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ADP011193

TITLE: Integrated Flight Experiment [IFX] Laser Payload Element [LPE] Progress

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TITLE: The Annual AIAA/BMDO Technology Conference [10th] Held in Williamsburg, Virginia on July 23-26, 2001. Volume 1. Unclassified Proceedings

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INTEGRATED FLIGHT EXPERIMENT (IFX) LASER PAYLOAD ELEMENT (LPE) PROGRESS

by
Matthew E. Zuber*
SMC/TL, Building 404
Kirtland AFB, NM 87117

J. Jackson and Marty Wacks****
TRW Space and Defense
1 Park, R-10-1356
Redondo Beach, CA 90278

Abstract

The US Air Force is pursuing a technology demonstration program aimed at launching an experimental laser into space. The program will help Department of Defense policy-makers decide whether to pursue an operational Space Based Laser (SBL) system designed to protect the United States and its allies from ballistic missiles as part of a layered defense. Designated the Integrated Flight eXperiment (IFX), it consists of four elements: Laser Payload Element (LPE), Beam Control Element (BCE), Beam Director Element (BDE) and Spacecraft Element (SCE).

Three of the world's premier aerospace companies, TRW, Boeing, and Lockheed Martin, have joined to form the Space Based Laser Integrated Flight Experiment Team as an equal partnership Joint Venture (JV). The JV is partnered with the Air Force Space and Missile Center and the Ballistic Missile Defense Organization to conduct the SBL IFX Project. The SBL IFX Project is to design, develop and test an on-orbit SBL and demonstrate the feasibility of an SBL for ballistic missile defense. The IFX Project is a pre-milestone zero research effort with its inherent technical uncertainties and funding variability. Risk management consists of balancing IFX costs with technical and schedule risks, while focusing on achieving the project objectives.

SBL is being pursued in a technology demonstration program aimed at launching an experimental laser into space in 2012 to shoot down a ballistic missile in 2013 (see Figure 1). The technology demonstration will be conducted in full compliance with all relevant international treaties, including the Anti-Ballistic Missile Treaty of 1972. In the future, an operational SBL would be integrated within the National Missile Defense architecture and the family of theater missile defense programs.

Acronyms

ABL	Airborne Laser
ABM	Anti-Ballistic Missile
AFSCN	Air Force Space Communications Network
AI&T	Assembly, Integration, and Test
ALI	Alpha Lamp Integration
ASE	Aperture Sharing Element
ATP	Acquisition, Tracking, and Pointing
BC	Beam Control
BCE	Beam Control Element
BDE	Beam Director Element
BEX	Beam EXpander
BMD	Ballistic Missile Defense
BMDO	Ballistic Missile Defense Office
CDR	Critical Design Review
CDS	Concept Definition Study
CWBS	Contract Work Breakdown Structure
DoD	Department of Defense
DVT	Development Validation Test
EOL	End Of Life
ETR	Eastern Test Range
FC	Fire Control
GGS	Gain Generator Subsystem
GPS	Global Positioning System
GS	Ground Segment
HABE	High Altitude Balloon Experiment
HEL	High Energy Laser
HOE	Holographic Optical Element
HP	High Power
HYLTE	HYpersonic Low Temperature (nozzle)
IFX	Integrated Flight Experiment
IPEP	Integrated Program Execution Plan
IPPD	Integrated Product and Process Development
IPT	Integrated Product Team
ITU	Integrated Test Unit
JV	Joint Venture

* Capt., US Air Force, Member of AIAA
** Member of AIAA

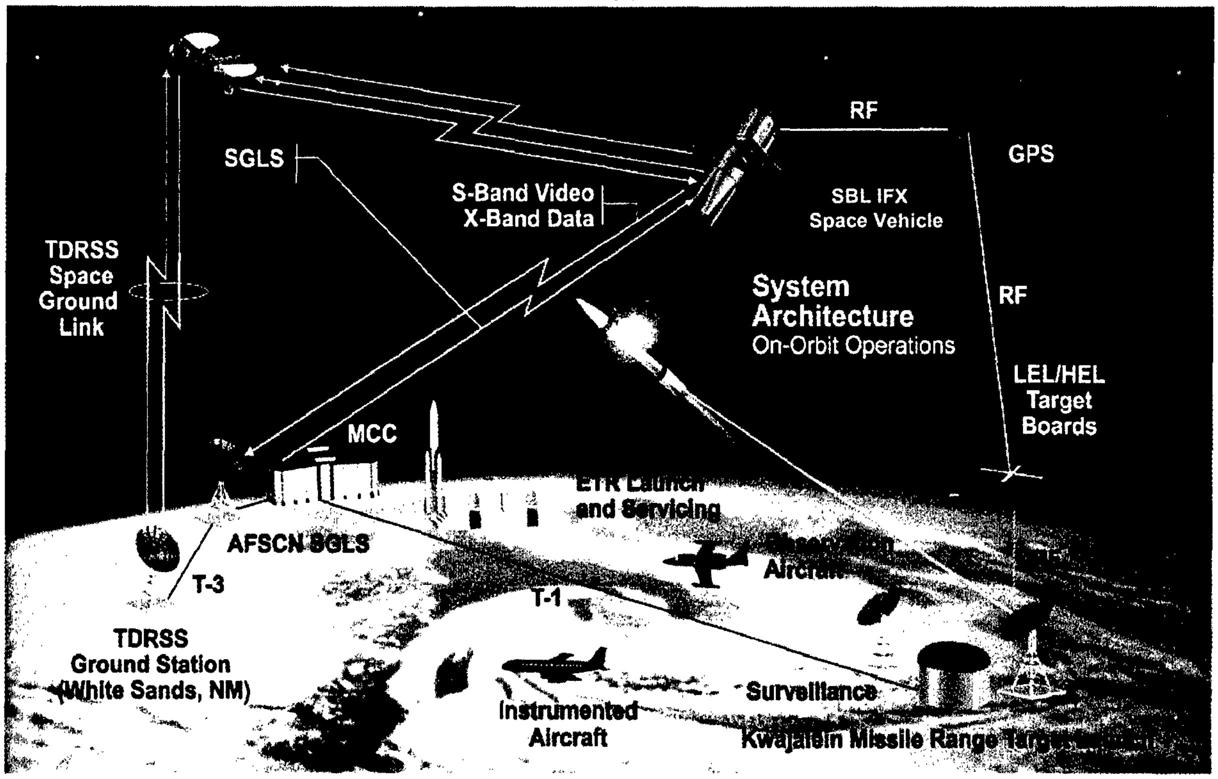


Figure 1: SBL IFX On-Orbit System Architecture

LEL	Low Energy Laser
LEO	Low Earth Orbit
LL	Long Lead
LPE	Laser Payload Element
LV	Launch Vehicle
MCC	Mission Control Center
NGST	Next Generation Space Telescope
NOP	North Oscura Peak
OPE	Optical Payload Element
PDR	Preliminary Design Review
PM	Project Manager
POM	Program Objective Memorandum
RD	Readiness Demonstrator
RF	Radio Frequency
RM	Risk Management
RMP	Risk Management Plan
RR	Requirements Review
SBL	Space Based Laser
SBLRD	Space Based Laser Readiness
SCE	Spacecraft Element
SEIT	System Engineering Integration and Test
SGLS	Space Ground Link System
SMC	Space and Missile Systems Center
SOO	Statement of Objectives
SRR	System Requirements Review
SS	Space Segment
STF	SBL Test Facility
SV	Space Vehicle
TDRSS	Tracking and Date Relay Satellite
TPM	Technical Performance Measure
TPO	Team Program Office
WBS	Work Breakdown Structure
WCM	Water Cooled Module
WF	Wave Front
WFS	Wave Front Sensor

Introduction

The Space-Based Laser (SBL) is a next-generation directed energy missile defense system being explored today to provide global, boost-phase intercept of ballistic missiles tomorrow.

In his February 2000 testimony on the Worldwide Threat, CIA Director George Tenet said that the proliferation of weapons of mass destruction had "become even more stark and worrisome" than just a year before. "Transfers of enabling technologies to countries of proliferation concern have not abated," he said. "Many states in the next ten years will find it easier to obtain weapons of mass destruction and the means to deliver them."[1]

Tenet added that "the missile threat to the United States from states other than Russia and China is steadily emerging. The threat to US interests and forces overseas is here and now." Tenet pointed out that, over the next 15 years, U.S.

cities will face ICBM threats from a wider variety of nations, including North Korea, Iran, and possibly Iraq. He also expressed concern about the security of nuclear weapons and materials in Russia.[2]

In its unclassified version of its 1999 National Intelligence Estimate, the intelligence community reiterated that "the proliferation of medium-range ballistic missiles (MRBMs) – driven primarily by North Korean No Dong sales – has created an immediate, serious, and growing threat to US forces, interests and allies, and has significantly altered the strategic balances in the Middle East and Asia."[3]

In South Asia, Pakistan and India are locked in a nuclear rivalry, and the intelligence community has assessed that both countries' short-range and medium-range ballistic missiles may have nuclear roles.[4]

Foreign assistance has played a key role in the increasing proliferation of missile technology, with Russia, China, and North Korea as the principal suppliers. And, Tenet warns, the recipients of missile-related technology, such as Syria and Iraq, "may emerge in the next few years as suppliers."[5]

High-energy laser (HEL) systems have the potential to form a robust tier of a U.S. ballistic missile defense (BMD) system. An orbiting constellation of HEL projectors (the objective SBL system for this research effort) provides the access to missile launch corridors that opens up the possibility for boost phase intercept of a hostile ballistic missile threat. The strategic advantages of a Space Based Laser platform, against intercontinental or theater ballistic missile threats, are sufficiently compelling that there is community consensus for development and demonstration of the key enabling technology. The SBL IFX Project will take a major step to prove the feasibility of the SBL for BMD, and validate the scalability of key technologies by collecting the engineering data to show that a SBL system can be affordably fielded and maintained.

The IFX Project will develop and place a low earth orbit (LEO) HEL satellite (Figure 2) with the following features:

- Enough brightness, run time and pointing accuracy to have substantial margin to achieve the destruction of a boosting ballistic missile,
- Technologies, traceable to a class of future operational SBL systems, where a space demonstration is essential, and
- Sufficient instrumentation and on-orbit life to collect data to characterize an integrated SBL on-orbit and to understand space-based effects.

The Government has granted the Joint Venture Team Program Office (JV TPO) Total System Authority (TSA) to conduct the SBL IFX Project. Within the dictates of TSA, the JV TPO has the responsibility for executing research, risk reduction, and demonstration activities while balancing program execution risk with legacy to an operational system. The Team has developed a programmatic baseline that is a balanced response to the Project Statement of Objectives (SOO), the Program Objectives Memorandum (POM), and reports of the DoD-sponsored Independent Review Team and other SBL community stakeholders.

Laser Payload Element

This section presents the LPE subsystem as a point of reference for the reader. The LPE development is on the critical path for SBL IFX demonstration. Design overview and risk reduction plans to mitigate and manage the development risk is presented here. Risk reduction is the primary goal for the LPE for the next few fiscal funding increments.

Subsystems

The SBL IFX LPE design concept is shown in Figure 2. It incorporates all major LPE subsystems and is consistent with driving requirements. The concept leverages knowledge obtained from previous SBL efforts (Alpha, Zenith Star, SBL Concept Definition Study (CDS), Hydrogen Fluoride/ Deuterium Fluoride (HF/DF) Program, etc.) as well as over 25 years of chemical laser research and development/lessons learned at TRW.

Driving requirements include: wavelength (HF fundamental), power (megawatt class), magazine size of 110 seconds, mass (22,900 pounds) and envelope (171.4 inches diameter x 270 inches length).

LPE subsystems include:

Gain Generator Subsystem (GGS). A HYpersonic Low TEmperature (HYLTE) nozzle based, 0.75 meter diameter cylindrical gain generator that leverages successful Alpha and HF/DF contracts. The gain generator consists of 92 rings, when stacked together form a central combustion chamber that is used to generate the fluorine required for the laser gain medium.

Optical Resonator Subsystem (ORS). A High EXtraction efficiency, Decentered Annular Ring Resonator (HEXDARR) employing uncooled mirrors based on single-crystal silicon substrates, very-low absorption and phase-control coatings, with the annular optics mounted on silicon carbide integrating structures. The optical system alignment is maintained with an automatic alignment system. The design has leveraged successes on Zenith Star Resonator Optical Materials Assessment (ROMA) and Alpha Uncooled Resonator (UCR) special study contracts.

Reactant Storage and Feed Subsystem (RSFS). An ambient temperature gas blow-down system featuring composite over-wound high pressure tanks.

Integrating Structure Subsystem (ISS). A composite cylinder that serves as both the launch load bearing and metering structure. All LPE subsystems are mounted to this cylinder, less the LELS.

Low Energy Laser Subsystem (LELS). A low power, in-band solid-state laser required to align the optical resonator, support space vehicle alignment and system low power experiments.

Thermal Management Subsystem (TMS). Heaters, coolers, radiators and insulation required to maintain the optics and structures at correct temperature and reject GGS, LELS and optical power management equipment (clippers and dumps) waste heat.

Instrumentation and Control Subsystem (ICS). Processors and harnesses required to monitor and operate the LPE, receive and execute commands and transmit data to the SCE for recording and transmission to the ground.

Risk Reduction Plan

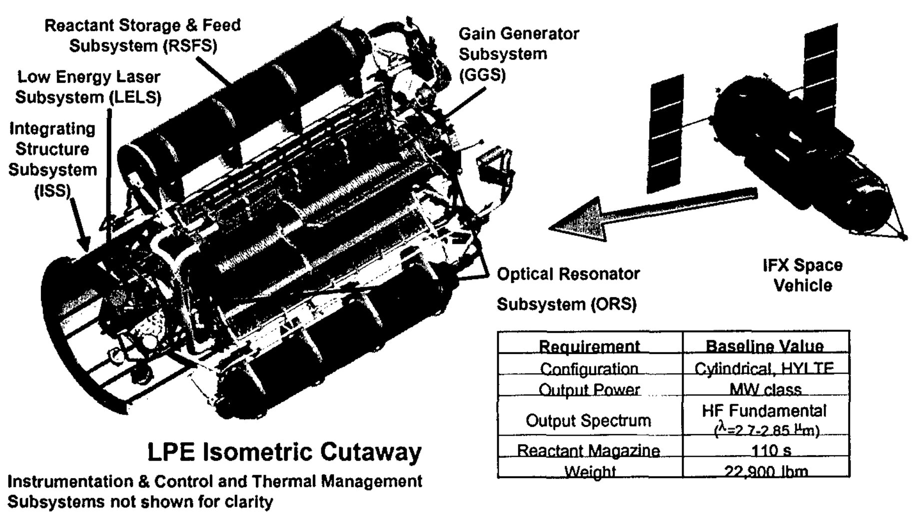
The risk management plan is part of the overall proactive management of the IFX Project.[6] Risk management is the process utilized to assess risks, develop mitigation approaches, and for the development of information (Technical Performance Parameters) for tracking risks and assessing alternatives to keep risks balanced. Therefore, effective risk management increases the likelihood of program success. The LPE is currently in a risk reduction mode to increase the probability of success required for the IFX lethal demonstration.

The LPE risk reduction plan was developed through an iterative process of assessing requirements, generating a concept that met the requirements, assessing the risks associated with the concept, generating a mitigation plan to address the risks and incorporating it into the program plan.

The individual LPE risks identified were grouped into three main categories: Gain Generator performance, Optical Resonator fabrication and Integrated Laser performance.

The LPE program plan incorporates the risk mitigation (or reduction) activities in addition to all other activities required to design, build and test the IFX LPE. The program plan was developed and is recorded in the form of a resource loaded MS Project™ network. Risk mitigation activity completions are tied to appropriate project milestones. Critical path hardware and risk reduction activities were identified using the MS Project™ network. Critical path hardware development items over and above risk reduction activities include the resonator optics and gain generator rings.

Our IFX funding increment 1 activity plans were derived from our network/plan and are described in the following three key areas: Gain Generator, Optical Resonator and Integrated Laser Performance. For each area, a summary of all activities is provided as well as a more detailed discussion of a particular activity in that area.



Requirement	Baseline Value
Configuration	Cylindrical, HYLTE
Output Power	MW class
Output Spectrum	HF Fundamental (λ=2.7-2.85 μm)
Reactant Magazine	110 s
Weight	22,900 lbm

Figure 2: Laser Payload Element Subsystems

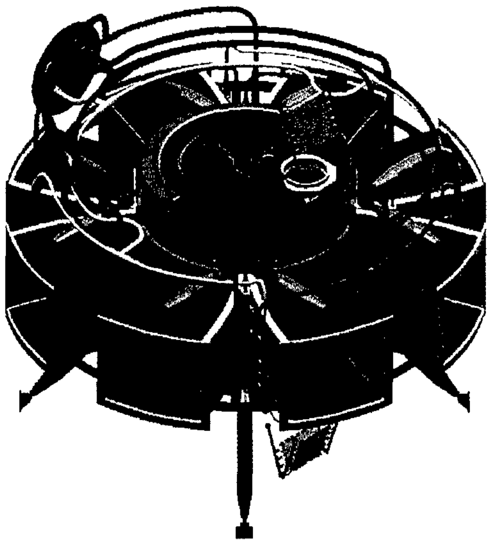


Figure 3: Pictorial of Short Stack to start testing in 2003 at TRW/CTS.

Gain Generator

The Gain Generator Subsystem (GGS) employs the HYpersonic Low TEmperature (HYLTE) nozzle to produce the flow field necessary for efficient HF* production. The HYLTE nozzle, originally developed under the HF/DF and predecessor programs, has been shown to provide as much as 30% mass efficiency improvement over the current Hypersonic Wedge Nozzle (HWN) technology employed on Alpha. This translates to a tremendous IFX LPE mass savings. The desire to reduce gain generator thermal/structural and laser performance risk combined with the ring fabrication schedule driving the LPE critical path motivated this increment's GGS effort. The cylindrical gain generator risk reduction and long lead hardware development activities focus on three areas: full scale ring fabrication, diffusion bond design verification test, and short stack verification testing.

Full scale ring fabrication goals: fabricate the first, full-scale, 0.75 meter diameter HYLTE nozzle ring; validating all the process required to do so. Diffusion Bond Design Verification Test goals: Subject diffusion bonded ring simulators (short, linear nozzle segment) to 800 equivalent laser firing thermal cycles to ensure the diffusion bonding process is capable of meeting the current 200 cycle life requirement.

Short Stack Design Verification Test goals: Design (to a CDR level during this year), fabricate, integrate and test a "short stack" of full-scale nozzle rings (10 rings total) (see Figure 3). This device will be an IFX GGS engineering model unit that is scaleable to the full length device. This activity will verify the thermal/structural performance of the ring nozzles and provide key inputs to Integrated Laser Performance modeling of a radially expanding flow field, including spatial and temporal measurements of laser power extraction, power spectral content and small signal gain.

The groundwork for the diffusion bonding approach was performed on the HF/DF program which produced the first diffusion bonded HYLTE nozzle ring. Nozzles are actually formed when two or more rings are stacked one on top of another, with the gap between the mating sides forming a nozzle. The IFX gain generator will require a ~3.5 meter tall stack of 0.75 meter diameter rings (a total of 92 rings).

The steps required to fabricate a diffusion bonded HYLTE ring are well understood. First, six individual plates are machined from flat aluminum stock. External machining of individual ring plates incorporates all internal ring geometry. Second, the plates are polished flat with a high surface finish. Third, a layer of bonding material is vacuum deposited onto each mating surface of the plates. Fourth, the individual plates are stacked together and placed into a stainless steel fixture which is placed into a vacuum oven for the diffusion bond cycle.

Friction generated during diffusion bond cycle distorts the ring to slightly non-circular shape at a reduced diameter. This is corrected for by applying a stretching process that increases ring diameter and circularizes in one step. The final step is to Electrical Discharge Machine (EDM) all fluid injector holes.

As of this writing all processes have been successfully demonstrated. Lessons learned during the fabrication of this ring are already being fed back into the design as updates that will allow us to reduce manufacturing tolerances, design better manufacturing support tooling and reduce overall cost and schedule for producing the gain generator rings.

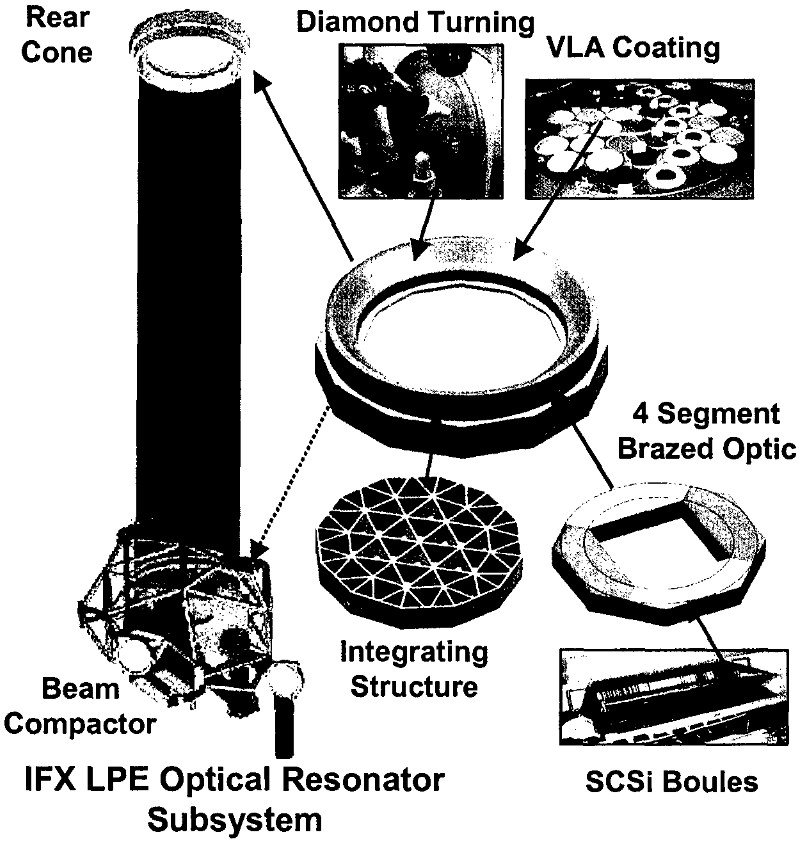


Figure 4: Optical Resonator Risk Reduction activities.

Optical Resonator

The resonator for the LPE consists of 2 optical modules; 1) the Rear Cone station where the recirculating cylindrical sleeve of light is sent back into the flowing gain medium (similar to a cylindrical roof prism) and 2) the Beam Compactor station where the cylindrical sleeve of light is compacted from an annulus into a solid beam for outcoupling and recirculation for continuous gain extraction, and subsequent uncompacting back into an annulus. The Beam Compactor consists of the inner and outer cones as shown in figure 5. Both optical modules contain large annular optics made up of single crystal silicon. Since raw silicon fabrication process does not exist to make large enough boules to make the annular size required for IFX, several boules must be brazed together to form a larger annular optical blank.

The rear cone demonstrator design and fabrication effort is broken down into two areas: annular optic fabrication and rear cone integrating structure fabrication.

The four-segment annular resonator optic fabrication is utilizing 300 mm diameter single-crystal (SCSi) silicon wafer technology from MEMC. The SCSi boules are 12 inches in diameter and approximately 29 inches long. MEMC has successfully grown all four of the boules required to date. The new zero-defect silicon allowed McCarter Technology to diamond saw the silicon segments to near net shape, rather than grind them. The new sawing method requires minimal grinding cleanup for each segment and provides additional sample material.

The integration structures to hold these large optics must be lightweight and stiff to be compatible with space flight requirements. These structures will be made out of machined Silicon Carbide to closely match the silicon optics CTE. Xinetics Corporation is responsible for fabricating the rear cone Silicon Carbide integrating structure. They are utilizing lessons learned from the Alpha-sized beam compactor integrating structure (BCIS) lower section being utilized as the pathfinder for the SBL IFX rear cone integrating structure. The BCIS has been cast, pre-fired, machined and siliconized. The SBL IFX rear cone integrating structure mold has been fabricated, the silicon carbide poured into the mold, frozen, and has been dried and fired.

The LPE is reducing the risk in the figuring process for the annular optics by further exploration of optic

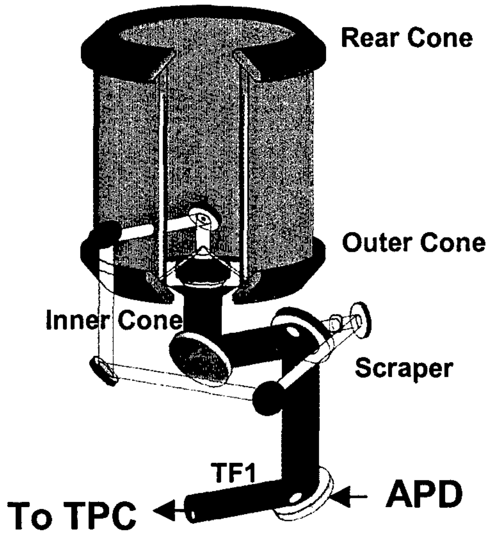


Figure 5: HEXDARR Configuration

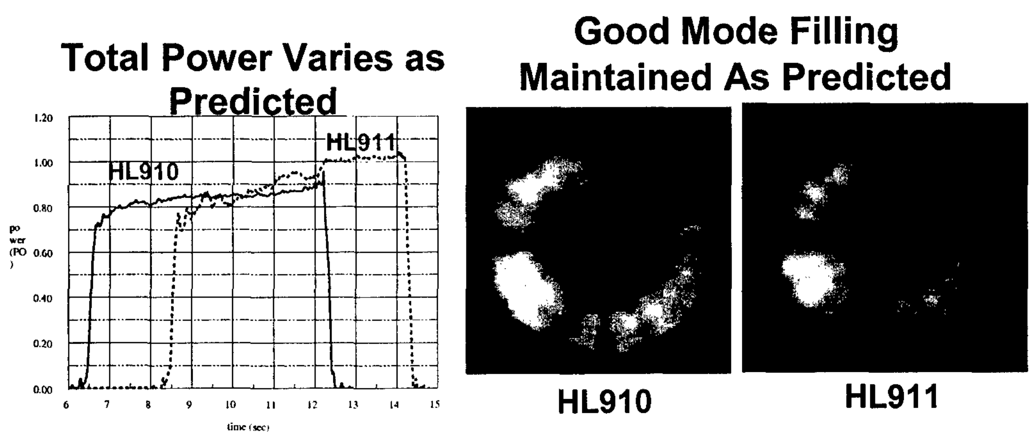


Figure 6: Integrated Performance testing risk reduction activities.

diamond turning parametric engineering space. This work is being done in cooperation with effort by Schafer Corporation.

Optical coating risk reduction is also being funded as part of the LPE effort. Laser Power Corporation (LPC) has completed witness sample check out of a 100 inch coating chamber. The chamber has produced witness samples with total losses less than 100 parts per million (ppm). The coating chamber has being configured to coat a silicon diamond-turned and post-polished Alpha-class waxicon conical test article (WCTA). The conical test article will be coated with the Alpha OCLI coating mask to allow early checkout of the very low absorbing coating process in the new chamber.

Integrated Laser Performance

The laser model development effort is upgrading Alpha models to the Space-Based Laser configuration. This configuration differs from the Alpha design in that the gain generator is based on the advanced, HYLTE nozzle design with a smaller diameter gain generator and optical resonator. The resonator is a cylindrical configuration similar to the concept used in Alpha but scaled in diameter to match the gain generator diameter. Small signal gain measurements from a linear gain generator are used to anchor the characteristics of the gain region via a Direct Simulation Monte Carlo (DSMC) fluid dynamics model. The gains obtained from this model are used in the TRW Cylindrical Resonator Optical Quality (CROQ) and the SAIC Laser Performance Simulation (LPS) wave optics models to predict power, intensity and spectral properties of the laser output. These predictions are anchored and validated with high and low power test data from Alpha. IFX LPE performance will be predicted using these validated models once changed to reflect the IFX configuration.

High power testing on Alpha will verify that the technique is capable of providing adequate alignment of this type of resonator. High power testing on Alpha will be used to: 1. demonstrate the predictive capabilities of our models under different run conditions; and 2. Use test results to obtain parameters for anchoring the models. As shown in figure 6, measured results agree well with model predictions.

The Alpha laser, a ground-based demonstration of key space-based laser device technologies, has proven to be a valuable test bed to validate the ability of our models to predict laser performance using both low and high power data.

A key example of this is Alpha test HL910. Alpha had previously been run with conservative beam compactor annular clipper settings that limit the annular mode to protect downstream components. This caused less power to be outcoupled and more to be clipped and intercepted by internal power management beam dumps. A critical factor in estimating the IFX laser design margin is the outcoupled power fraction. The conservative clipper settings were yielding an outcoupled power fraction of ~60% of the total laser power. Our laser models predicted that by moving the clippers we could safely increase the outcoupled power fraction to almost 75%. Successful HL910 testing, employing less conservative clipper setting, indeed showed an outcoupled power fraction of ~75% – validating the models. This extra outcoupled energy results in an LPE mass savings of ~ 3,000 pounds!

In addition to high power testing, low power testing also provides LPE risk reduction opportunities. A good example of Alpha low power test data allowing us to significantly reduce program risk is the autonomous alignment task. An algorithm, suitable for autonomous implementation on-orbit, was invented. Low power (injected beam, non-lasing) tests on Alpha allow us to verify that our alignment technique will lead to an approach that can work autonomously on-orbit. The alignment approach relies on sensing characteristic signatures of the near field phase of the beam that is due to the rear cone lateral displacement and compact leg tilts. These are the major misalignment mechanisms of the cylindrical resonator. By monitoring the tilt/shear of the resonator output when a low power laser is inserted into the cavity, it is possible to simultaneously determine these quantities and subsequently align the optical system by minimizing these parameters.

Preparations are underway (sensor calibrations, etc.) to apply this algorithm on Alpha and directly compare its alignment to that obtained with the current alignment method to validate that the algorithm works as modeled. Preliminary data indicates the algorithm has a linear behavior, and that the algorithm will work as predicted when demonstrated later this year.

Conclusions

The IFX consist of four elements: Laser Payload Element (LPE), Beam Control Element (BCE), Beam Director Element (BDE) and Spacecraft Element (SCE). This paper highlighted the seven LPE subsystems and their current risk reduction activities status. The LPE is continuing to reduce the risk associated with the critical path of IFX.

Activity in other Directed Energy (DE) HEL programs also help to reduce the risk of the IFX demonstration. In June 2000, the Tactical High Energy Laser, or THEL, successfully shot down a Katyusha rocket at the White Sands Missile Range in New Mexico. On several occasions in August and September, THEL managed another feat by engaging and destroying two-missile salvos of Katyusha rockets. To date, THEL has negated a total of 21 Katyusha rockets. Although the U.S. Army and the Israeli Army are designing THEL for tactical use, its success demonstrates how far directed energy research and development have progressed in recent years. In addition, THEL has been useful in defining integrated DE weapon system design and operational requirements as well as reducing risk in field-tested very low absorption coatings. The success of the THEL program has instilled confidence upon the war fighter to the reliability and accuracy of directed energy weapon systems. Currently, the Airborne Laser is scheduled to attempt a lethal intercept of a theater missile in 2003. The ABL development in parallel with the SBL will help in maintaining industrial base resources, which are common to both programs. The SBL's flight experiment will attempt its first intercept ten years later in 2013. If both systems were to become operational in the future, they would provide the United States a robust first line of defense during for boost phase missile defense. This directed energy progression will grow from protecting the skies over a battlefield such as the Airborne Laser mission, to that of the Space Based Laser; the ultimate high ground – Space.

Acknowledgments

Such an undertaking is not the work of one person. Special appreciation is directed towards the Joint Venture and the Program Management Office at Los Angeles Air Force Base, CA.

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