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The Alpha Program

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In the late 1970s DARPA initiated a program to develop the technologies necessary to fly a space-based laser weapon. The encompassing effort was known as Triad, and the three programs were the Alpha Program to develop the laser source, the Large Optics Demonstration Experiment (LODE) to develop the beam control, and the Talon Gold Program to develop the precision pointing capability. This paper provides an overview of the Alpha Program from its antecedents through its final, most successful, tests. Alpha was intended to develop a hydrogen fluoride (HF) laser to megawatt-class levels in a configuration compatible with space operation. We begin with a brief history of the development of HF [and deuterium fluoride (DF)] lasers up through the demonstration of megawatt-class performance with MIRACL, a DF laser designed for sea-level operation. We then cover the program goals, design, and hardware of the Alpha Program. The early tests led to some hardware modifications, following which Alpha achieved megawatt-class performance. We then discuss the diagnostics suite used with Alpha, which recorded the data that fed into a data review task under the Alpha Laser Optimization program. The results of this review allowed for the refinement of Alpha test operations and allowed the program to culminate with a series of highly successful tests. Although Alpha is now being dismantled, and no direct descendant is planned, what we have learned from the Alpha program will be very useful to future high-energy laser programs.

KEYWORDS: Alpha laser, HF lasers, High-energy lasers, Missile defense

1. Background

Hydrogen fluoride (HF), and the chemically similar deuterium fluoride (DF), high energy lasers grew out of early development work and power scaling at The Aerospace Corporation and subsequent power scaling at TRW, now Northrop Grumman Space Technology (NGST). The Navy funded scaling on DF for sea-level operation, and the Defense Advanced Research Projects Agency (DARPA), Strategic Defense Initiative Organization (SDIO), and Ballistic Missile Defense Organization (BMDO) funded scaling on both HF and DF for space operation. Table 1 shows key milestones in the scaling history.

HF lasers can be discharge or combustion driven, but the high-power devices are combustion driven. They are typically based on "burning" NF_3 with D_2 to generate heat to

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Table 1. Key milestones in HF/DF laser scaling

Device	Date	Power
Aerospace	1969	1 W
Aerospace	1970	2 kW
Aerospace	1971	20 kW
TRW/BDL	1975	100-kW class
TRW/NACL	1977	100s-kW class
TRW/MIRACL	1980	Megawatt class
TRW/Alpha	1991	Megawatt class

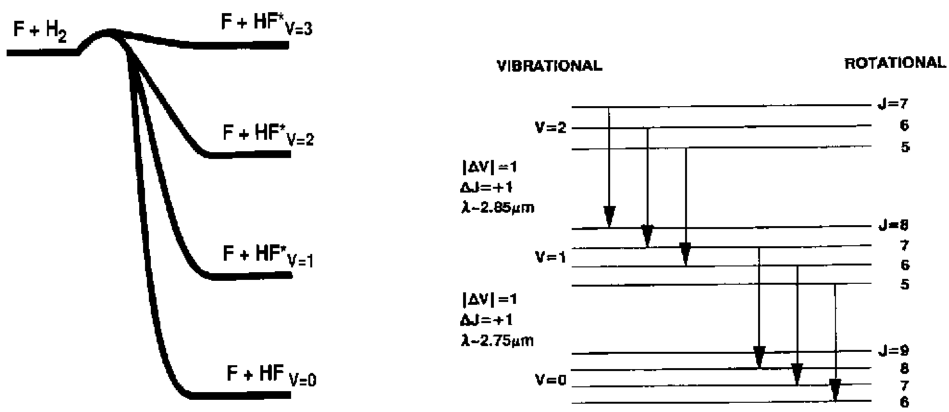

Fig. 1. Left: Energy profile for HF lasers. [Note that no HF(0) is formed in the $F + H_2$ reaction.] Right: Rotational splitting of the HF lines.

dissociate additional NF_3 to produce F, then "burning" the F with H_2 to create HF*. F_2 and N_2F_4 have also been used as F sources. Note that if you swap D_2 and H_2 you have a DF laser! For ground- or sea-based DF lasers the fluorine source has often been combusted with a hydrogen-rich fuel such as ethylene, which is cheaper and easier to handle, but not as mass efficient, as H_2.

Figure 1 shows the energy profiles for HF lasers, and how rotational splitting leads to multiple lines.

DF lasers have been pursued for missions involving atmospheric propagation, and their ~4-μm wavelength propagates well through the atmosphere, while the ~3-μm wavelength of HF is highly absorbed. DF laser development proceeded through the Navy ARPA Chemical Laser (NACL), which in 1975 demonstrated multihundred-kilowatt power from a linear gain generator intended for sea-level operation, followed by the Mid Infrared Advanced Chemical Laser (MIRACL), which in 1980 demonstrated megawatt-class power. More recently, the Theater High Energy Laser (THEL) has demonstrated multihundred-kilowatt power in a transportable system.[3] These systems have demonstrated lethality against a variety of targets (Fig. 2).

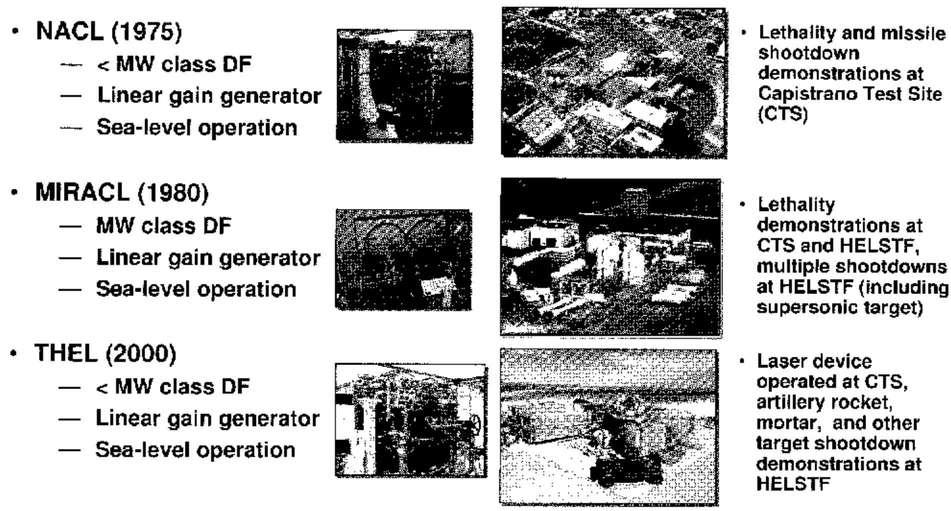

Fig. 2. Development of DF laser weapons.

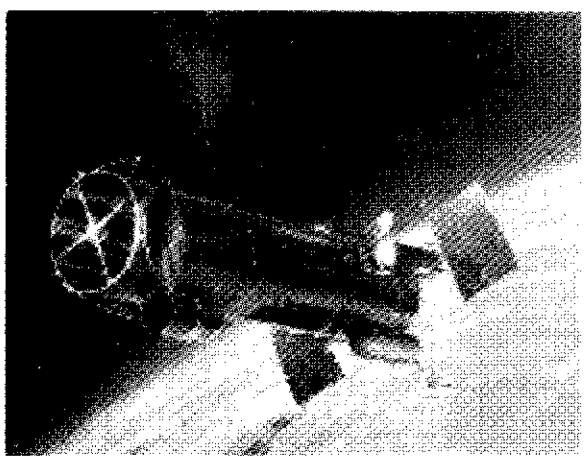

Fig. 3. Early SBL concept.

2. TRIAD and the Alpha Program Goals

In the late 1980s DARPA considered the possibility of putting a multimegawatt laser weapon system in space. To advance this goal, they began programs to develop the laser source (Alpha), the beam control needed by the high-energy laser beam, the Large Optics Demonstration Experiment (LODE), and the pointing control needed to place a beam on a distant target, Talon Gold. The development of a large, lightweight primary mirror, now known as the Large Advanced Primary Mirror Program (LAMP), grew out of the LODE program. Figure 3 shows an early artist's concept of a space-based laser (SBL) weapon.

The original goals of the Alpha program were as follows:

- To show the feasibility of a space-based chemical laser by demonstrating
  - Volume-efficient cylindrical gain generator technology
  - Maximum scalable nozzle area with minimum gain medium optical distortion
  - Lightweight aluminum construction
  - Robust thermal and mechanical properties
- Full-scale optical resonator matched to gain generator output
  - Scalable to higher laser output power
  - Ability to model key performance parameters
  - *Note:* Alpha resonator built for gain generator 2.5 times length actually installed in Alpha (3 times the power)

3. Alpha Laser Overview

The Hypersonic Wedge Nozzle (HWN) was chosen for the Alpha laser because it provided efficient mixing in a compact gain region[1,5] (Fig. 4). Although a cylindrical geometry was chosen for Alpha to maximize the power that could be extracted from the available volume, a verification module (VM) was constructed in a linear configuration to test the HWN performance (Fig. 5).

Performance of the 65-cm VM was scaled to the 110-cm diameter ×200-cm-gain-length Alpha gain generator (Fig. 6). Alpha VM data provided design criteria, small signal gain, and saturated power data to anchor fluid mechanics codes and gain media models for the Alpha design.

To efficiently extract the power in the annular flow region, the High Extraction Decentered-feedback Annular Ring Resonator (HEXDARR) was chosen.[1,4,5] The HEXDARR was the result of several years of annular resonator development, and is shown in Fig. 7.

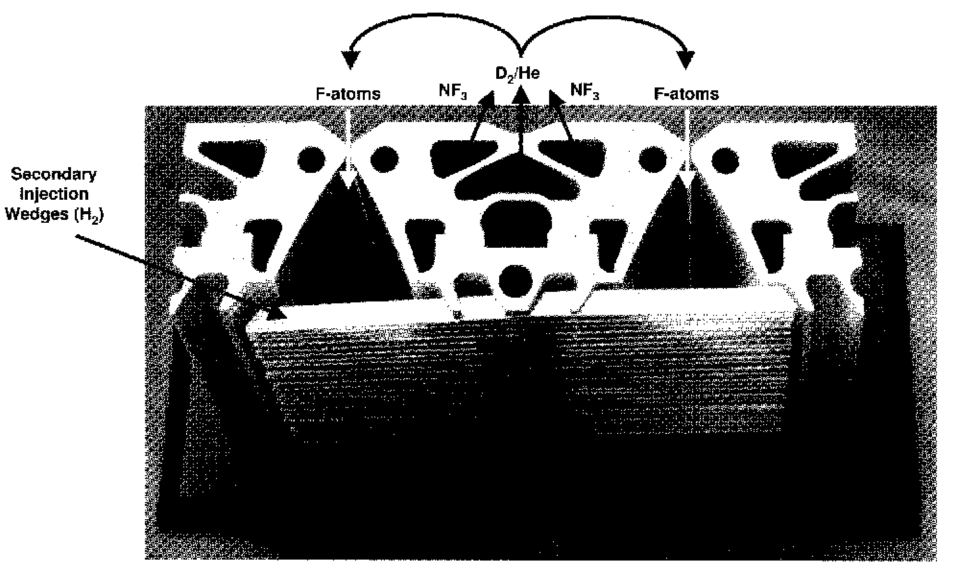

Fig. 4. Hypersonic wedge nozzle (HWN).[1,5]

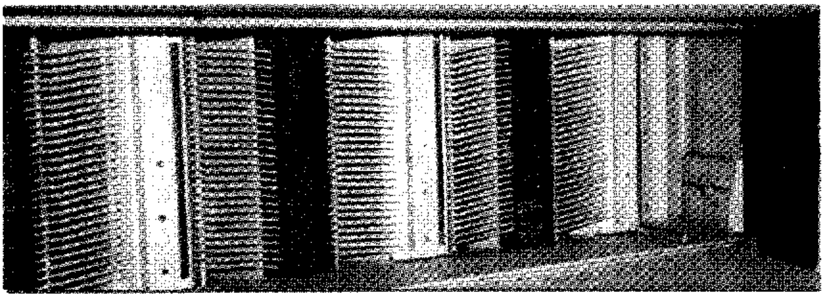

Fig. 5. Integrated Alpha Verification Module (VM) gain generator.

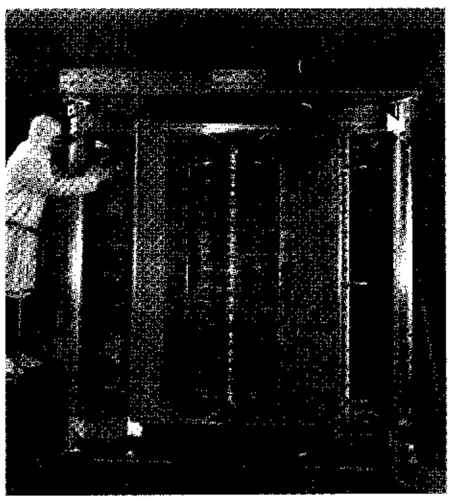

Fig. 6. Alpha cylindrical gain generator.

Together the cylindrical gain generator and annular resonator became the Alpha laser (Fig. 8).

Key to understanding Alpha's behavior was the suite of diagnostics built up over the years. Originally known as the Output Diagnostics Assembly, it became the Input Diagnostics Assembly (IDA) when Alpha became the input laser source for the Alpha-LAMP Integration tests. The IDA provided measurements of power, intensity, phase, jitter, spectrum, and polarization, including spatial and temporal variation. Figure 9 shows a schematic of the IDA.

Measurements included power and wave front, which were performed with the Total Power Calorimeter and the IDA Wavefront Sensor. Additional information on these diagnostics is shown in Fig. 10.

One of the challenges to testing the Alpha laser was that it was designed to be operated in the hard vacuum of space. To simulate the space vacuum, an extensive pressure recovery system was constructed at the Capistrano Test Site (CTS) operated by TRW (now NGST).[1,5] Figure 11 shows this system.

First light of the Alpha laser occurred 7 April 1989, although additional work was required before it began to meet its objectives. Major milestones were as follows:

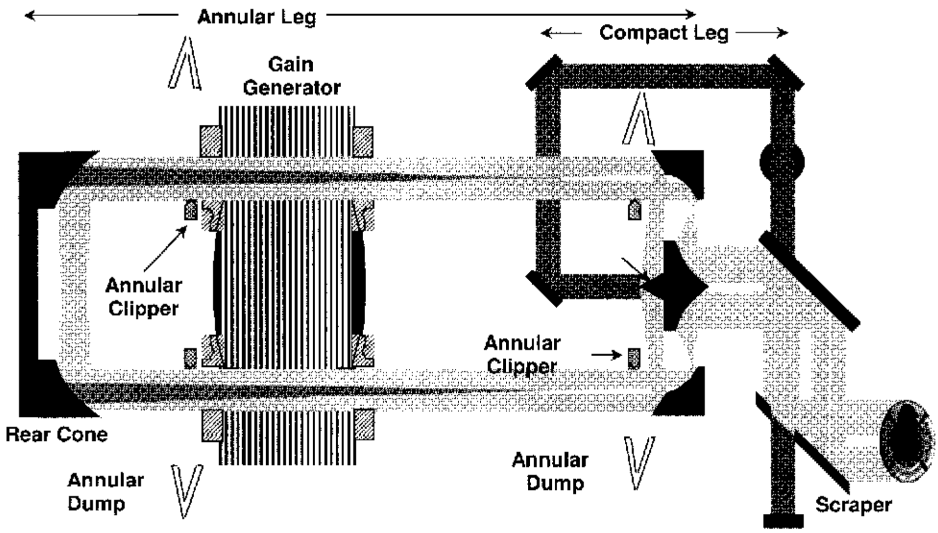

Fig. 7. High Extraction Decentered-feedback Annular Ring Resonator (HEXDARR).[1,4,5]

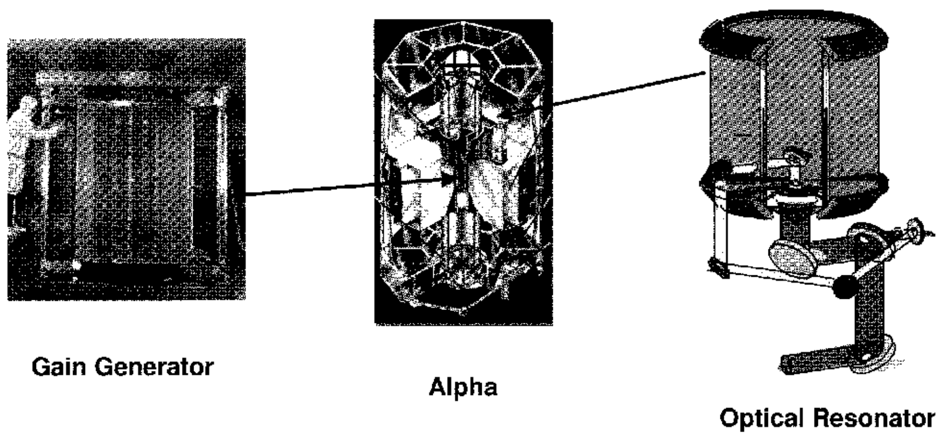

Fig. 8. Cylindrical gain generator and annular resonator comprising the Alpha laser.[1,5]

- 1980, Conceptual design review
- 1981, Preliminary design review
- 1983, Critical design review
- 1987, (June) Capistrano Test Facility completed
- 1987, (December) Gain generator, resonator optics, and diagnostics integrated
- 1988, (April) First combustor test
- 1989, (April) First lasing test
- 1990, (November) First megawatt-class lasing test
- 1991, (May) Repeatable megawatt-class lasing demonstrated
- 1992, (July) Uncooled optics demonstrated at megawatt-class levels
- 1992–1994, Multiple high-power lasing tests conducted
- 1994–1996, "Preservation status"

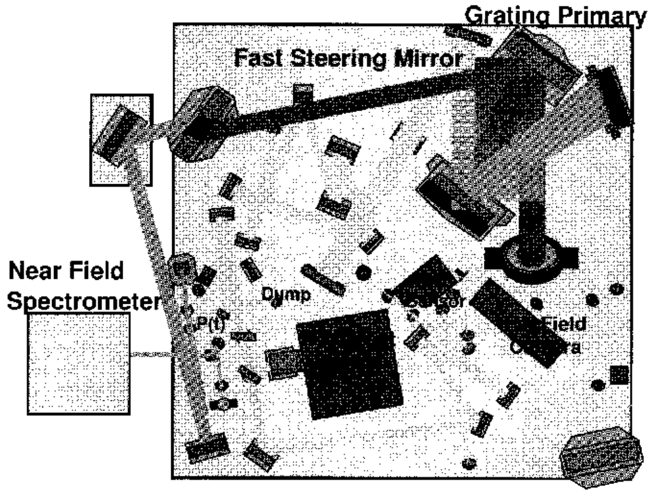

Fig. 9. Alpha input diagnostics assembly.

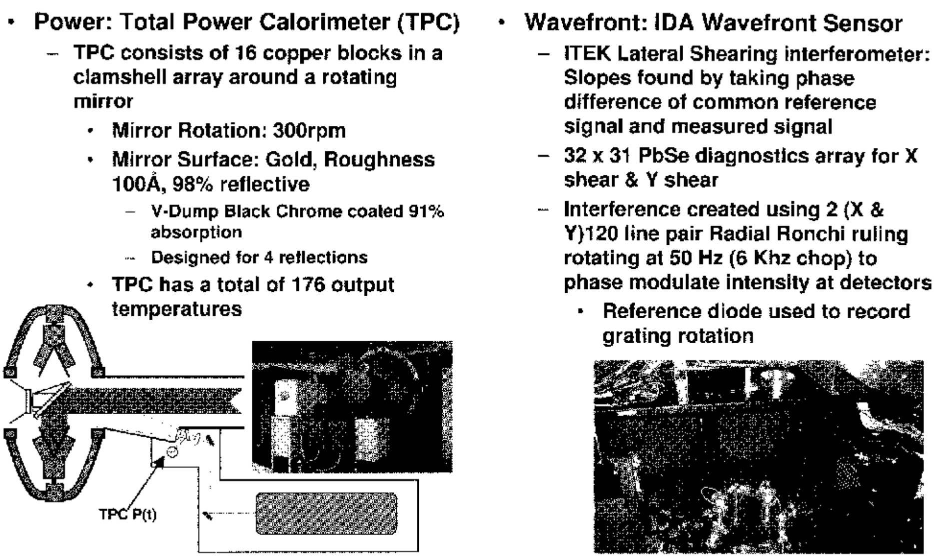

Fig. 10. Total power calorimeter and IDA wavefront sensor used to measure the power and wavefront of the Alpha beam.

- 1996, (September) Reactivation lasing test
- 1997–1998, Integration experiments (Alpha LAMP integration)
- 1997–2000, Performance optimization (Alpha laser optimization)
- 2000–2002, Flow optimization and megahertz intensity and tilt sensor

4. Alpha Test History

A total of 27 high-power tests were run with the Alpha laser. These are summarized in Table 2 and discussed below.

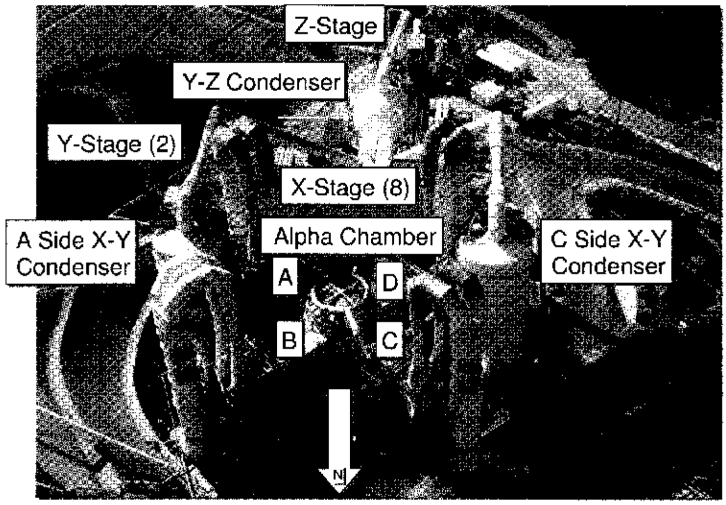

Fig. 11. Pressure recovery system at CTS used to simulate the vacuum of space for Alpha laser operation.

The HL501–HL550 tests were conducted under the Alpha and BETA (Bridge Effort to ALTO) Programs during the period May 1987–April 1990. Facility testing starting in May 1987 provided an early assessment of ability to support low-pressure dynamic chemical laser flows. First light with Alpha was achieved 7 April 1989 (HL501), but facility performance and resonator alignment were nonoptimum, and rework was required on the gain generator to improve the base purge. Tests HL520, 530, 540, and 550 then evaluated facility performance during lasing and initial optimization tests.

Tests HL601–HL901 were conducted under the ALTO (Alpha Laser Test and Optimization) program during the period November 1990–July 1992. Adequate single-line power for initiation of the ALI program was demonstrated, optimization of gain generator flows continued, system jitter was investigated and reduced, and longer lasing (up to 6.2 s) duration was achieved. It was also during these tests that an external cavity uncooled optic was demonstrated, providing the impetus for further uncooled resonator research with a goal of eliminating cooled optics in future devices.

Tests HL902–HL910 were conducted under the Alpha Laser Optimization (ALO) program during the period November 1992–March 2000.[5] The ALO program goals were as follows:

- Primary objective: Support the Alpha-LAMP Integration (ALI) program goals
  - Upgrade the Alpha facility
  - Perform general maintenance activities
  - Increase the general efficiency of operating the system
- Secondary objective: Gather scientific and engineering data for the development of space-based chemical lasers for strategic defense
  - Continue selected performance improvements
  - Technology developments, investigations, and demonstrations

Eleven high-power lasing tests were performed. These are listed in Table 2, and some results from HL907, HL908a and b, and HL910 are given below.

Table 2. Alpha high-power test history

Test	Contract	Date	Duration (s)	Description
HL501	Alpha	04-07-89	0.3	Demonstrated safe lasing
HL520	Alpha	08-10-89	0.8	Optimization test
HL530	Alpha	09-26-89	4.0	Optimization test
HL540	BETA	12-08-89	4.0	Optimization test
HL550	BETA	04-19-90	1.4	Optimization test
HL601	ALTO	11-30-90	1.2	Met ALI power goal
HL701	ALTO	05-16-91	4.6	Power repeated with long duration
HL901	ALTO	07-16-92	6.2	Higher power and uncooled optic
HL902	ALO/ZS	11-12-92	4.1	Uncooled optic (flat) in resonator
HL903	ALO	07-16-93	4.1	Alignment excursion
HL904	ALO	08-17-94	4.1	Reconfigured to provide beam to ALI
HL905	ALO	09-18-96	5.1	Reactivated after 2 years mothballed
HL410	ALI	02-20-97	0.5	Demo safe power through ALI
HL420/906	ALI/ALO	07-16-97	0.9	ALI jitter loop closed; test aborted
HL430	ALI	10-22-97	1.2	ALI control loops closed; test aborted
HL907	ALO	01-28-98	5.9	Two flow conditions
HL440	ALI	06-09-98	4.9	ALI test with uncooled DM
HL908A	ALO	07-23-98	5.9	Rear cone scan (x axis)
HL908B	ALO	07-30-98	5.9	Rear cone scan (y axis)
HL909A	ALO	08-10-99	5.9	Improved alignment
HL909B	ALO	08-19-99	5.9	Repeatability
HL910	ALO	03-28-00	5.9	More outcoupled, less clipped power
HL911-1	IFX	08-29-00	5.9	Lower flow condition; some data lost
HL911-3	IFX	10-12-00	5.9	Lower flow condition; retest
HL912	IFX	12-08-00	5.9	Beam director test
HL913-2	IFX	11-15-01	5.9	MITS
HL913-4	IFX	03-07-02	8.0	MITS; retest with feed tube repair
Total 27 tests			114.4	

Tests HL410-HL440 were conducted under the ALI program—part of the Zenith Star (ZS) program—during the period February 1997–June 1998. These four high-power lasing tests demonstrated integrated beam control by using the Alpha laser, uncooled beam control optics, and the Griff 4-m Telescope (LAMP primary mirror) and demonstrated survival and closed-loop operation of the telescope, uncooled deformable mirror, and fast steering mirror under megawatt-class lasing.

5. HF Laser Maturity Assessment Panel Key Findings

When Air Force Space and Missile Systems Center (SMC) assumed responsibility for developing a (now canceled) SBL Integrated Flight Experiment (IFX), program leadership was concerned about the readiness of the HF laser technology to support the program. To address this concern an expert panel was chartered. The HF Laser Maturity Assessment

Panel was chaired by David Johannsen, and included members from the Department of Defense, Federally Funded Research and Development Centers (FFRDCs), and industrial contractors. The panel met April–May 1998 with the following goal:

- To evaluate the status of HF as a megawatt-class laser in light of
  - Test results
  - Modeling capability vis-a-vis test results
  - Risk reduction activities required to make an HF-based SBLRD feasible with moderate risk
  - Scalability to operational power levels

Although the Panel addressed six specific questions related to the above goal, the one relevant to this paper was as follows:

- Are HF laser models and codes and the Alpha performance results consistent?
  - Consensus: Qualified yes
    - Alpha power output from best tests at reduced NF_3 flow consistent with expectations
    - Why power dropped in some tests only partially understood
    - Since Alpha has not been fully characterized, it is impossible to fully understand its performance in terms of the models
    - Input uncertainties limit modeling accuracy

6. ALO Data Analysis Task

Based on the HF Laser Maturity Assessment Panel findings, SMC added a task to the ALO contract to analyze and understand the results of the HL907, HL440, HL908A, and HL908B tests with an overall goal to provide data to anchor models.

Key insights gleaned from this effort were as follows:

- NF_3 flows were 4% higher than intended
  - Improves agreement between modeled and actual power
  - Indicates Alpha has not been operated at optimum flow rate
- Resonator alignment methodology deficient
  - Resonator not properly aligned during tests
  - Probable modest impact on power
- Pressure recovery effects appear not to have affected data
  - Evaluation continues
- Instrumentation calibration corrections were needed

Several diagnostics were added at this point. A Beam Compactor Annular Dump Diagnostic provided a fiber-optic-fed intracavity measurement of clipped power spatial distribution and magnitude to help understand where available power was lost in the system. A Reverse Wave Near Field Intensity camera to measurement intracavity forward and reverse wave intensity was added to help understand losses due to the reverse wave in the resonator[2] (Fig. 12). An Alternate Power Diagnostic (APD) based on a novel use of transmitted power through a high-power optic to accurately measure outcoupled power was added as a proof-of-concept approach for measuring outcoupled power when the main beam was used for beam control experiments rather than dumped into the TPC.[2]

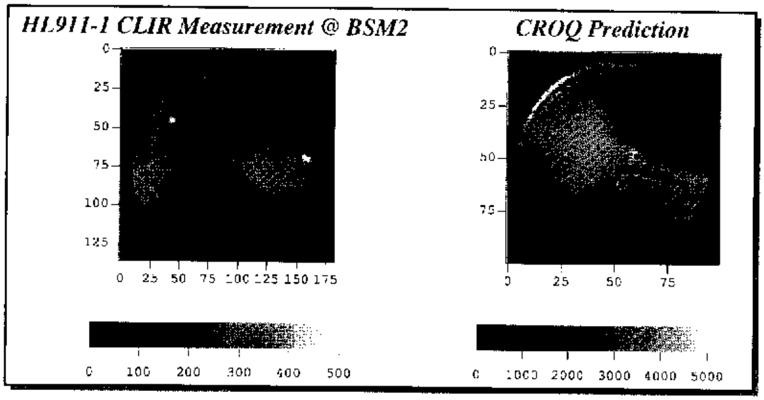

Fig. 12. Measured and predicted intensity on a feedback mirror showing the reverse wave.[2]

7. HL910 Test

The HL910 test objectives were as follows:

- Primary:
  - Run Alpha with the same gain generator operating point as HL909B
  - Move the Beam Compactor Annular Clippers to reduce clipped power
- Secondary:
  - Acquire high-energy laser (HEL) data with new and upgraded diagnostics

The HL910 test objectives were successfully met. A greater than 75% outcoupling fraction with a more uniform beam was demonstrated, as was the highest outcoupled power ever achieved with Alpha. The near-field intensity pattern is shown in Fig. 13.

8. HL911 and HL912 Tests

The HL911 test objective was to measure performance at a new flow condition to anchor models.

A reduced fluorine atom flux was expected due to increased flame temperature and increase fluorine dissociation. The objectives were successfully met, with increased sigma (power per unit reactant mass) and very stable laser performance was demonstrated.

The HL912 test objectives were as follows:

- Verify the closed-loop operation of
  - Telescope Alignment Assembly (TAA)
  - Alignment Annulus Assembly (AAA)
- Provide another anchoring point for laser performance models
  - Provide data to be compared with the HL910 predicted and HL910 measured data
  - Assess the effect of coupling the laser to the external chamber and [a beam control] (ALI configuration) beamtrain

The objectives were successfully met. The TAA and AAA operated successfully, and the outcoupled power was not reduced by interaction with the ALI beamtrain.

Fig. 13. Near-field intensity of the Alpha beam from the HL910 test.[2]

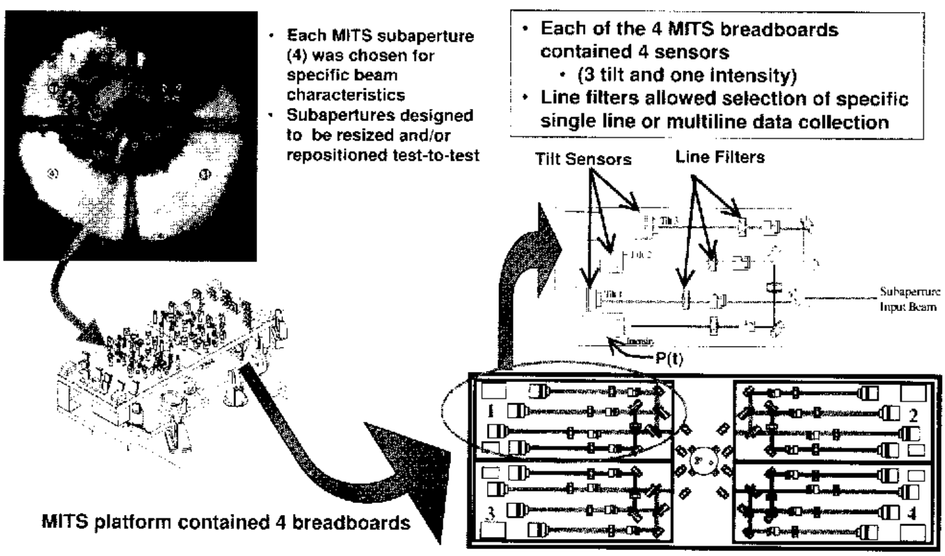

Fig. 14. Overview of the MITS and test.

9. HL913 Test

The HL913 test was performed with the new megahertz Intensity and Tilt Sensor (MITS) to measure subaperture wavefront behavior at high temporal frequency. Figure 14 provides an overview of MITS.

The primary objective of HL913 was to obtain MITS data and was successfully met. As hoped, the data showed a $1/f^2$ roll-off of subaperture tilt and intensity with no evidence of high-frequency structure. It also showed good correlation between lines. Although this suggests the beam would have been highly correctable, more data would have been useful to characterize correctability limits. Figure 15 shows a sample power spectral density (PSD).

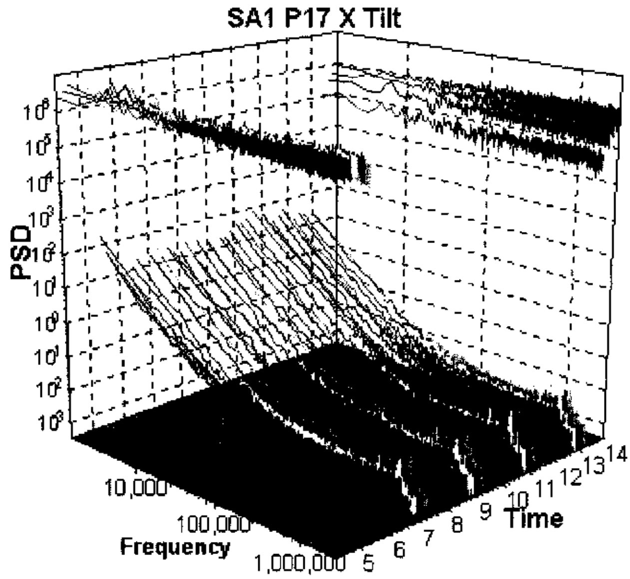

Fig. 15. Sample MITS PSD. PSDs over a succession of time slices during the test are shown. (Time slices with no signal are seen before and after the lasing period.) As expected, the power falls off as $1/f^2$ until the noise floor of the sensor is reached.

Fig. 16. Alpha test stand at dusk.

10. Summary

Early work on HF and DF lasers indicated that scaling to high enough power for weapon application was possible. The Alpha program was initiated to provide the source for a space laser weapon. After some adjustment, the Alpha laser demonstrated megawatt-class power and then served as the source for the ALI tests, generating good data. The HF Laser Maturity Assessment Panel raised questions about Alpha operations, which led to the Data Analysis task on the ALO contract that uncovered alignment and flow problems. Later Alpha tests were very successful:

- HL910 showed increased power with reduced clipping
- HL911 showed improved reactant efficiency at lower flow
- HL912 showed telescope alignment performance in the presence of an HEL
- HL913 provided MITS data—data that increased confidence that combustion-driven high-energy laser beams are correctable to near the diffraction limit

11. Postscript

After 27 high-power tests, the final four of which demonstrated that, in its maturity, it had realized the goals of its developers and was able to return data of great value to understanding high-power HF/DF lasers, Alpha is in the process of being dismantled.... (Figure 16 shows the Alpha test stand at dusk.)

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The Authors

Mr. Robert Geopfarth graduated with distinction from the University of Kansas in 1972 with a Baccalaureate degree in Mechanical Engineering, and in 1979 earned a Master's degree in Aeronautical Engineering from the Naval Postgraduate School (NPS). He retired from the U.S. Navy as a Lieutenant Commander in 1986 after a 20-year career that included assignments in electronics (radar), nuclear power, aircraft carrier flight operations (tactical reconnaissance), and R&D field operations. During his final 6 years he served as a Navy Technical Liaison Officer on the Air Force Airborne Laser Laboratory program, on a flight crew during test missions involving that device, and finally as Operations Officer for the Navy High Energy Laser Program Office, where he gained integration and operational experience on TRW's MIRACL laser system at White Sands Missile Range. He joined TRW in 1986 and was the lead test engineer during all phases of integration, activation, and test operations conducted with the Alpha high-energy laser system at the Capistrano Test Site. After serving as Program Manager for the SBL Disposition effort and as Lead Test Conductor for the successful Liquid Booster Development Program, he retired from what had become Northrop Grumman Space Technology and joined The Aerospace Corporation in the Space Tracking and Surveillance System program office.

Dr. David Johannsen has a B.S. in Physics from the California Institute of Technology and an M.S. and a Ph.D. in Physics from the University of California, Riverside. After teaching at Loyola Marymount University and working at Hughes Aircraft Company, Allied Corporation, and Northrop Corporation, he joined The Aerospace Corporation in 1987. In addition to Space Based Laser (SBL), he has supported a variety of Missile Defense and Air Force space programs. Since the demise of SBL he has been a Senior Project Leader supporting MDA's Space Tracking and Surveillance System.

Ms. Lorraine E. Ryan has a B.S., Chemistry, from Loyola Marymount University at Los Angeles and was enrolled in the Materials Engineering Masters Program, UCLA, 1971–1973. Ms. Ryan is currently a Senior Project Leader at The Aerospace Corporation in the Missile Defense Space Systems Space Based Surveillance Division. Her past employment was with NGST's Systems Engineering Center as the Airborne Laser (ABL) Laser Segment Systems engineering manager. This engineering management assignment included the incremental evaluation and upgrading of requirements and the management of the technical work of 52 systems, technology, and laser engineers working on Block 04–Block 08 ABL activities. Her past assignment at NGST was as a Sr. Technical Specialist with the Laser and Sensor Products Center. Ms. Ryan managed the Alpha Laser Program. This Air Force Program was the centerpiece testbed for the Space Based Laser Integrated Flight Experiment Program. This High Energy Laser Program conducted the tests that anchor the predictive models for the SBL IFX flight payload design.

Mr. Martin Wacks is a Senior Systems Engineer/Manager with Northrop Grumman Space Technology (NGST). His involvement in the development and testing of high-energy lasers began in 1980 when he joined TRW (now NGST) as an optical engineer supporting the MIRACL laser at TRW's Capistrano Test Site. He was then involved in the development and testing of the Alpha laser. As the Laser Payload Element lead for the SBL Integrated Flight Experiment (IFX) program, he was responsible for evolving the Alpha technology toward a flight experiment. After the cancellation of the IFX program he worked on the ABL and THEL lasers. His career has also included managing TRW and NGST functional organizations supporting optical systems and testing.