Space Flight Laser Development: Lessons Learned

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NASA Technology Readiness Levels (TRL)

Basic Tech Research

Level 1 Basic principles observed and reported

Research to Prove Feasibility

Level 2 Technology concept and/or application formulated

Level 3 Analytical & experimental critical function and/or characteristic proof-of-concept.

Technology Development

Level 4 Component and/or breadboard validation in laboratory environment.

Level 5 Component and/or breadboard validation in relevant environment.

Technology Demonstration

Level 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

System/Subsystem Development

Level 7 System prototype demonstration in a space environment

Level 8 Actual system completed and "flight qualified" through test and demonstration (ground or space).

System Test, Launch and Operations

Level 9 Actual system "flight proven" through successful mission operations.

Some Initial Considerations For Space Flight Laser Design

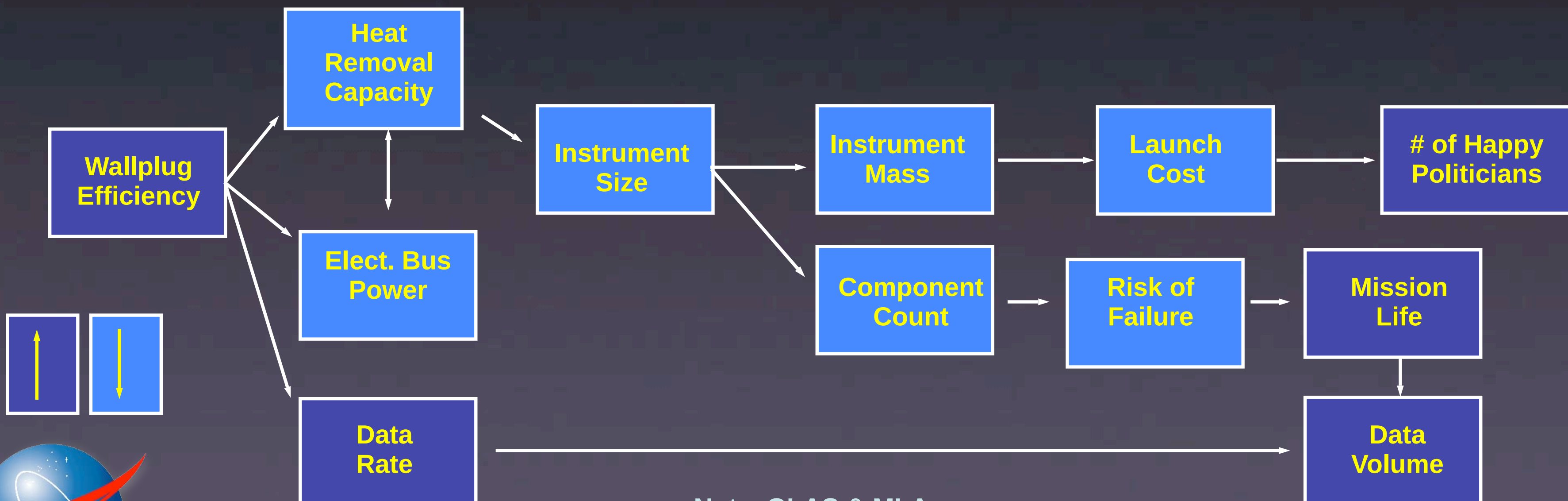
Example Science Applications: Wind/Atmospheric LIDAR [0.5 - 1 J/pulse @ 100 Hz]
Vegetation/Ice/Topography [15 - 25 mJ/pulse @ 300 Hz]
High Res Vegetation [1 - 10 mJ/pulse @ 10 - 100 kHz]

Our efforts must improve, in some significant way, one of the following solid state laser technology issues:

- Efficiency (optical, wallplug)
- Reliability (damage, lifetime)
- Ruggedness (alignment, cleanliness)

Efficiency is a significant weakness of DPSSL technology.

GLAS 4% (MOPA 100 mJ / 4 W)
MOLA 2.4% (mulitmode laser - 40 mJ / 0.4 W)
VCL >6% (never flew, 17 mJ / 4 W)
MLA ~3% (MOPA, 20 mJ / 0.16 W)



Note, GLAS & MLA are currently operational.

GLAS: mission passed 1 billion shots!

Critical Environmental Parameters for Flight Qualification

- Vacuum requirements
- Vibration requirements
- Thermal requirements
- Radiation requirements

Thus, the laser design must take these into account at the earliest possible stage.

Critical Environmental Parameters for Flight Qualification

- Vacuum tests
- Vibration tests
- Thermal tests
- Radiation tests

test

test

test again

Lifetest!

Upon designing schedule and procedures, “enough” testing must be provided for the ETU development.

Every bit done here pays off with HUGE dividends on recurring copies.

Environmental Parameters: Vacuum

Vacuum outgassing requirements:

- ASTM-E595,
  - 100 to 300 milligrams of material
  - 125°C at 10^{-6} Torr for 24 hours
  - Criteria: 1) Total Mass Loss < 1%
    2) Collected Volatile Condensable Materials < 0.1%

- Configuration test
- Is ASTM-E595 enough?
- Ask your contamination expert:
  Their answer is typically "no" for laser systems

Space environment; vacuum is actually 10^{-9} torr, best to test as close as possible for laser systems. Many chambers don't go below 10^{-7} torr.

Environmental Parameters: Vacuum

Trade studies are open "again" on the issue of vacuum vs pressurized laser vessel.

GLAS, MLA, MOLA, NEAR, others...: Evacuated
    GLAS likely suffered from contamination issues probably amplified by presence of a vacuum. (Independent GLAS Anomaly Review Board 1 & 2)

MLA :will only need ~ 1 million pulses, but needs to survive 6.6 year transit. Composed of essentially the GLAS oscillator and 1st stage amplifier.

BioMM (BioMass Monitoring Mission) - under proposal, Baselining the HOMER (High Output Maximum Efficiency Resonator) as a pressurized cavity.

Calipso has launched a pressurized vessel WITH lifetested ETU as a demonstration.

Should You Fly Pressurized or Evacuated?

Pressurized

- Diffuse Transport
- Air Oxidizer
- Alignment
  - Bench/laser flex
  - Inter-optic refraction
- Coatings Stability
- Heat dissipation
- Mass
- Seal Lifetime
- Surface Energy

Vacuum

- Ballistic Transport
- Minimal Oxidizer
- Alignment
  - Bench/laser flex
  - Inter-optic refraction
- Coatings Stability
- Heat dissipation
- Mass
- High Voltage
- Surface Energy

Environmental Parameters: Vibration

Use GEVS (Goddard Environmental Verification Specifcations) as a guideline for testing.

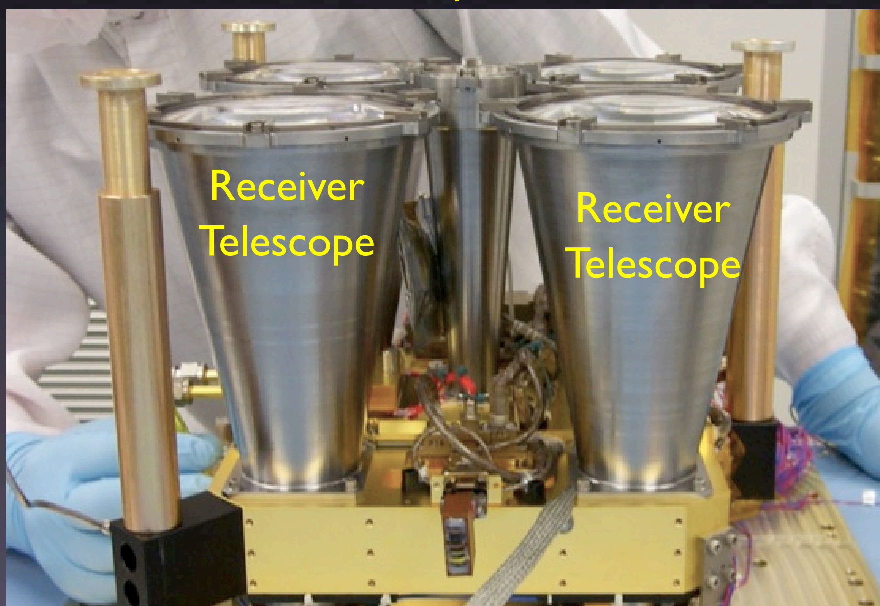
Launch vehicle vibration levels for small subsystem (established for EO-1)

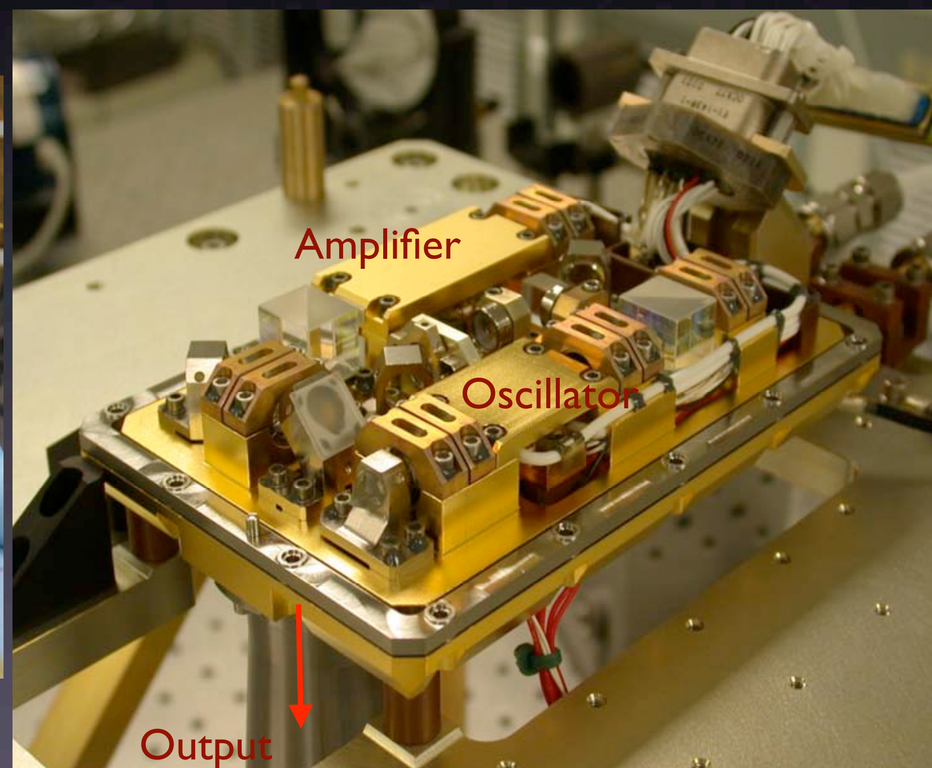
Frequency (Hz)	Protoflight Level
20	0.026 g^2/Hz
20-50	+6 dB/octave
50-800	0.16 g^2/Hz
800-2000	-6 dB/octave
2000	0.026 g^2/Hz
Overall	14.1 grms

Assuming that the total system level 10 grms is the total and the profile values per frequency are half of what they are as listed in the table.

Packaging for Low Sensitivities

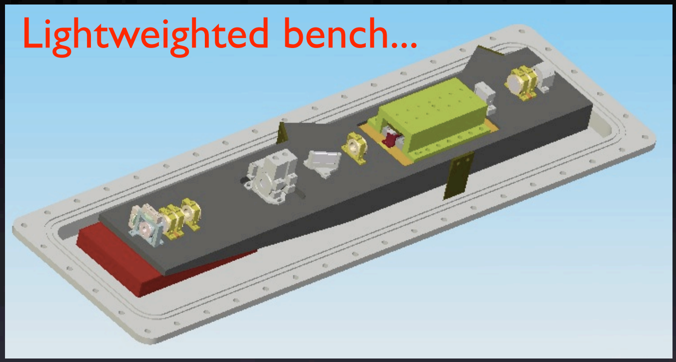
The MLA laser design and packaging are both inherently stable and rugged.





Packaging for Low Sensitivities

Lesson: Revisit why your laser design is what it is. Check all the usual assumptions and do some early conceptual studies.



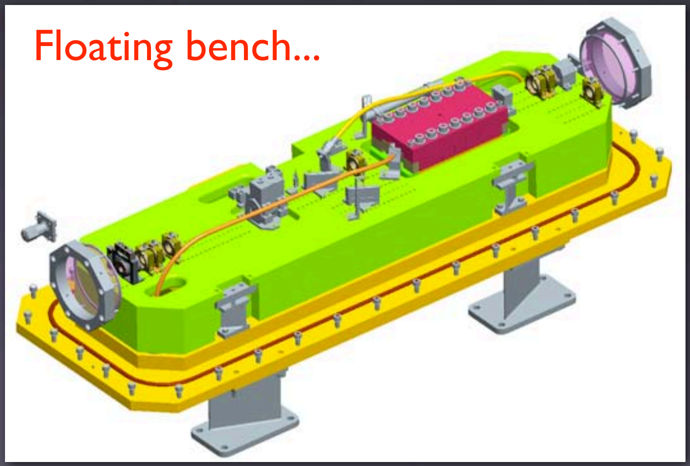
1. Do you need all the optics?

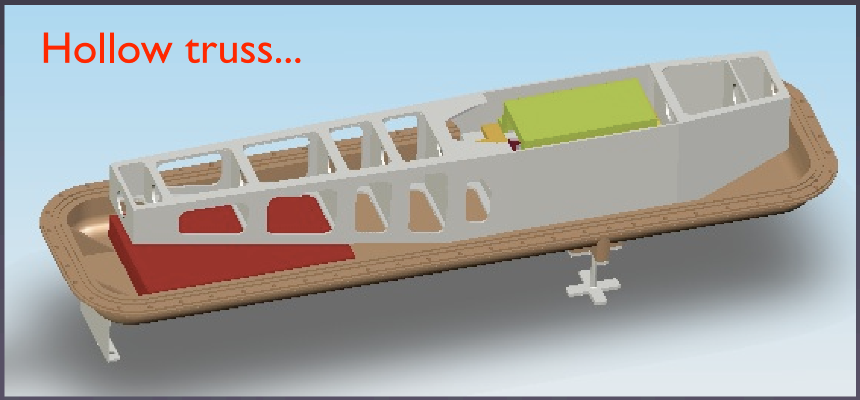
2. Does folding a long cavity really help?

3. Is an optical bench always best?

4. What's the best way to handle thermal? What about using the heat to your advantage?

5....





Environmental Parameters: Thermal

Depending on the part for testing;

- Insitu testing where possible
- Add 10°C to each extreme for box level operational for insitu tests
- Add 10°C if possible for survival non operational range

Thermal cycles determined by part type;

- 60 cycles for assemblies for high reliability
- 30 cycles minimum for assemblies, high risk
- 100 or more, optoelectronics.
- More for high power systems

Knowledge of packaging and failure modes really helps with cycles determination.

Environmental Parameters: Radiation

Typical space flight background radiation total dose
30 Krads – 100 Krads over 5 to 10 year mission.

Dose rates for fiber components:

- GLAS, 100 Krads, 5 yr, .04 rads/min
- MLA, 30 Krads, 8 yr, .011 rads/min (five year ave)
- EO-1, 15Krads, 10 yr, .04 rads/min

Any other environmental parameters that need to be considered? For example, radiation exposure at very cold temp, or prolonged extreme temperature exposure based on mission demands.

Flight Laser Design Process: Modeling Requirements

Once your science application is determined, a set of requirements is agreed upon. Then the laser transmitter can be designed. COTS must be considered for many of these items since flight laser heritage is relatively young.

Before designing/selecting hardware, mission requirements must be known for…

1. Output power
2. CW/Pulsed
3. Pulsewidth - us, ns, ps,…
4. Rep rate
5. Duty cycle
6. Size constraints
7. Wavelength & Linewidth
8. Beam Quality (TEM_{00} or TEM_{mn})
9. Single frequency or broad bandwidth
10. Tunable?
11. Expected lifetime?

    … and most importantly…
12. **Environmental**

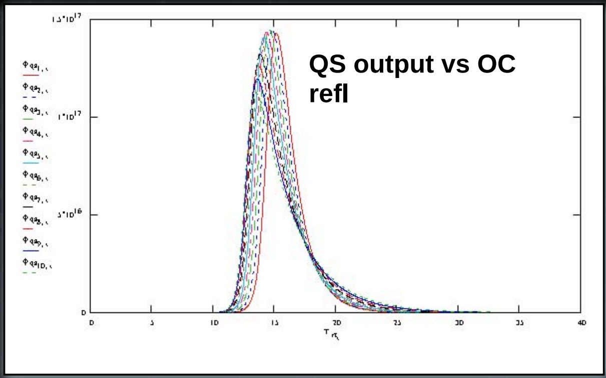
Once these questions are answered, models must be developed.

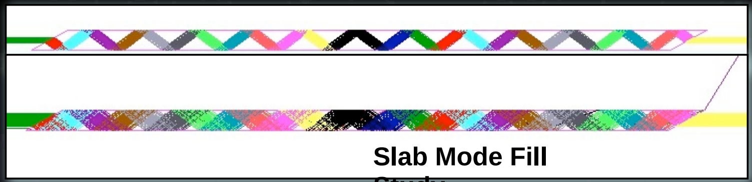
Parameter essentials to calculate are:

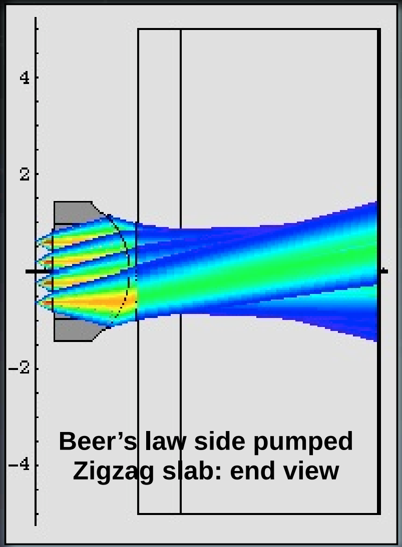
1. Cavity length
2. Mode size
3. Pump volume in gain medium
4. Pump source, diode array layout, etc…
5. Pump coupling scheme
6. Cavity stability

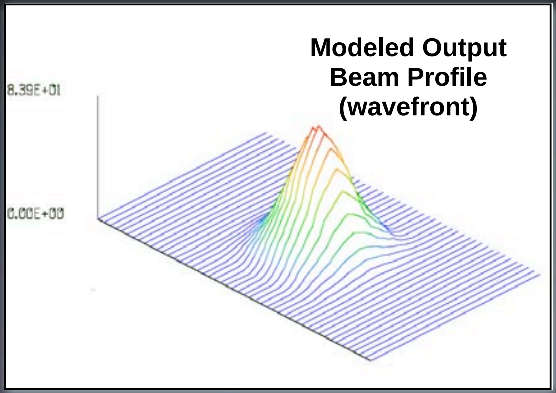
6. Output coupling
7. Heat removal
8. Intracavity thermal lensing
9. Thermal lensing compensation
10. **System Efficiency**

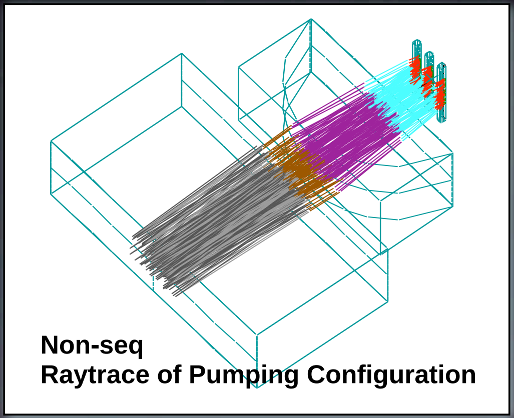
Some Methods for Nd:YAG Candidate Laser Design and Components

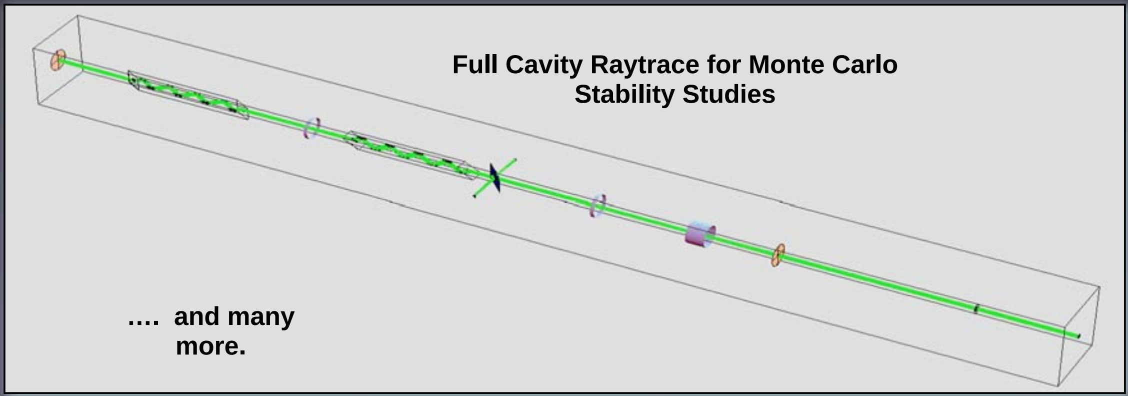






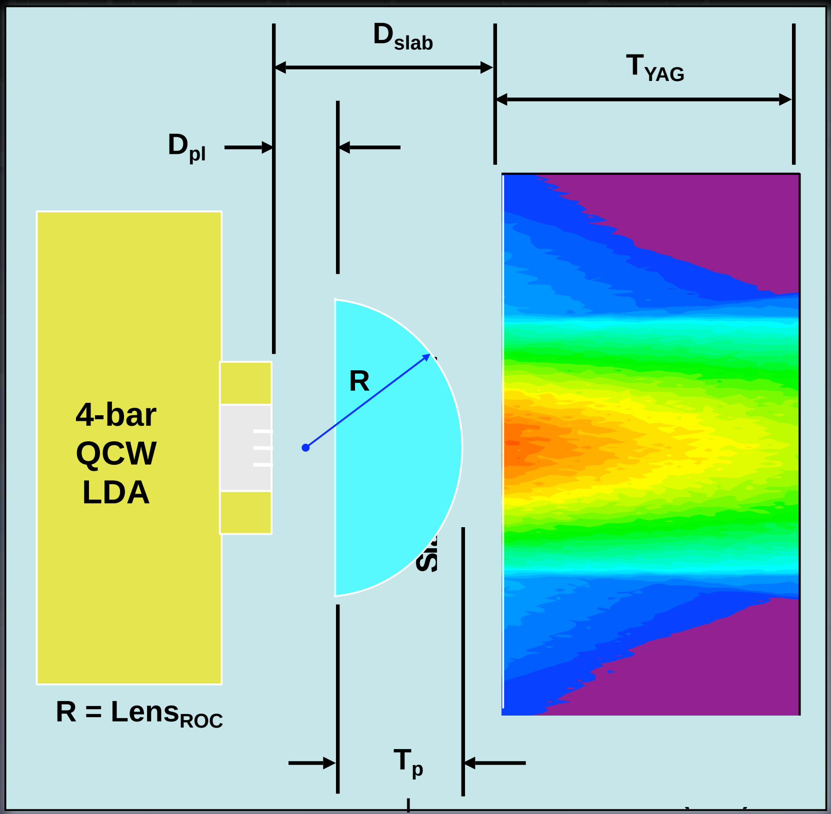




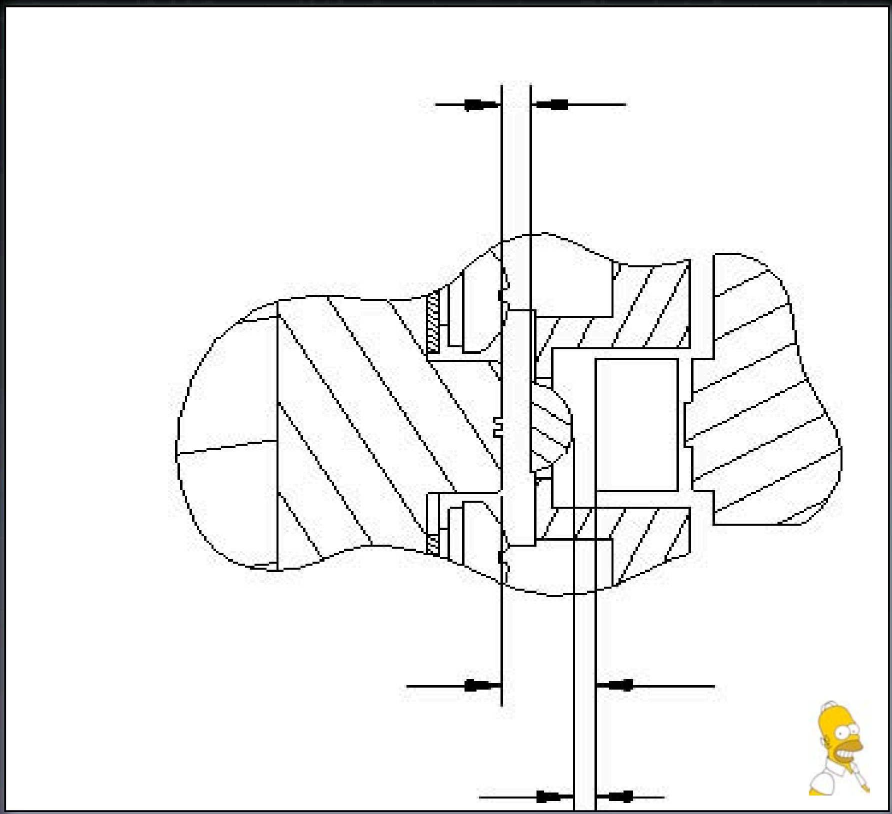


Lesson: It is important to use various modeling techniques, software, tools, and sources for as many components as possible. This provides overlap with each of the laser's parameters which reduces the modeling errors.

Example: High Output Maximum Efficiency Resonator (HOMER) for the Biomass Monitoring Mission (BioMM)
[Subsystem: Laser Head Assembly]

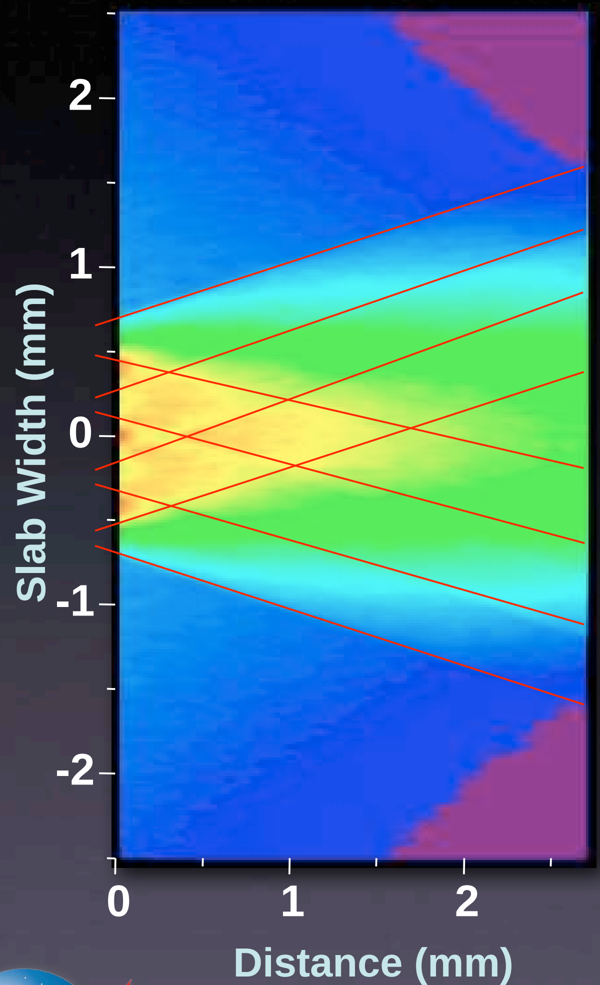


Side pumped HOMER head layout with one of 3 methods of modeling energy deposition shown.

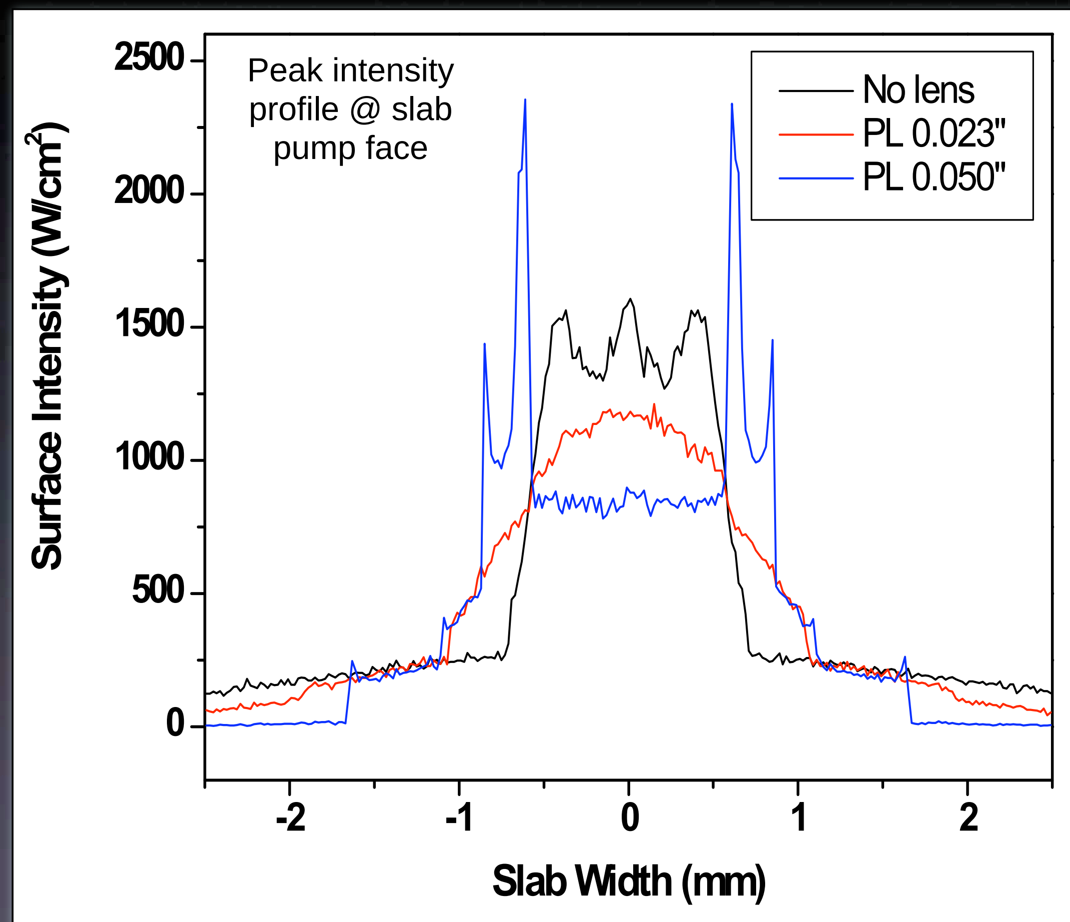


CAD cross-section view - used as reference and documentation in thorough study to replicate, iterate, and verify the modeled performance.

Direct Coupled 4-bar LDA Pumping of the HOMER Head

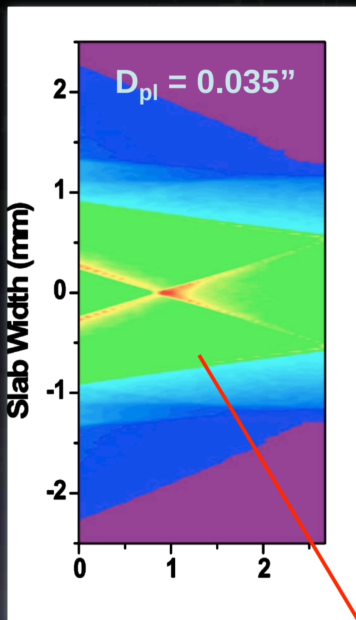


DC Pumping vs Bulk Collimated 4-bar LDAs



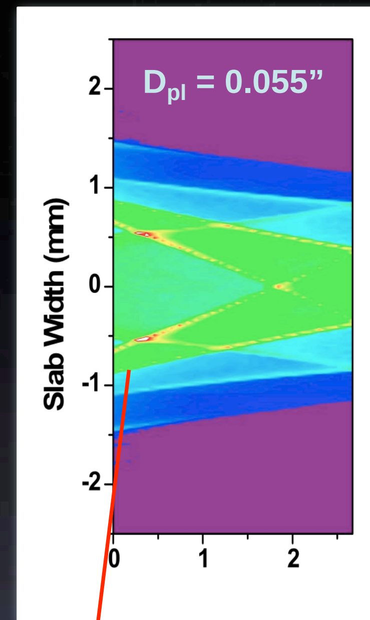
"Safe" assumptions can be found to have hidden risks.
Trade-off study in efficiency and added complexity performed.

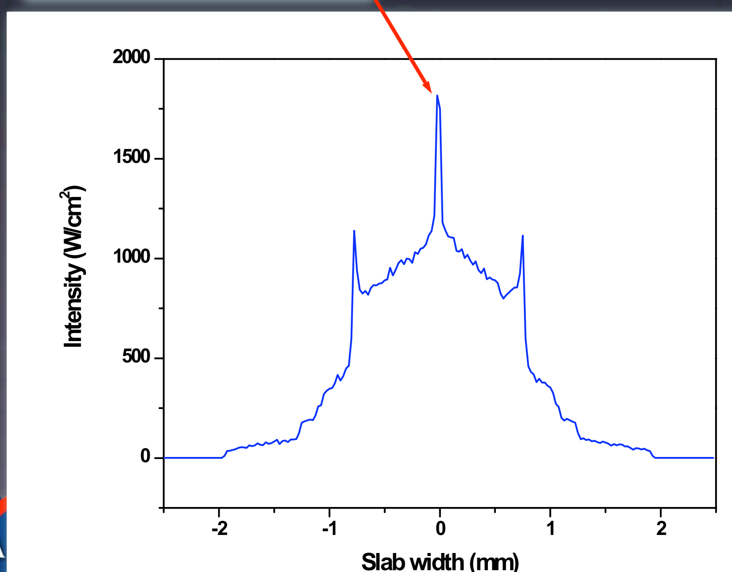
Absorbed Pump Energy Distribution

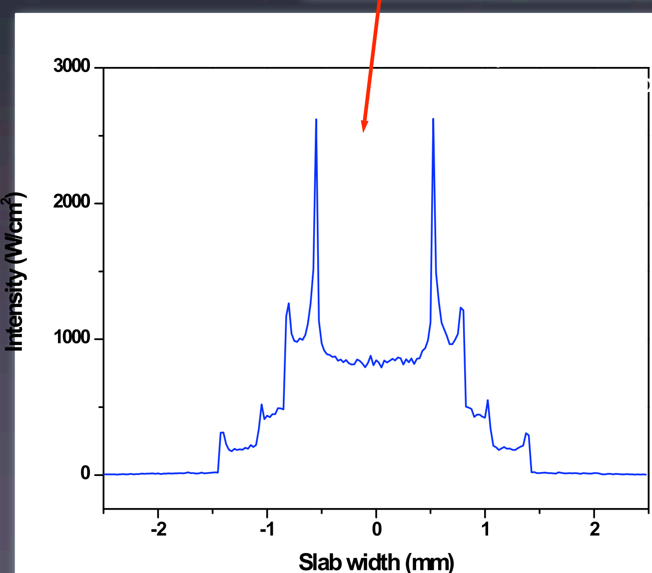


Better confinement of the pump volume is achieved with a cylindrical lens but small regions of high gain and transient temperatures (ie… thermal lenses) are produced.
These can fragment the cavity beam to form small beamlets within the TEM00 mode.

We believe this is another trigger for Small Scale Self Focusing





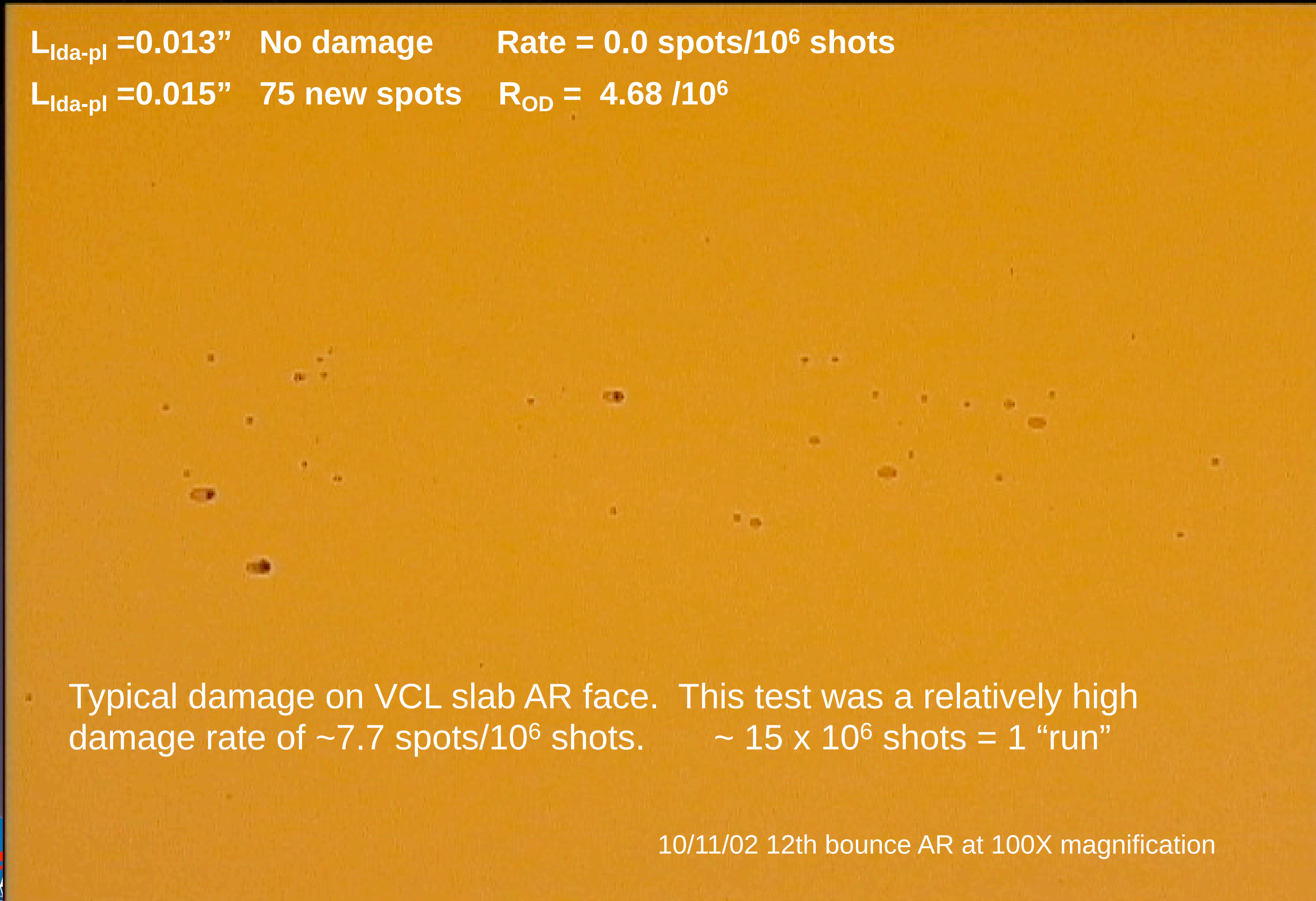


mp lens

Pumping Configuration Damage Test: Sample Run

L_{lda-pl} =0.013"   **No damage**   **Rate = 0.0 spots/10^6 shots**

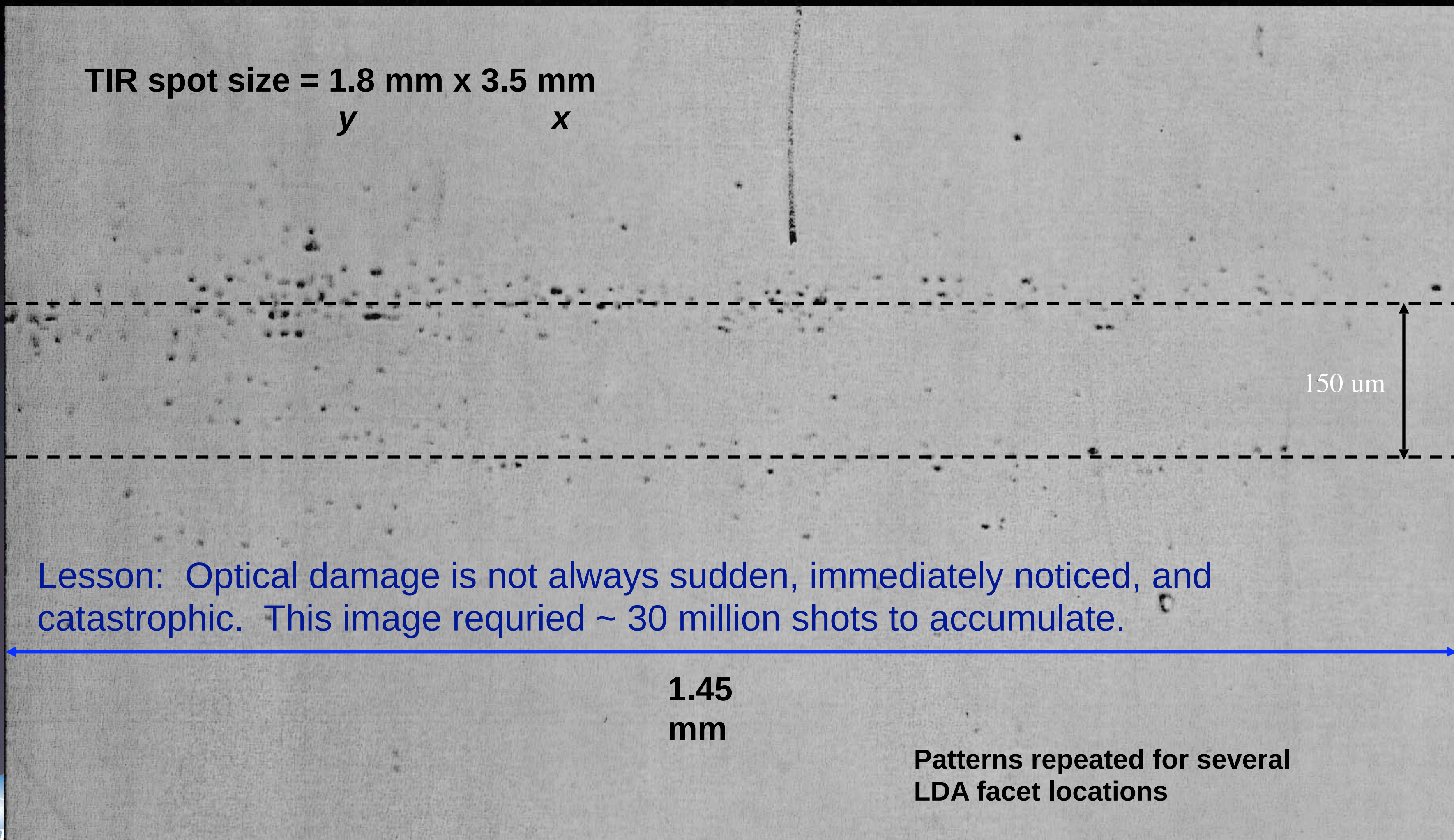
L_{lda-pl} =0.015"   **75 new spots**   **R_{OD} = 4.68 /10^6**



Typical damage on VCL slab AR face. This test was a relatively high damage rate of ~7.7 spots/10^6 shots.   ~ 15 x 10^6 shots = 1 "run"

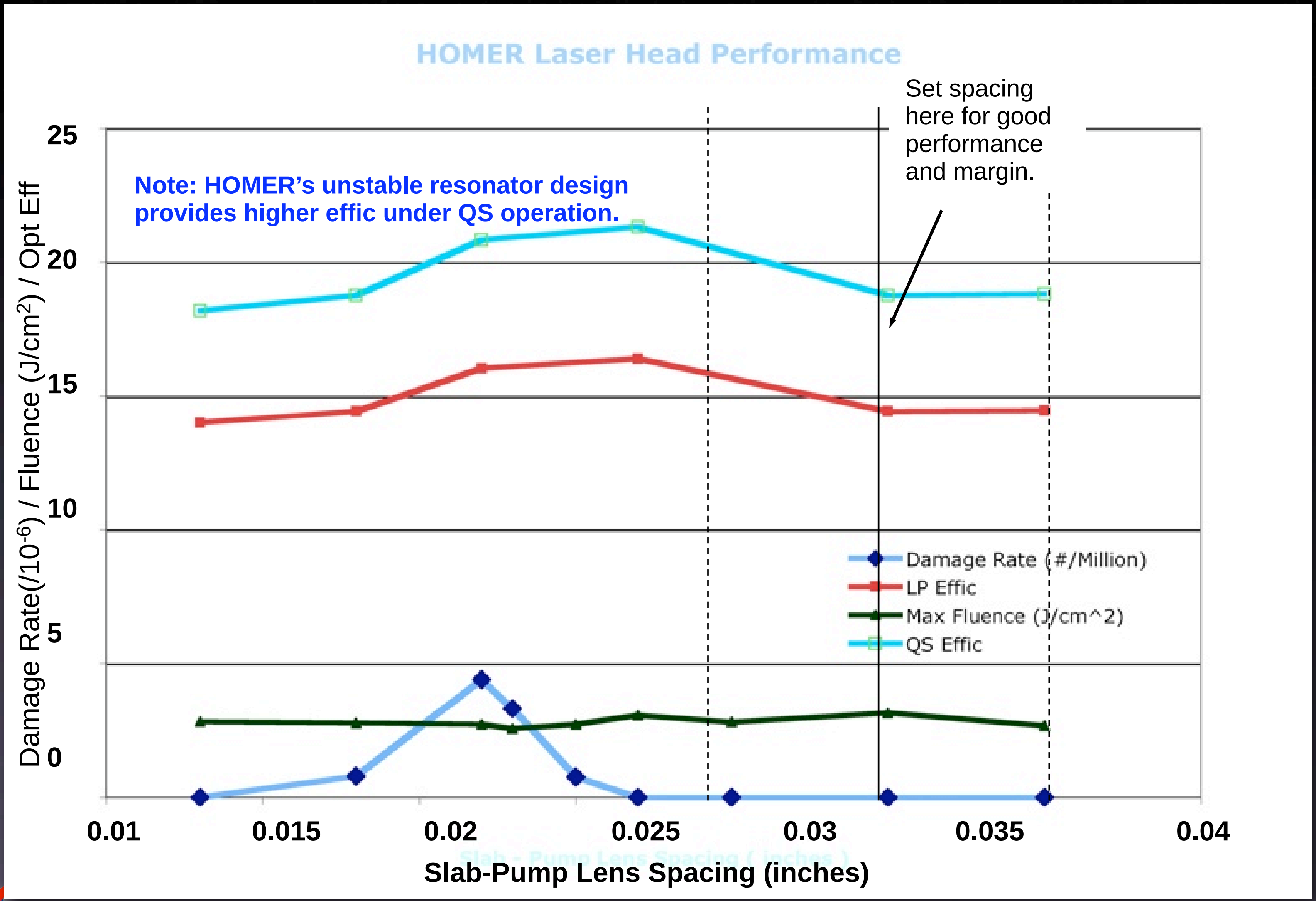
10/11/02 12th bounce AR at 100X magnification

Sample Burn Pattern (Slab AR Face) Indicating Possible Diode Array Influence



Lesson: Optical damage is not always sudden, immediately noticed, and catastrophic. This image requried ~ 30 million shots to accumulate.

Nd:YAG AR Pump Face Micro-Pitting Rates vs Pump Lens Placement



Lesson: Always provide margin with any laser design weakness. (Every laser has some...) This means you must ***know*** the weaknesses.

Some Causes of Design-Related Optical Damage in High Index Media (Nd:YAG Laser Systems)

Small Scale Self Focusing (SSSF)
Large Scale Self Focusing
Longitudinal Mode Beating (LMB)
Small Scale Thermal Lensing (SSTL)

When running non-SLM, one must be careful to track, predict, and take action to prevent these effects from arising.

We have witnessed runs of > 30 million pulses with no degradation in performance as the pit production rate was low. However, eventual catastrophic performance hit WILL occur if allowed to continue.

When near the final assembly stage of a cavity, each change in assembly requires at least a 10×10^6 shot run, or longer, with detailed inspections to follow.

SSSF Optical Damage References

" Mechanisms, for Self-Focusing in Optical Glasses", A. Feldman, D. Horowitz, and R.M. Waxler, IEEE JQE, vol.QE-9, No. 11, (1973).

"Light Propagation Through Large Laser Systems", W.W. Simmons, J.T. Hunt, and W.E. Warren, IEEE JQE, vol.QE-17, No. 9, (1981).

"Compensation of Nonlinear Self-Focusing in High-Power Lasers", U. Roth, F. Loewenthal, R. Tommansini, J.E. Balmer, And H.P. Weber, IEEE JQE, vol.36, no. 6, (2000).

"Self-Focusing and Optical Damage in a Diode-Pumped Neodymium Laser", G. Arisholm, OSA TOPS, Adv. Solid State Lasers, vol. 10, (1997). *

"Self Mode Locking of Solid State Lasers without Apertures", Opt Lett, vol. 18, (1993).

Correspondence with M. Kushina, Northrop Grumman Space Technology, CEO Laser Inc. Several occasions between 1998 - 2004. **

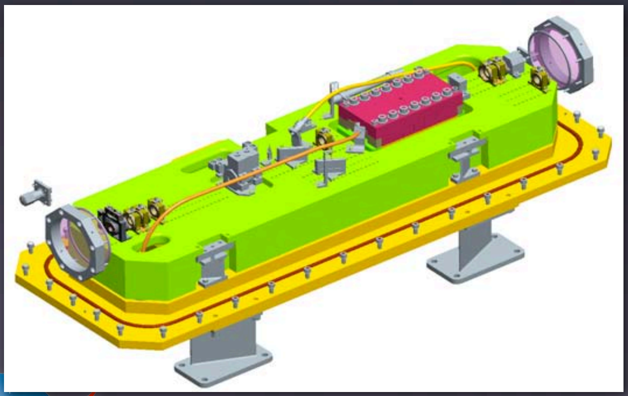
"Solid State Laser Engineering - 4 Ed.", W. Koechner, Chapters 4 and 11, Springer Series in Optical Sciences, Springer Verlag, (1996).

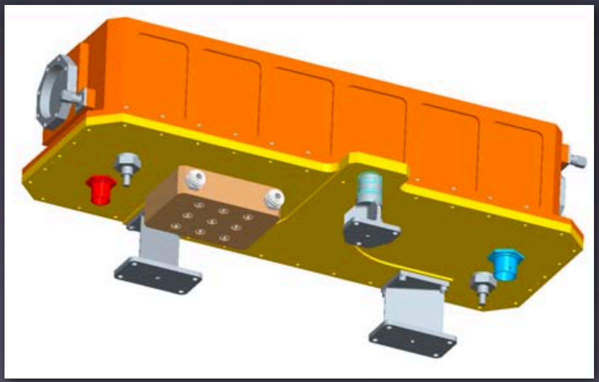
* Based on similar HOMER-like laser

** Personal experience is invaluable.

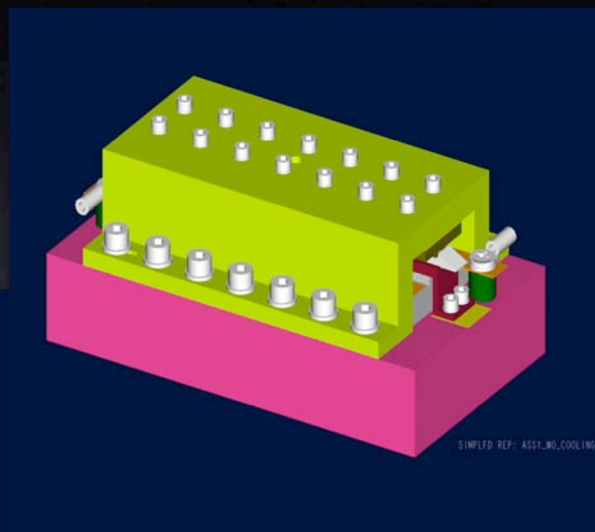
COTS Component Section & Qualification

Example: HOMER/BioMM QCW Diode Array Selection

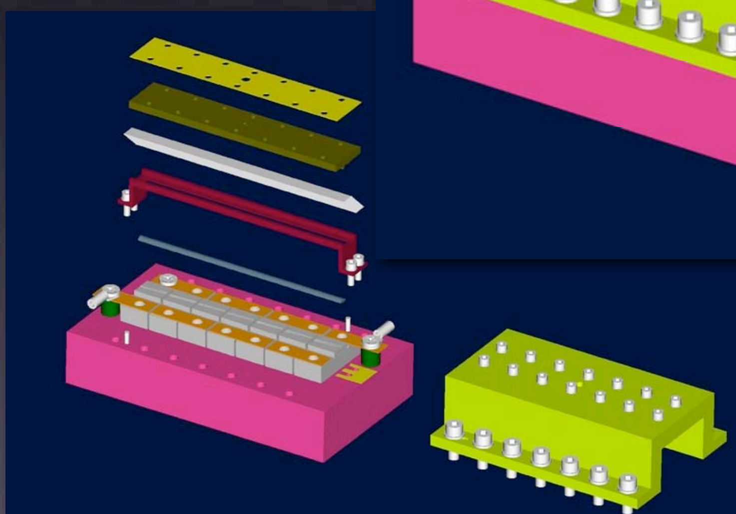


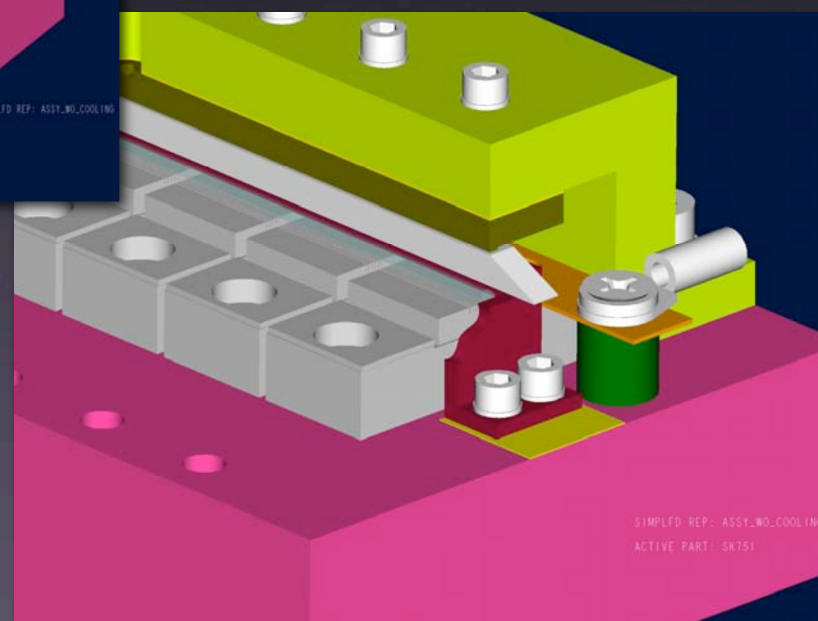


Example: High Output Maximum Efficiency Resonator (HOMER) for the Biomass Monitoring Mission (BioMM) [Subsystem: Laser Head Assembly]



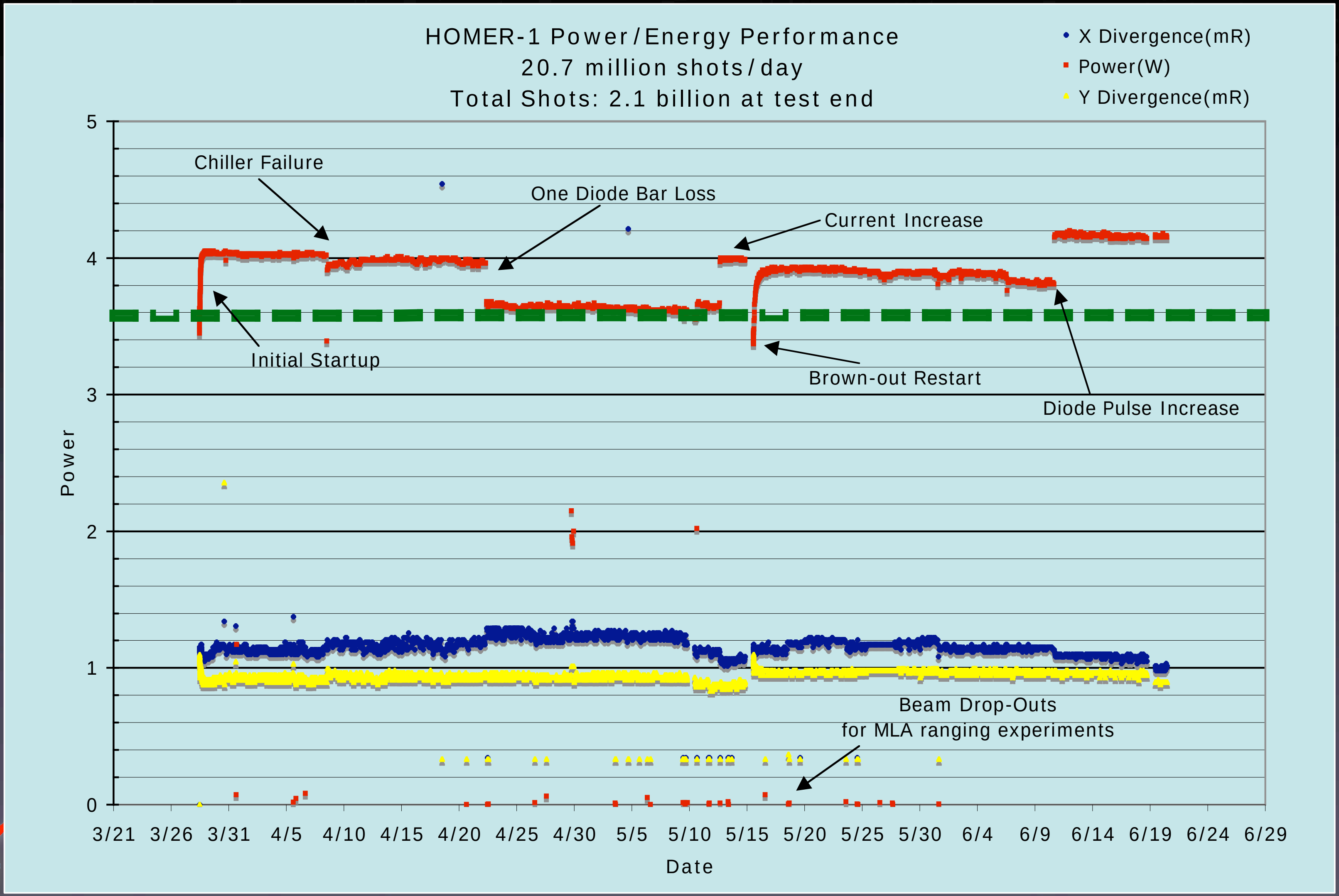
“Standard” side pumped zig-zag pumped head design employs G-package arrays and a suspended Nd:YAG slab, thermo-mechanically bonded to a “bridge” heat sink. Tungsten:Copper or Molybdenum:Copper material matches the CTE to the Nd:YAG. (Similar technique used on MLA, GLAS, LOLA, Calipso, ...)





Lesson: Build many copies, pinned, and easily reproducible. Multiple and frequent inspections must be done through all system builds with no impact on alignment.

Initial Long Term Testing: Verify decay rates and performance



High-Power Laser Diode Arrays

Mark Stephen, NASA GSFC, Code 554, mark.a.stephen@nasa.gsfc

Objectives

•Quantify effect of operational and environmental parameters on Laser Diode Array (LDA) performance.

•Develop procedures for purchasing, handling, storage, testing and operation.

•Develop prediction/screening capability.

•*Enable improved reliability and performance of future laser missions.*

Diagnostic, Test Capabilities & Accomplishments

Optical power measurements
- Average
- Spatially resolved
- Polarization resolved
- Temporally resolved

Electrical parameters
- Voltage
- Current
- Efficiency

Thermal Profiling
- Temporally, spatially resolved surface imaging
- Thermal modeling

Spectral Measurements
- Spatially, temporally Averaged
- Time-resolved spectroscopy
- Spatially resolved spectroscopy

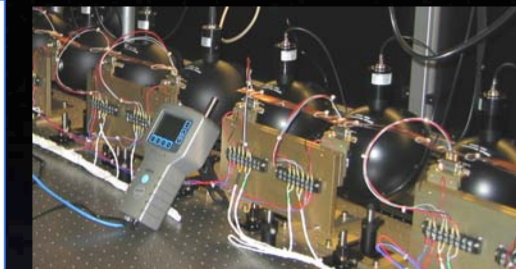
Facet Microscopy
- Near, dark field
- Extended focal imaging
- Side view
- SEM

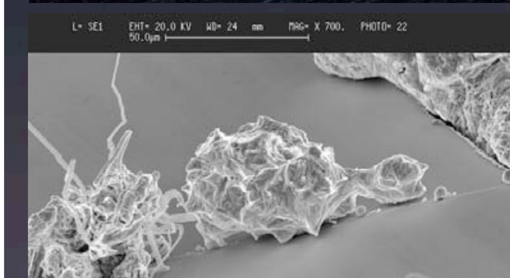
Long duration performance testing
- Laminar flow environment
- Vacuum operation

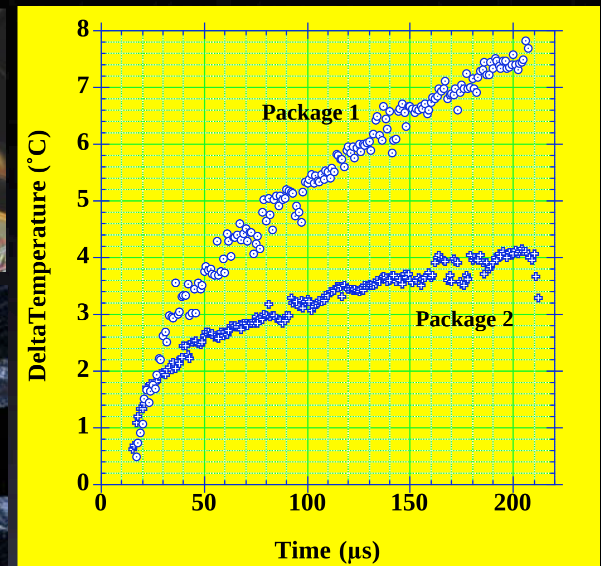
Space qualification
- Radiation
- Vibration

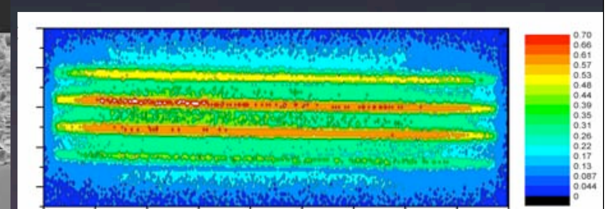
Destructive Physical Analysis

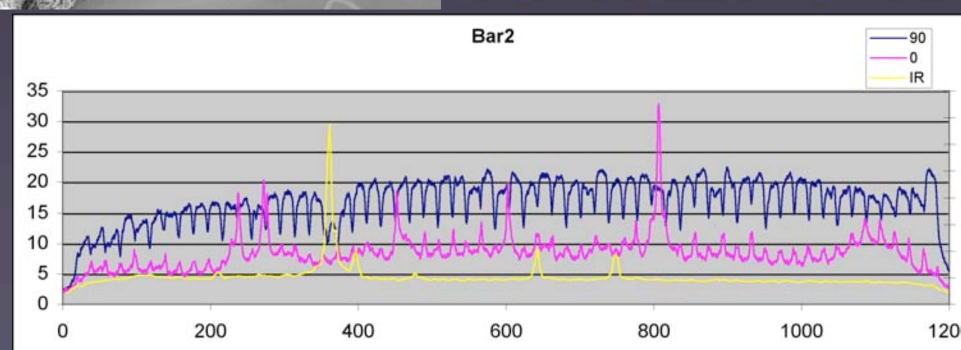
Developing Measurement
- Micro-Photoluminescence Spectroscopy







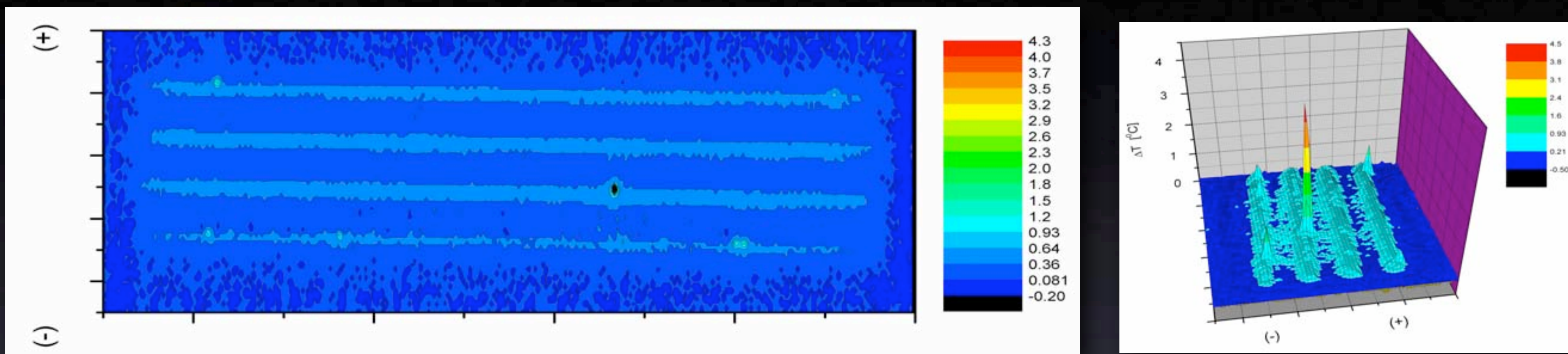




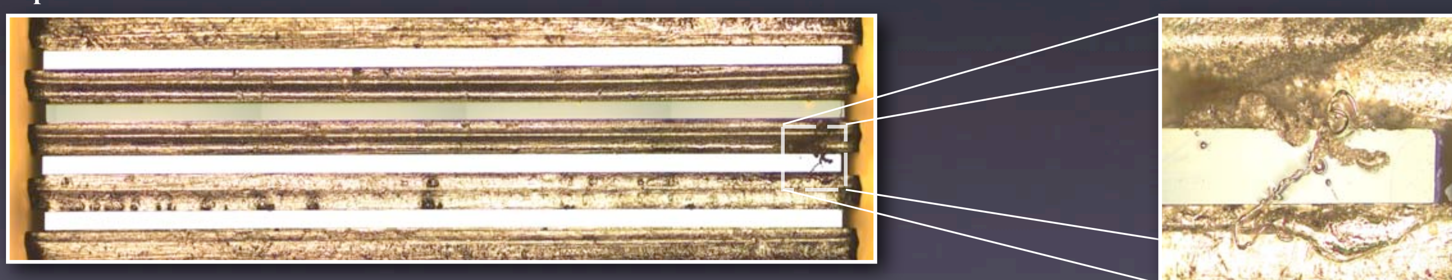
Diode Damage and Hot Spots

Example: Diode 4X60W QCW array

Thermal Images: Supplied by Mark Stephen et al.



Damage Inspection: Gordon Blalock



*Note that, while the hot spot is on the same diode bar, it is not where the indium arced thereby shorting the electrical circuit.

Laser Diode Packaging Issues/Concerns

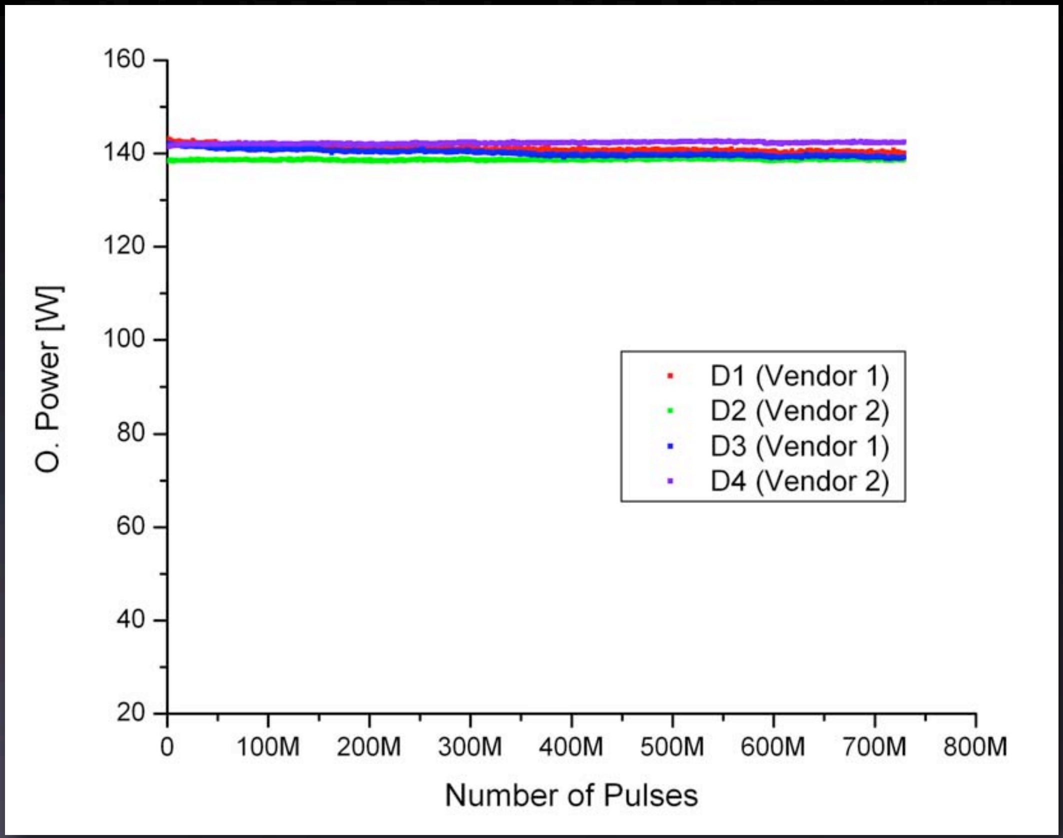
GLAS, MOLA, MLA, Calipso use high power QCW laser diode arrays.

Indium creep (shorting, intermetallics)
Cracking of semiconductor from wedgebonds
Diffusion layer pinholes
Dendrite (whiskers) growth of tin/lead solder
Contamination related failure
Workmanship Issues (application of indium solder)

Possibly most important: Heritage and knowledge of selected vendor’s processes and technology.

LOLA/LRRP*: Extended Operation in Air of LDAs For Vendor Selection: (2 vendor products)

Mark Stephen, NASA GSFC, Code 554, mark.a.stephen@nasa.gsfc



This is an ongoing, accelerated performance test of 4 LDAs (G2 packages) to qualify two vendors, observe potential problems and compare performance to assist choosing the flight vendor for the LOLA mission.

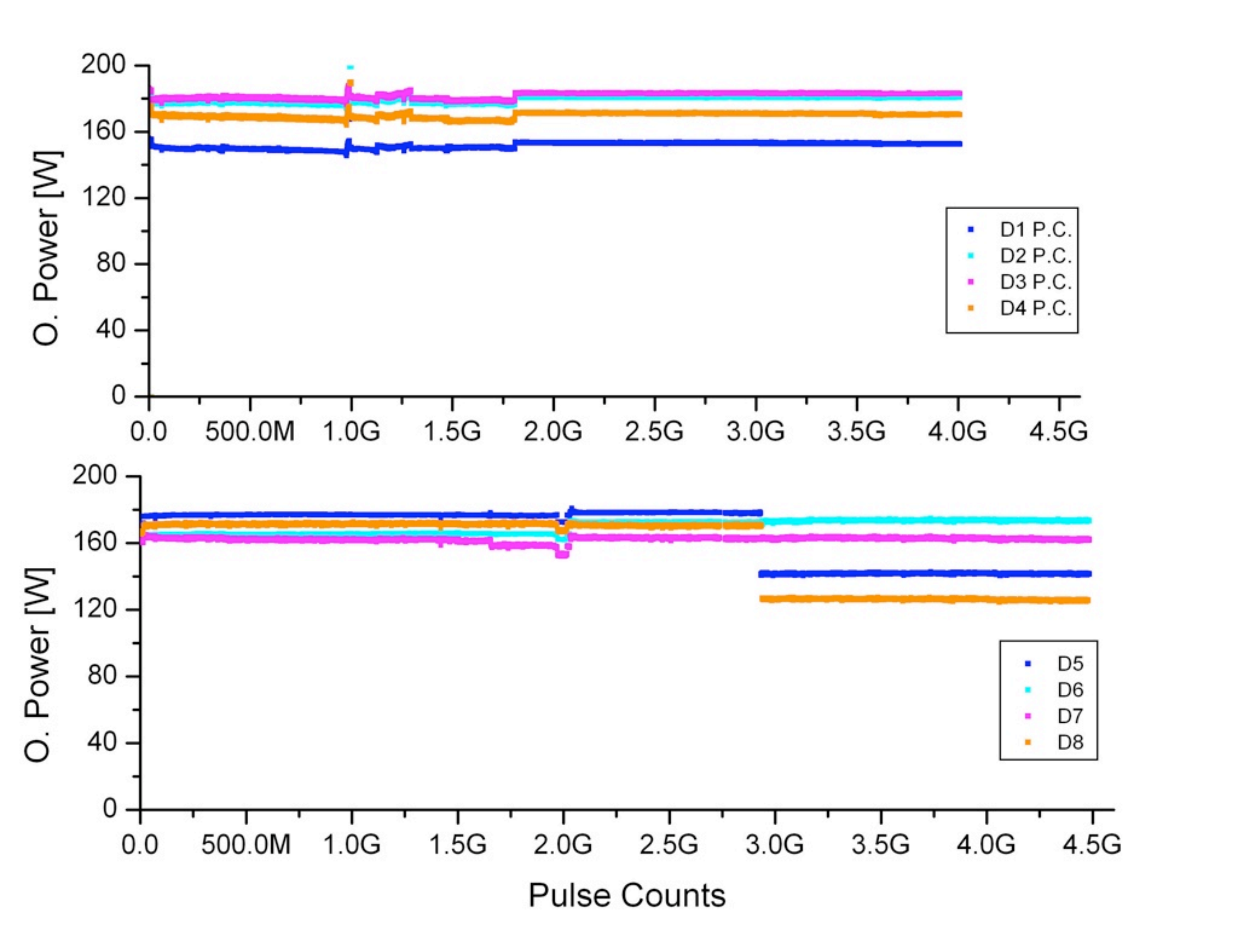
Operating Conditions:

I = 70 A
PW= 170 μs
f = 250 Hz
T= 25 °C

*Research jointly funded by Lunar Orbiter Laser Altimeter (LOLA) and Laser risk reduction program (LRRP)

BioMM/LRRP* LDA Long-Term Power Cycling Test

Mark Stephen, NASA GSFC, Code 554, mark.a.stephen@nasa.gsfc



- Operating Conditions: I = 50 A, PW = 80 µs, f = 242 Hz, T= 25 °C
- All LDAs have accumulated more than 4 billion pulses.
- 4 G-4 LDAs (top) are power cycled: ON cycle is 18 min.; OFF cycle is 2 min. [~7,800 cycles]
- 4 G-4 LDAs (bottom) are at constant power.
- Fluctuations in curves are due to test electronics and not indicative of changes in LDAs
- 2 bars dropped would have been dropped @ prescreening. We chose to run these anyway to support the Mark's screening process.

Power cycling appears to have little or no effect on QCW diode lifetime.

*Research jointly funded by Biomass Monitoring Mission (BioMM) and Laser risk reduction program (LRRP)

Laser Diode Array Selection

Lessons: Laser Diode Arrays

1. Proper laser diode array selection must begin ASAP and as much testing and verification performed as budge/time will allow. This will help in vendor selection and final volume of arrays to purchase for flight.

2. Maximum current derating has dramatic effect on lifetime. Finding this optimum operating point with drive current, pump pulsewidth, and rep rate depends on the mission specs.

3. Too much current derating < 40% (60% of peak) can have negative effects on system efficiency as the voltage drop across semiconductors begin to drop.

4. Set point operating temperatures may not have as dramatic effect as thought. Our tests in HOME and on lifetest are > 35C with very little decay. This is important since it could reduce heat removal capacity required by spacecraft, yet imply more make-up heat power when laser is off.

Finally:

5. Place the responsibility of diode array vendor selection to an expert. Any mistakes, shortcuts, oversights can have mission catastrophic costs in $ and time.

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Lessons Learned Summary

- Component selection is as important as system design.

- Identify assumptions and re-evaluate. Experiment if necessary.

- Vacuum vs. Pressurized: It really depends on the mission.

- Improving the efficiency of a 4% laser by only 1% is still HUGE.

- Use multiple and overlapping modeling schemes to reduce error and constantly re-evaluate during ETU builds.

- "Test as you fly, fly as you test."   Characterize to meet flight qualification and specifications, but **test** ETU or flight spare to replicate full mission operation lifetime. (...or as long as $ and manpower will allow.)

- Lifetime margin is critical. A 1 billion shot mission laser should demonstrate 2, 3, or more billion shots on the ground, thus derate the diode arrays as much as possible.

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