp) | 4x2 | 8 | $300 | $2 | $12 |
| | 2x2 | 4 | $300 | $1 | $13 |

| **Bundle Size** | **Delta Repair Cost (K$)** | **NIF Baseline Cost (K$)** |
|---|---|---|
| **4x12** | **$0** | **$634** |
| **4x4** | **$82** | |
| **4x2** | **$272** | |
| **2x2** | **$475** | |