Three Year Aging of Prototype Flight Laser at 10 kHz and 1 ns pulses with external frequency doubler for ICESat-2 mission

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ABSTRACT

We present the results of three year life-aging of a specially designed prototype flight source laser operating at 1064 nm, 10 kHz, 1ns, 15W average power and external frequency doubler. The Fibertek-designed, slightly pressurized air, enclosed-container source laser operated at 1064 nm in active Q-switching mode. The external frequency doubler was set in a clean room at a normal air pressure. The goal of the experiment was to measure degradation modes at 1064 and 532 nm discreetly. The external frequency doubler consisted of a Lithium triborate, LiB_3O_5, crystal operated at non-critical phase-matching. Due to 1064 nm diagnostic needs, the amount of fundamental frequency power available for doubling was 13.7W. The power generated at 532 nm was between 8.5W and 10W, depending on the level of stress and degradation. The life-aging consisted of double stress-step operation for doubler crystal, at 0.35 J/cm^2 for almost 1 year, corresponding to normal conditions, and then at 0.93 J/cm^2 for the rest of the experiment, corresponding to accelerated testing. We observed no degradation at the first step and linear degradation at the second step. The linear degradation at the second stress-step was related to doubler crystal output surface changes and linked to laser-assisted contamination. We discuss degradation model and estimate the expected lifetime for the flight laser at 532 nm. This work was done within the laser testing for NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) LIDAR at Goddard Space Flight Center in Greenbelt, MD with the goal of 1 trillion shots lifetime.

Keywords: Lidar, Frequency Doubling, Laser Contamination, Laser Reliability, ICESat-2.

1. INTRODUCTION

The Advanced Topographic Laser Altimeter (ATLAS) instrument for ICESAT-2 mission [1] has doubly redundant laser in its core. The laser should operate at 532 nm, 10 kHz, 1.5 ns with average power as high as 9W. Each of the two redundant cold spare lasers are expected to have lifetime of 3 years and 2 month, closely corresponding to 1 Trillion shots lifetime. The 532 nm operation is achieved through doubling fundamental pulses at 1064 nm.

The major specifications for doubly-redundant laser are listed below:

1. Center wavelength 532.272 nm ±15pm, in vacuum
2. Center wavelength tunable over 50 pm
3. Wall-plug efficiency to 532 nm > 5% at laser box case temperature 25C
4. Repetition rate 10 ±0.3 kHz
5. Pulse energy adjustable within 250 uJ – 925 μJ (in at least 12 closely equal increments)
6. Mean pulse width < 1.5 ns
7. Polarization linear, contrast >100:1
8. Spatial mode 1.6X diffraction limit ($M_2 < 1.6$)
9. Shot-to shot pointing stability < 11 μrad
10. Boresight shift during vibration testing < 200 μrad
11. Lifetime: 3 years + 60 days for each laser
12. Vibration qualification testing to GEVS (14.1 g_{rms})

The conceptual design considerations for the laser can be found in [2]. The technological development and qualification of various aspects of the laser can be found in [3, 4, 5, 6]. The optical design of the laser is a master oscillator/power amplifier (MOPA) that includes an actively Q-switched short-pulse oscillator, a pre-amplifier, and a dual-stage power amplifier. All of the gain media are Nd:YVO_4 crystals that are end-pumped at 880 nm with fiber-coupled diode modules. The diode modules are not individually thermally stabilized and all have common plate cooling due to relatively high overall efficiency requirement. A Volume Bragg Grating (VBG) in the oscillator narrows the spectral output of the laser and provides for the required wavelength tunability.

1.1 **Motivation**

One of the most critical reliability item is the degradation of pulse energy through degradation of the second harmonic in the frequency doubler. It is speculated that one of the ICESat-1 mission laser lifetime limitation came from a limited lifetime of frequency doubler [6]. A couple of early laser prototype demo units for ICESAT-2 (also interchangeably called Engineering Design Units or EDUs in this presentation; these were similar in design to that of used in this study) delivered to NASA from the vendor (Fibertek Inc.) in 2011 for demonstration and short life-aging tests, showed a substantial degradation of 532 nm energy and power, while insignificant changes in 1064 nm laser sub-systems. The 532 nm pulse energy degradation of early prototypes is shown on Figure 1.

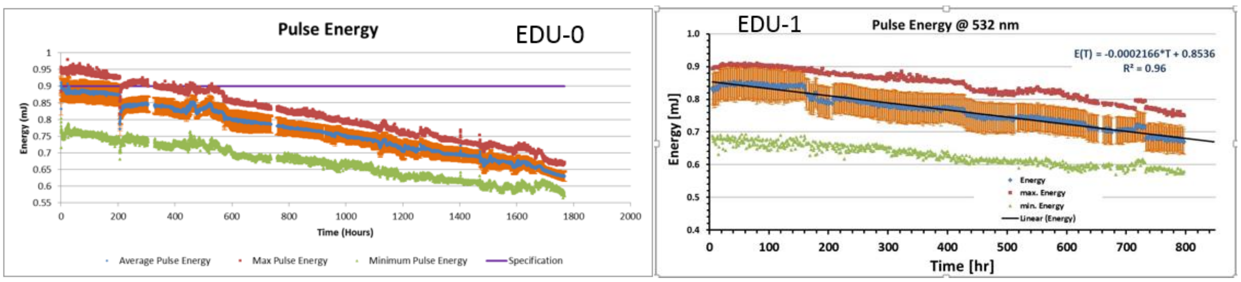

Figure 1. Short test-aging of early Engineering Design Units, EDU-0 and EDU-1 operated with frequency doublers installed inside the self-enclosed units. They both showed early degradation of pulse energy and average optical power at 532 nm. The measured lifetime (EOL=-1dB) was between 1200 hours (EDU-0) and 800 hours (EDU-1).

The "postmortem" analysis of these two early prototypes corroborated that degradation of the 532 nm energy was highly likely connected with surface degradation of frequency doubler and transport optics. The output surfaces of frequency doubler and downstream transport optics that were exposed to intense 532 nm radiation were darkened and acquired characteristic to photo-assisted contamination bumps with height close to or in excess of 100 nm, similar to the reported in [7]. On both of the early prototypes, the level of fluence was set relatively high, at about 1.4 J/cm^2. One of the critical action items at this point was to investigate possibilities of running frequency doubler at lower peak fluence by using larger spot and less tight focusing. The SHG efficiency can be still maintained through the use of a longer LBO crystal.

1.2 **The goal of this Study**

The goal of this study was to measure degradation modes at 1064 and 532 nm discreetly. Simultaneously with vendor, NASA Goddard team tried to experimentally demonstrate that operation at lower fluences can prolong the lifetime to durations required by the ICESAT-2 mission. For this purpose, a special Engineering Design Unit, namely EDU-2, was manufactured. The EDU-2 has frequency doubler and all doubler-related transport optics removed. The doubling of fundamental harmonics was done externally on optical table. This allowed us to observe degradation of 1064 nm and 532 nm mode independently and with greater details.

1.3 **EDU-2 Laser details and differences with flight laser**

EDU-2 is a self-enclosed, clean and pressurized air laser system. It was manufactured with standards of cleanliness and reliability considerations comparable to those of the flight laser. The delivered EDU-2 system is shown on Figure 2. The details of the design of EDU-2 can be found in [3].

As it was already mentioned, EDU-2 has second harmonics block completely removed. The output beam has ~ 14.5-15W power at 1064 nm. The more subtle design traits of EDU-2 laser and optical performance differences with flight laser are summarized below:

1. 1st or 2nd Generation Prototype, sealed in pressurized container
2. Frequency doubler is removed, output radiation is at 1064 nm.

3. 1-30 modes (1-28 declared safe by vendor). All life-aging studies are done at Mode #28.
   14.5-15 W of 1064 nm max, Electrical-to-optical efficiency at 1064 nm was near 8-10% (excluding the power spent for external cooling).
4. An older version of resonator:
   Non-folded, Smaller waist size. Typical spectrum consisted of 4 longitudinal modes, two full and two half intensity modes. As the result, temporal shape of the pulse had deep, up to 100% in depth modulations with characteristic period ~ 400 ps.
5. A Shorter VBG: Spectral width @ 1064 nm ~ 15-20 pm (versus ~ 10 pm or less for flight laser).
6. Slightly non-optimized mode-adjustment of pulse energy spacing

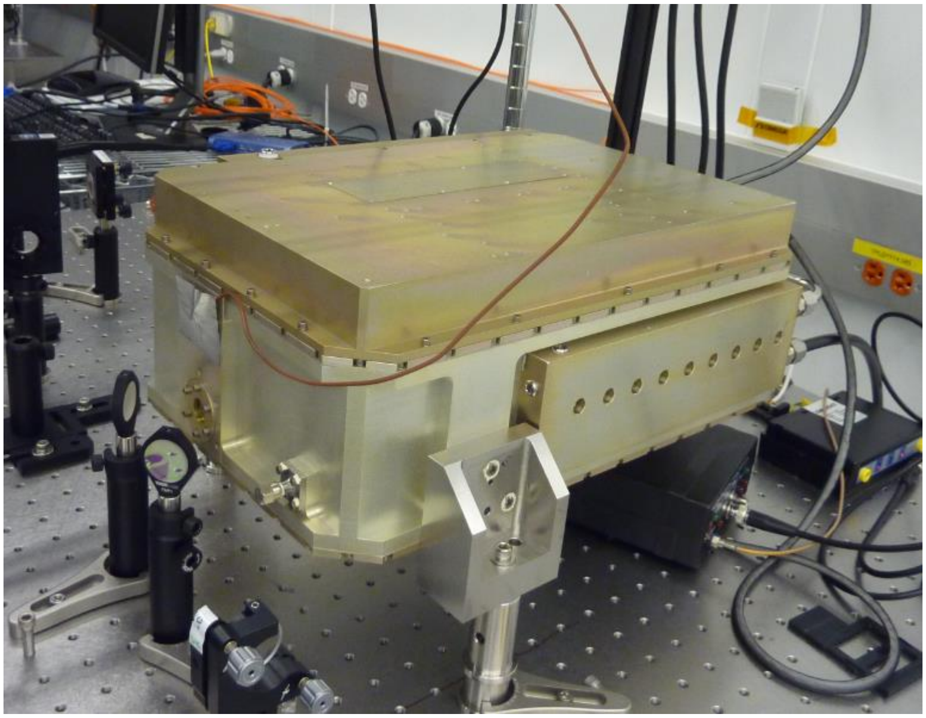

Figure 2. EDU-2 Laser system. The cooling is done through water block on the right side. The cooling temperature was set close to room temperature and was dictated by the choice and match of the central wavelength of the laser diode pumps operated at 885 nm to the absorption band of $Nd:YVO_4$ laser host material.

2. EXPERIMENTAL SETUP

The experimental setup consisted of two set of diagnostics of the laser system outputs, before and after frequency doubling, at 1064 nm and at 532 nm. The setup is shown in Figure 3. A portion of the light was picked off of the 1064nm laser beam, using a 3° wedge, before frequency doubling. This was done to monitor the IR going into the double as well as to monitor the laser's characteristics. From this pickoff we monitored the time-profile, power, energy, wavelength, beam profile, and M^2. This information was needed in order to accurately understand the IR laser characteristic before frequency doubling. The light that passed through the uncoated 3° wedge then passed to a half-wave plate for the polarization conditioning. This is important because we need to make sure to properly orient the IR laser polarization for optimal frequency doubling. After all of these losses, approximately 94% of the initial energy was available for frequency doubling. Next the beam passed through a pair of lenses, the down-collimator, DC, in order to condition the beam size and focal point. This allows us to optimize the stress (fluence level) to the desired on LBO crystal. The down-collimator details are shown on Figure 5. Next the 1064nm laser light travels to the LBO and is converted to 532nm laser light. The 532nm light is cleaned up of any residual IR using two harmonic separating mirrors, HS1 and HS2. The leakage through the HS1 was directed towards a power meter to monitor the unused IR light. Then, the 532 nm beam was further cleaned from 1064 nm residual by reflecting from HS2. This beam was then directed towards 3° wedge in order to provide pickoffs for time-profile, power, energy, wavelength, spatial profile, and M^2 measurements. Table 1 lists the components we used for the optical setup.

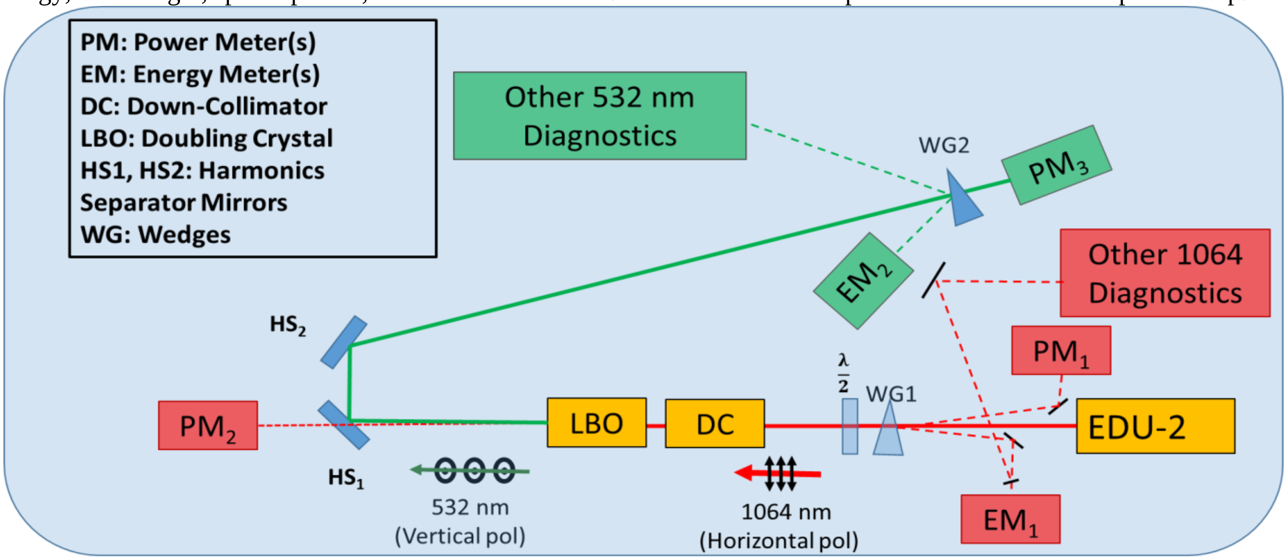

Figure 3. Experimental Set-up for EDU-2 Aging. The setup consisted of two set of diagnostics of the laser system outputs, before and after frequency doubling, at 1064 nm and 532 nm. The other diagnostics include spectral, spatial and temporal measurements parameters of the beam.

Table 1. The diagnostic and optics component list included in the set-up for life-aging.

Component(s)	Manufacture	Model(s)
1064 nm Laser	Fibertek	EDU-2
Power Meters	Coherent	PM30 & PM2
Energy Meters	Coherent	J-10MT-10KHZ J-25MT-10KHZ
Wavemeter	Highfinesse	WS/6-200
M^2 Measuring System	Ophir-Spiricon	M^2-200s
12 GHz Photodiode	NewFocus	1577A
CCDs	Foculus	
Oscilloscope	LeCroy	Wavemaster813Zi (12.5 GHz)
Wedges	CVI/IDEX	3°/Fused Silica
Half-wave Plate	Thorlabs	WPH10M-1064
Mirrors	CVI/IDEX	Various

3. THE CHOICE OF DOUBLING CRYSTAL

The doubling crystal choice was dictated by reliability considerations. The SHG crystal should be able to run without degradation and work on 24/7 and 365 days per year schedule, without time lapses. The doubler should also be able to operate at relatively high efficiencies, preferably in excess of 50-60%. Lithium Triborate, LiB_3O_5, was chosen as the doubler both for the ICESAT-2 mission and for this study. The flight laser will operate with critically phase matched LBO crystal, but in this study, we use non-critically phase matched (NCPM) LBO. The rationale for NCPM choice are listed below:

- Insufficient power and pulse energy @ 1064 nm BOL. NCPM configuration produce higher efficiencies.
- No {immediate} automatic temperature tuning scanner/maximizer availability (needed due to 1064 nm beam pointing drift)
- At the time of the test start, Fibertek team was not 100% sure for the choice of CPM or NCPM crystal configuration. Fibertek has purchased and sampled both crystal cuts from the vendor and gave both LBO samples to NASA.
- CPM crystal would not allow "clean" step-stress due to walk-off and SHG efficiency reduction when beam is focused tighther.

The doubling crystal details are listed below:

- LBO is manufactured and coated in-house by Coherent Advanced Crystal Group [8], procured through Fibertek
- Crystal Dimensions: 6 mm x 6 mm x 22.3 mm
- Cut: Non-critical
- Phase-Matching type - Type-I (o+o→ e)
- T_{op} (NCPM) ~ 149 °C
- Coating AR/AR 1064nm /532 nm, both sides
- Damage threshold for 1064 nm and 532 nm for 1-1.5 ns pulses is in excess of 5 J/cm2.

The Figure 4 shows main components of the doubling cell. The crystal was fixed in the crystal holder with 8 mils Teflon stripes. We distinguished input (S1) and output (S2) surfaces pre-selected by vendor for further failure mode analysis.

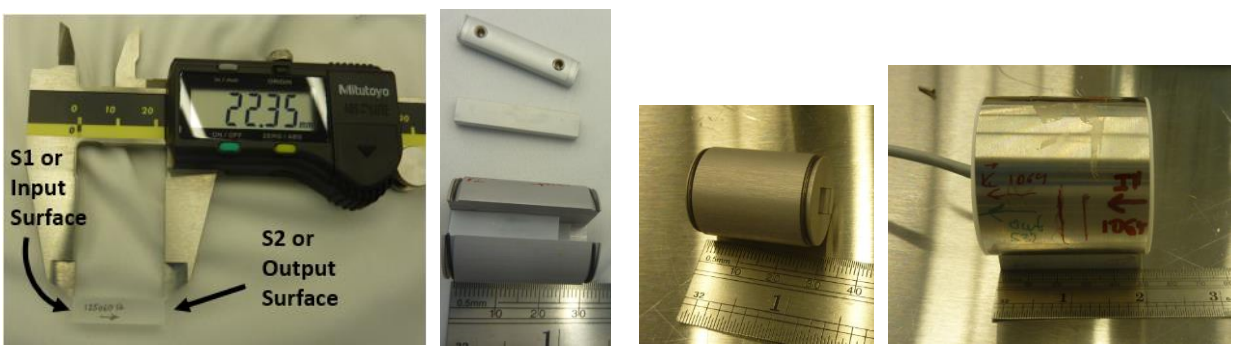

Figure 4. Details of the crystal assembly. From left to right: 22 mm crystal sized with calipers; 30-mm crystal holder with crystal inside the holder (crystal was symmetrically positioned inside the holder, the shown position is not centrated); crystal holder assembly (as it is inserted to oven); and 50 mm oven.

4. THE SHG OPTIMIZATION

The beginning of life (BOL) optical test parameters of EDU-2 relevant for frequency doubling with budget of available power are listed in Table 2. The EDU-2 laser was delivered with slightly less power (~ 0.5W less) than what is needed for both second harmonic generation (SHG) up to flight specs and comfortable amount of energy for 1064 nm diagnostics. We still reached the goal through minimizing diagnostic loss through custom-coated wedge (for splitting less power to 1064 nm), through of non-critically phase-matched crystals, and SHG optimization.

Table 2. EDU-2 Energy and Power Budget estimates for SHG at BOL. The mission goal of ≥ 900 uJ/pulse at 532 nm was only achievable with NCPM LBO. The power is shown for mode #28.

			Assumptions: Add Coated wedge for 1064 nm Diagnostics , remove Pol cube, Add down-collimator to optimize 1064 nm beam size and SHG effciency			Optical surfaces
Item #	Parameter Description and/or Name	Dimension	Pre-Delivery Expected Values	Actually Delivered EDU-2 02/14/2012, expected values with CPM LBO crystal	Actually Delivered EDU-2 02/14/2012, measured values with NCPM LBO crystal	
1	Expected or Measured Ex-Laser Power, BOL (Watts)	Watts	>15.0	14.55	14.55	
2	Losses on WP +cube%	%	0%	0%	0%	0
3	Power After WP+Cube, max Transmission (Watts)	W	15.0	14.6	14.6	
4	Losses on Wedge (for 1064 nm diagnostics) %, actual numbers	%	2.65%	2.65%	2.65%	2
5	Losses on Wedge (for 1064 nm diagnostics) (Watts)	W	0.40	0.39	0.39	
6	Power After Wedge (W)	W	14.6025	14.2	14.2	
7	~~Throughput of HR 45 deg Mirrors~~	%	100.0%	100.0%	100.0%	0
8	Beam Focussing and/or DownCollimators Throughput	%	98.4%	98.4%	98.4%	4
9	Throughput HWP1064 (pol adjuster to doubler)	%	99.3%	99.3%	99.3%	2
10	Diffraction and Scattering losses	%	1%	1%	1%	
11	Power delivered to Doubler	Watts	14.1	13.7	13.7	
12	Estimate on SHG Efficiency (CPM based on PDR Fibertek, NCPM- based on NASA Tests)	%	65% {up to 70%}	65%	68%	
13	Expected Average SHG power ex-LBO @ 532 nm	Watts	9.2	8.9	9.316	
14	Expected Energy per pulse @ 10kHz, ex-LBO (uJ), BOL, in house test doubler	uJ	918 {up to 987}	891	932	
14a	Mission Goal (Pulse Energy)	uJ	900	900	900	
14b	Estimated BOL Pulse Energy Margin for SHG (above mission goal)	%	2.0%	-1.1%	3.5%	
15	Fundamental Power/Energy Throughput before beam reaches the first doubler surface	%	94.2%	94.2%	94.2%	
16	Fundamental Power/Energy Losses before beam reaches first doubler surface	%	5.8%	5.8%	5.8%	
	Critical Numbers in Red					

The output beam out the EDU-2 laser system was diverging and had waist size about 0.5 mm located about 20 cm inside the laser box. In order to be able to focus the beam on the crystal and adjust the fluence at the required level, we assembled simple two-element Galilean down-collimator (DC). The DC details are shown on Figure 5.

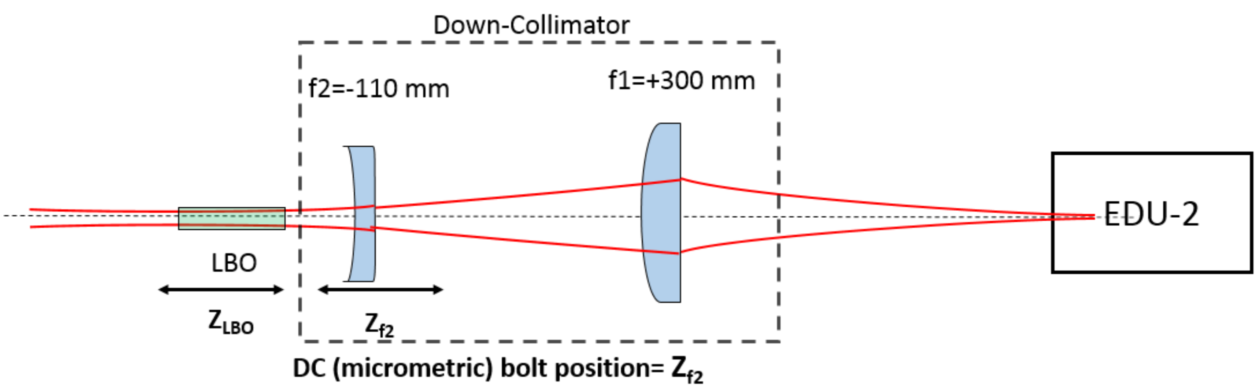

Figure 5. Down-Collimator (DC) Schematics. The down-collimator was two-lens Galilean telescope with adjustable distance between lenses. By varying negative lens position - Z_{f2}, and by translating LBO center, Z_{LBO}, to a new waist location for each Z_{f2}, it was possible to continuously vary waist size on LBO from ~ 0.5 mm to 1 mm.

The variation of the beam size after down-collimator versus negative lens position is shown in Figure 6. Z_{f2} is also called (micrometric) DC bolt position in the text below.

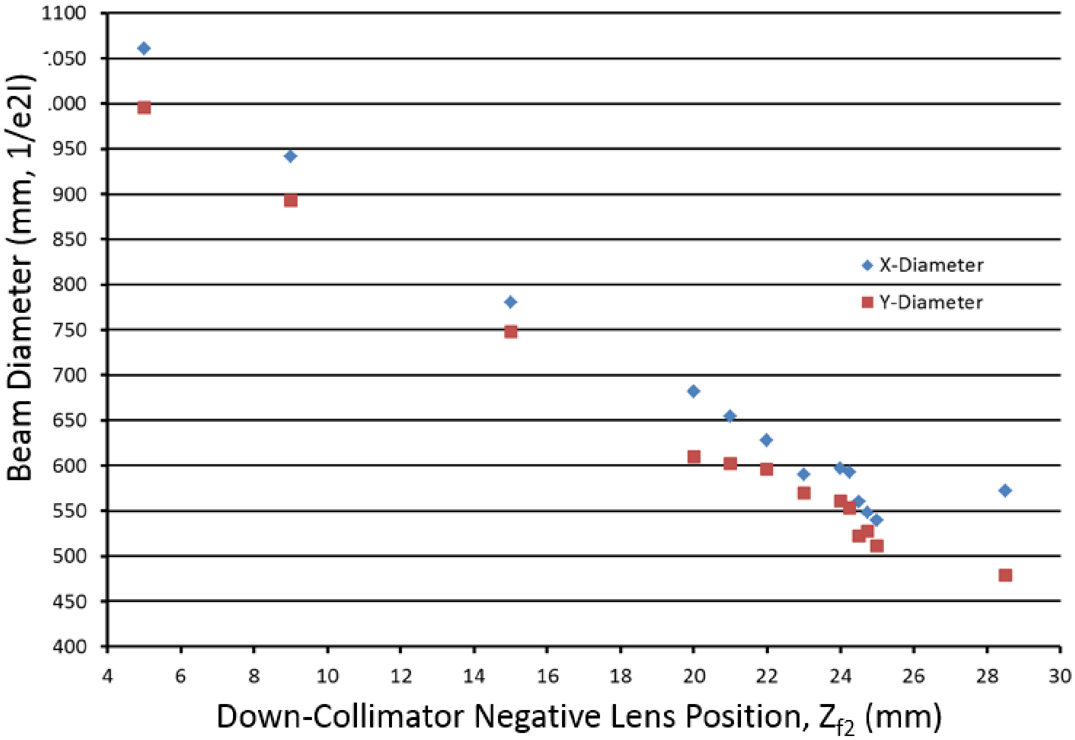

Figure 6. The 1064 nm beam diameter as the function of negative lens position of the telescope. The waist is formed about 60-80 mm behind the negative lens where the doubling cell was inserted.

Typical beam spatial profile (close to Gaussian in both directions) and M2 parameters of the 1064 nm beam are shown in Figure 7. M2 parameter of the 1064 nm beam was not dependent on the DC bolt position but rather dependent on the output power, controlled by the settings of the lasing Mode Number.

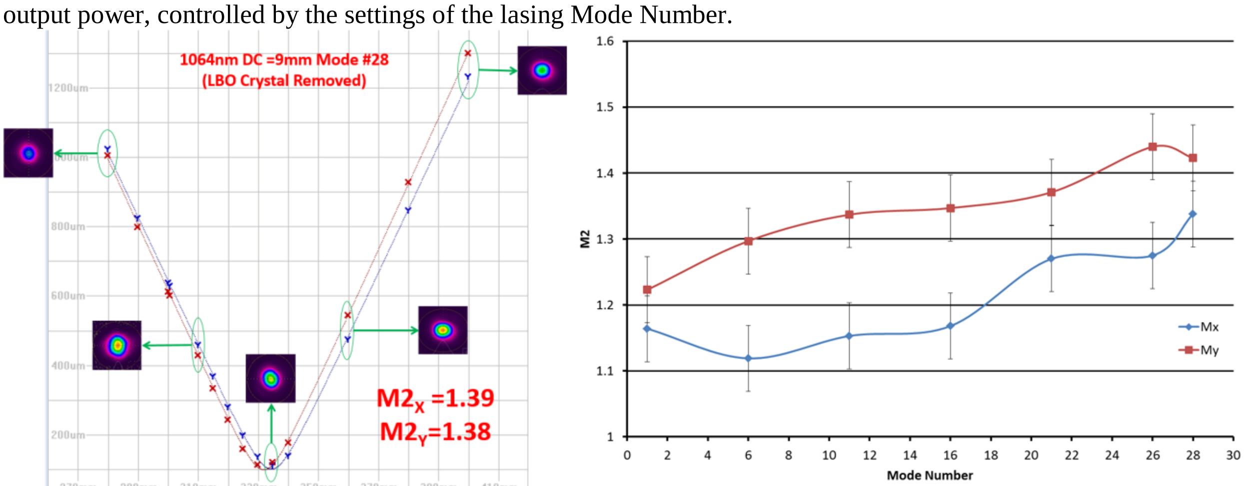

Figure 7. The 1064 nm spatial beam quality. Left Picture: The beam exhibited M2 close to 1.4 at Mode #28 with 14.5-15W output power. Right Picture: The M2 degrade from 1.2 to 1.4 while system is scanned from Mode #1 (Output power ~ 8W) to Mode #28 (Output Power 14.5-15W).

The SHG optimizations steps included few multiply repeated scans:

- Temperature scan
- Angular Scan
- Input Polarization Rotation scan
- Z-scan (M2 tests)- and adjustment of X-Y

- Spot Size Variation with Galilean down-collimator
    - And re-adjustment of LBO cell location along the beam
- Conditions: 0-1.5 mJ @ 1064 nm (up to 1.35 mJ/pulse on LBO)

A typical thermal scan is shown Figure 8. The thermal acceptance of LBO was relatively low. This was however consistent with theoretical numbers. The SHG efficiency is sensitive to a fraction of degree. This factor require stabilization of crystal temperature for ~20 millimeter long crystal to 0.1C degree accuracy. Simultaneously, any non-homogeneous distribution of absorption in bulk or on the surface can throw crystal out of phase synchronism and reduce SHG efficiency. Arguably, the degradation of the SHG of LBO is connected with darkening observable typically on output surface.

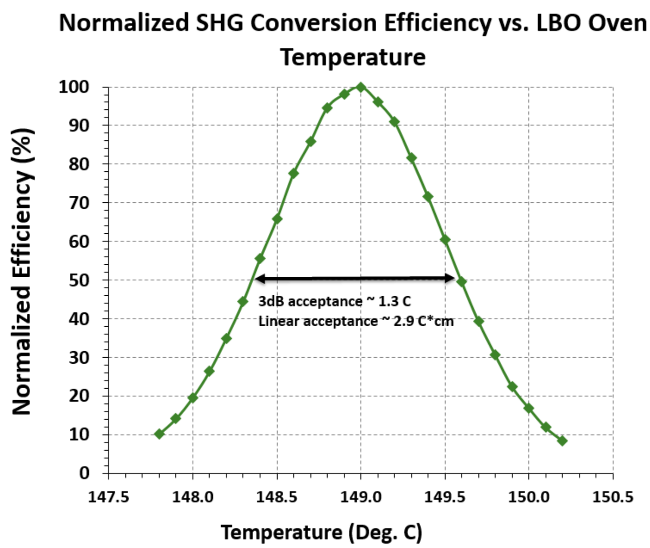

Figure 8. Thermal scan of the LBO doubling. 3dB thermal acceptance was ~ 1.3C and corresponded to linear acceptance 2.9C*cm.

The scan of measured SHG efficiency and peak fluences for 1064 nm and 532 nm beams versus down-collimator bolt position is shown on Figure 9 on the left graph. The right graph shows the same dependencies as the function of input fluence. Both graphs shows the same data but casted with different X-axis.

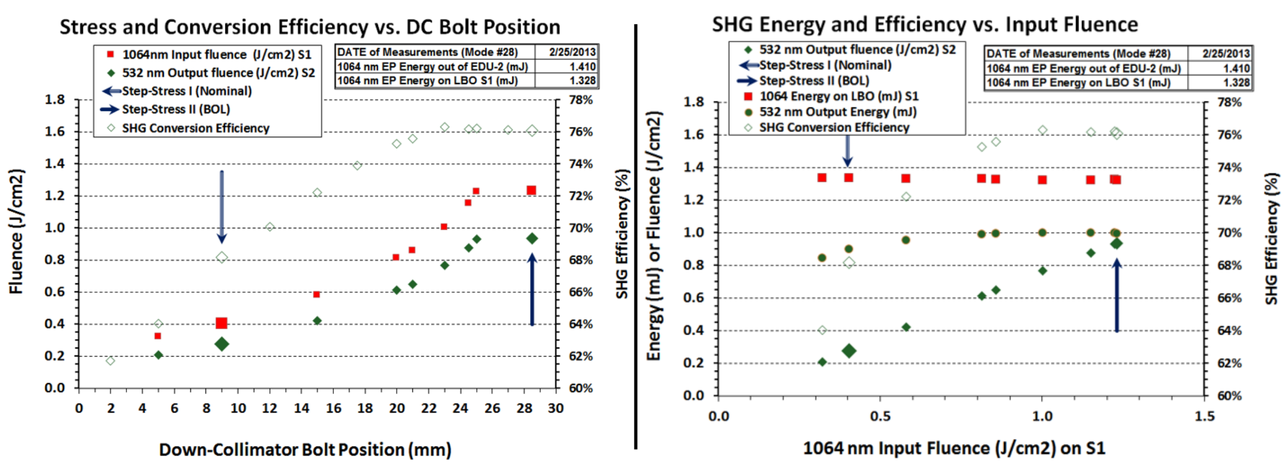

Figure 9. Scan of SHG and fluence levels versus down-collimator adjustment or 1064 nm focus tightening degree. Energy of the 1064 nm pulse is being kept constant. Both graphs shows the same set of data. On the left graph, X-axis is down-collimator bolt position, on the right graph X-axis is 1064 nm input fluence, or 1064 nm fluence on surface S1. Both Graphs are double- Y axis, with left Y-axis used for Fluence or Energy level and the right Y-axis used for SHG efficiency.

The left graph shows SHG and fluence level as the function of down-collimator adjustment, while the right graph is the recast of the same data with X-axis as 1064 nm input fluence level. The SHG efficiency as high as 76% was obtained with tighter focusing.

The aging occurred in two steps with two distinctly different stresses set on the crystal. The first stress was set close to that of the flight conditions, while the second was about 3 times higher but lower than stress set on early EDU. The condition of stresses are summarized in Table 1.

Table 3. Summary of major and critical parameters set and measured at two different life-aging steps.

Parameter	Step-Stress 1 (~1,000-7,500 Hrs)	Step-Stress 2 (7,500-27,000 Hrs)	Dimension
Mode #	28	28	#
DC Bolt Position	9	28.5	mm
E_p @ 1064 nm S1 (BOL)	1.32	1.32	mJ
E_p @ 532 nm S2 (BOL)	0.9	1.0	mJ
SHG Efficiency (%)	68%	76%	%
Fluence @ 1064 nm S1 (BOL)	0.4	1.23	J/cm2
Fluence @ 532 nm S2 (BOL)	0.28	0.94	J/cm2
M2x @ 1064 nm	1.35	1.35	X
M2y @ 1064 nm	1.42	1.42	X
M2x @ 532 nm	1.60	1.68	X
M2y @ 532 nm	1.65	1.66	X

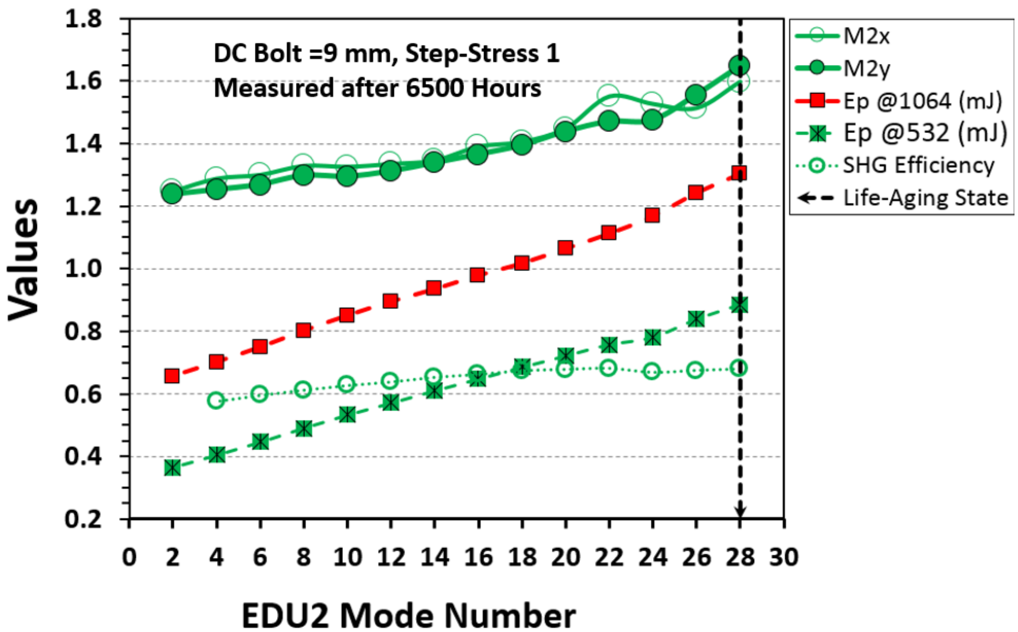

Figure 10. Scan of the pulse Energy at 1064 nm and 532 nm, SHG efficiency and beam spatial quality at 532 nm versus EDU-2 mode number for settings corresponding to Step-stress 1. The graph shows slow degradation of the beam quality (gradual increase

of M2) with increasing pulse energy. The relative increase of M2 for 532 nm is approximately the same as M2 increase for 1064 nm.

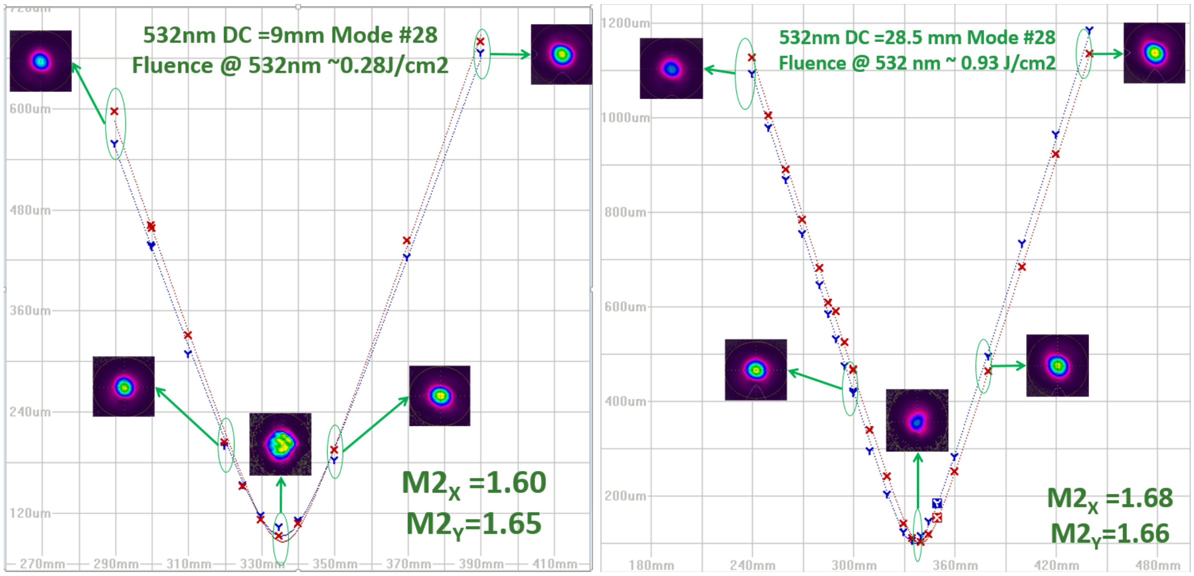

Figure 11. The M2 scans for 532 nm corresponding to two conditions of focusing and stress on the LBO crystal. The left scan was done at focusing corresponding to fluence level 0.28J/cm2 (Step-Stress 1) , while the right scan corresponds to the fluence level 0.93 J/cm2 (Step-Stress 2). Each scans showed five insets of false color plots of 2D spatial beam intensity profiles.

One of the important trade-offs for frequency doubler is pulse-to-pulse energy fluctuations and stress. It is

5. LIFE-AGING RESULTS

The EDU-2 aging originally started without frequency doubler. This allowed to ascertain inherent stability of the system and diagnostics at 1064 nm and prepare for calibrated frequency doubling. The timelines of the aging are summarized below:

EDU-2 Life Aging @1064 nm

- 3/20/2012 → 05/15/2015 (~ 26,998 Hrs. reached @ 1064 nm)
- In addition, ~ 600 Hrs of burn-in was not monitored, while laser was aging.
- With all time counted, aging at 1064 nm reached ~99.6% of the goal of 3yrs +2 month (=27.8 kHrs).

Proto-Flight LBO cell was added on 5/10/2012

- Step-Stress-I, Doubler Aging (Nominal Stress)
  - Started 5/10/2012 ; Ended 3/05/2013
  - Total Hours Accumulated : ~ 6,513 Hrs.
  - Power & Energy Degradation: ~ 0% (≤ 0.68%/KHr)
- Step-Stress-II, Doubler Aging (Increased Stress)
  - Started 3/07/2013 ; Ended: 5/15/205
  - Total Hours Accumulated : ~ 18,708 Hrs.
  - Power & Energy Degradation: ~ 20%, linear.

The add-on aging of LBO-based frequency doubler occurred in 2 steps. We completed close to 0.75 year (6,500 Hrs.) of testing doubler at nominal stress (~0.28 J/cm^2 for 532 nm) with no measurable degradation. After that the stress was moderately increased to the level ~ 0.93 J/cm^2. This was done with the pre-estimated goal to observe slow gradual degradation over period of ~ 2 years, with end result to measure degradation rate and life prediction.

The major life-aging trend parameter was power and energy of 1064 nm and 532 nm beams. The 1064 nm power and energy trends are shown in Figure 12.

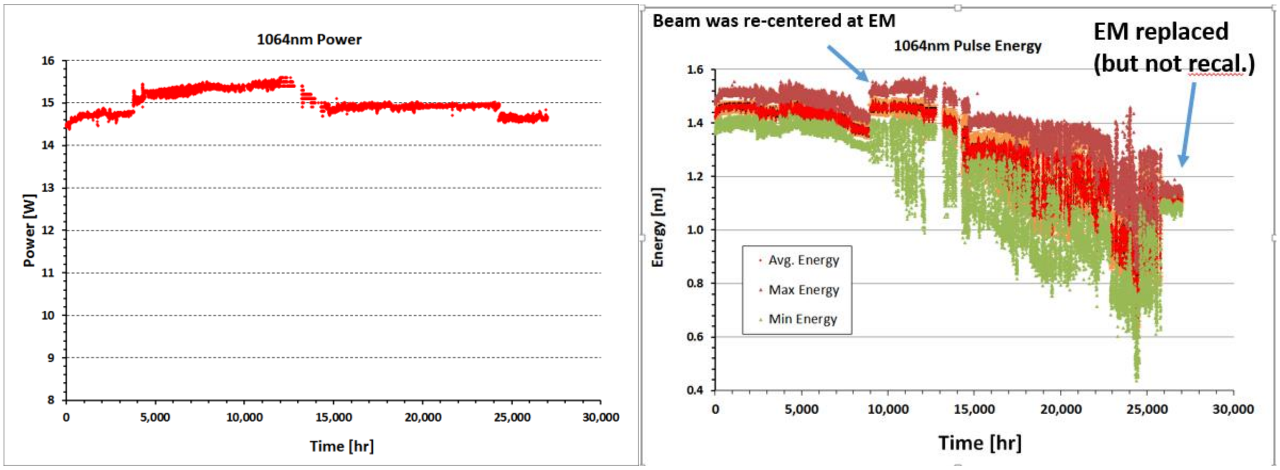

Figure 12. The changes and degradation of the power and energy for 1064 nm beam. Power and Pulse Energy measurements at 1064 nm were inconsistent with each other after ~ 5,000 hrs. Fundamental pulse energy fluctuations (especially large min energy excursions after ~9.3 kHrs) were also inconsistent with those at 532 nm. The large excursions were removed when energy meter (EM) was replaced (without recalibration to the main output beam) near 26 kHrs.

After approximately 4350 Hours of life-aging we noticed that at 1064 nm there appeared an excess of ~5% of power measured by power meter and average power derived from the measurement of pulse energy multiplied by pulse repetition frequency, f_{REP}. The 5% excess might have been attributed to calibration drift of the absolute values of power and energy meters. We also measured the low energy prepulse which exhibited about 5 small peaks. This is shown in Figure 13.

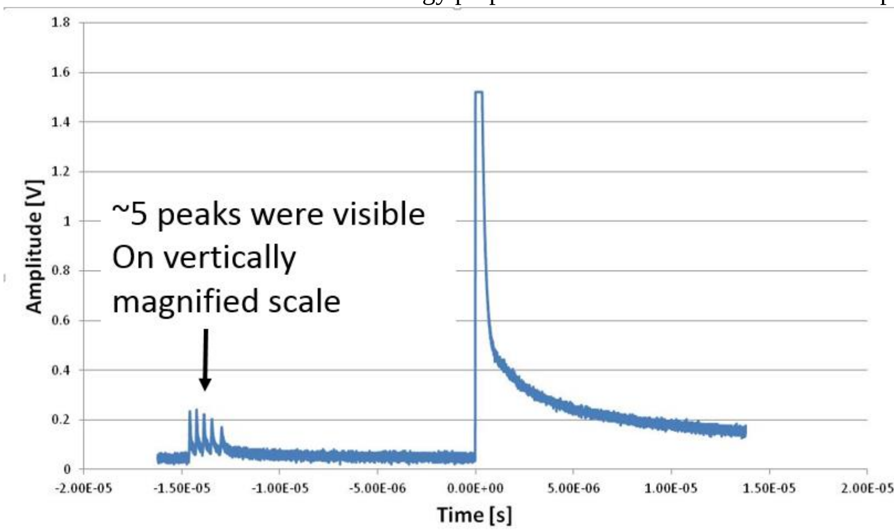

Figure 13. Measurement of prepulse after 4350 Hours of aging. About 5 peaks were visible at about 15 us before the main pulse. Numerical integration of 1064 nm power contained in the prepulses gave about 5% and was consistent with the measurement of excess of average power between power and energy meter.

After 16 kHrs of life-aging the number of preleasing spikes increased to 11. The relative amount of power measured by both methods showed that about 15% of the 1064 nm energy was contained in the low intensity structures. This is shown in Figure 14.

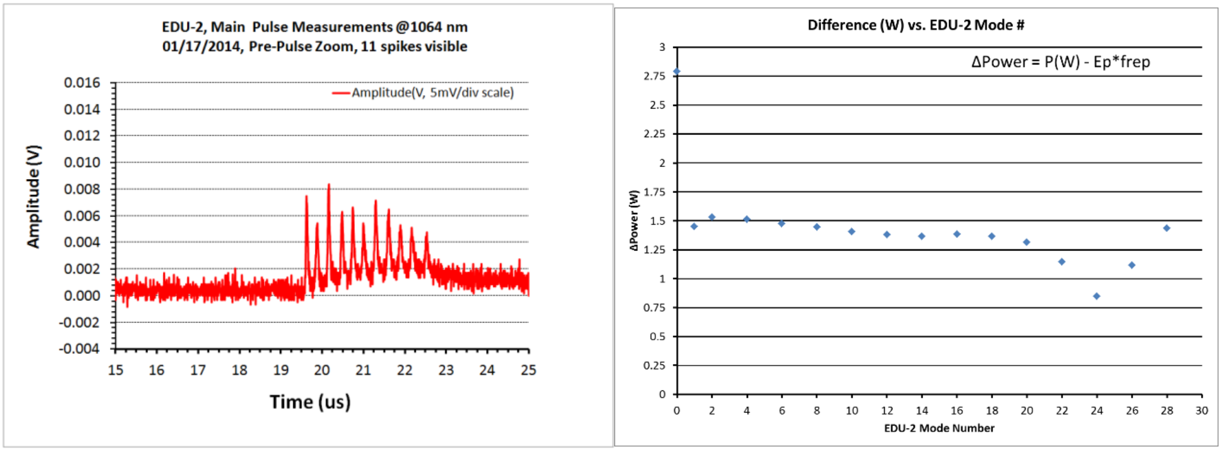

Figure 14. The low intensity prepulse measurements (left graph) after 16 kHrs of life-aging revealed the presence of 11 spikes located ~ 15 us before the main Q-switch pulse (not shown). The excess of power measured versus mode number showed that the were about 1.5W excess of power in low intensity structure.

The trend in power and energy of the frequency doubled beam is shown in Figure 15.

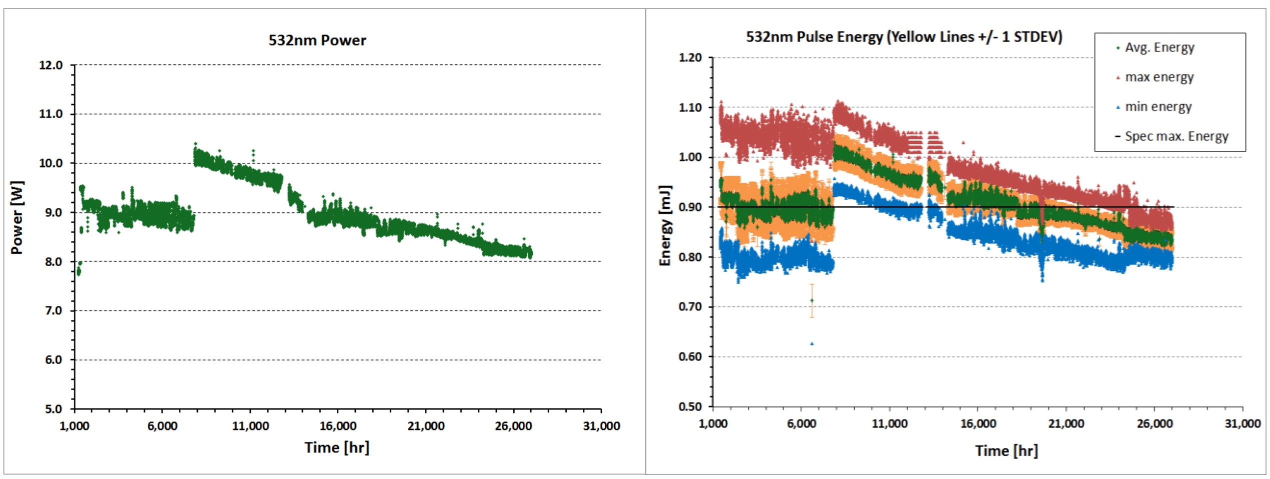

Figure 15. The trend of power (left graph) and energy (right graph) of the 532 nm beam. Power and Energy (multiplied by PRF) were consistent with each other.

6. DOUBLER CRYSTAL POST-MORTEM

The LBO crystal surfaces were inspected and profiled using 3D Zygo white-light interferometry based microscope, model NewView 7300. The LBO surfaces pre-test is shown on Figure 16.

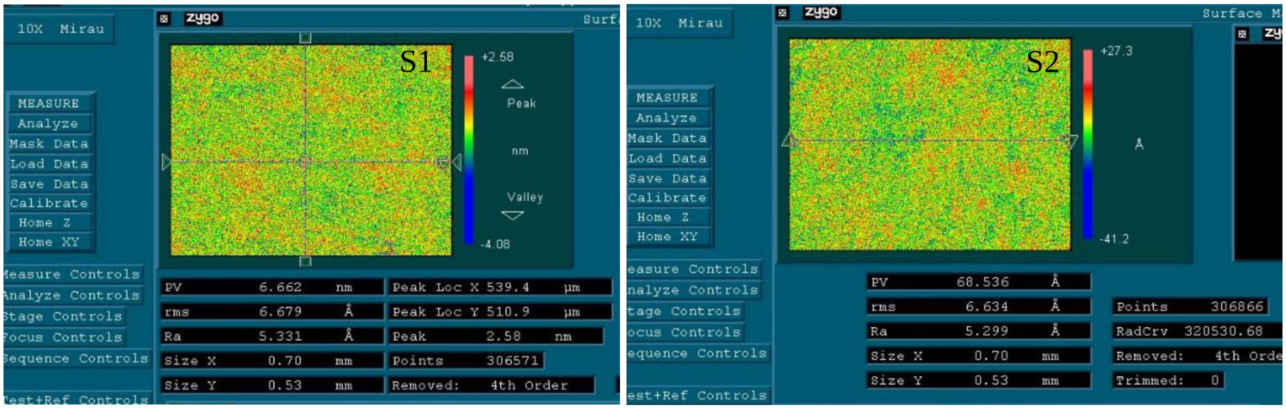

Figure 16. 3D surface profilometry and surface roughness measurements with 10X magnification and 0.7X0.53 mmxmm FOV. Lateral resolution is 1.1 um. The left figure is S1 (input surface) and right Figure is S2 (output surface). Single interferometric scans without averaging is shown. Both surfaces had featureless profiles with r.m.s. roughness below few Angstroms. After averaging (not shown) r.m.s. roughness was below ~ 2-3 Angstroms.

The low magnification post-test 3D profiling is shown on Figure 17. The left scan shows S1 profiling with magnification 1X and field of view (FOV) 7x 5.3 mmxmm. It essentially capture the full surface. The S1 surface got a round pit with depth of less than few of 10nm. The output surface, S2, was damaged much more.

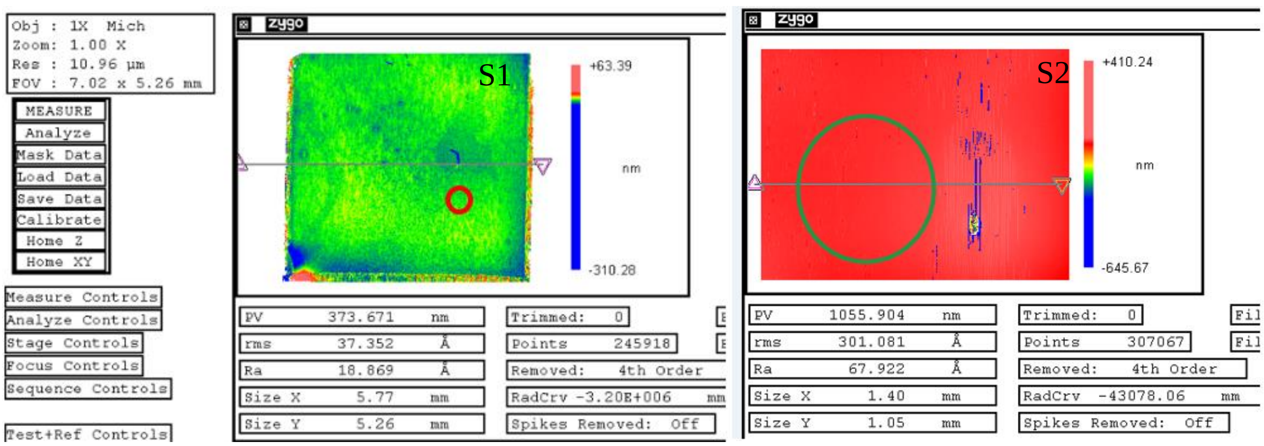

Figure 17. Post-test of the surfaces with low magnification. On the left, essentially the full S1 surface is shown. The small red circle is inserted to show the size of the fundamental beam at step stress 2. The S1 surface got one small pit comparable with the size of the incident beam. The output surface, S2 is shown with magnification 5X, FOV 1.4X1.05 mmxmm. The most damaged part of the surface shown. The green circle shows the approximate size of the 532 nm beam at step-stress 2. The S2 surface has numerous microcracks.

The somewhat expected darkened bumps, corresponding to photo-assisted contamination, were not found on either of the surfaces.

The high magnification profiling with 50X microscope (FOV 140x110 um, lateral resolution ~ 0.25 um) of S2 is shown in Figure 18. After life-aging, the output LBO Surface (Coating) exhibited shallow linear & parallel surface cracks, ~ 20-50 um long, ~ 5-10 um wide and 10-20 nm deep. This is shown in Figure 18. The majority (but not all of them) of the crack discovered on S2 surface were located compactly within ~ 1x1 mmxmm surface area as shown in Figure 17 (left 3D scan).

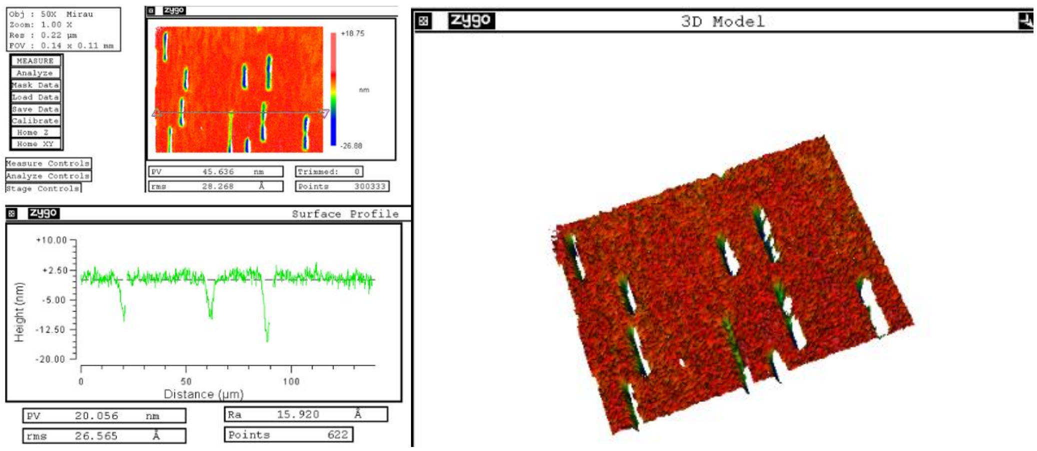

Figure 18. S2 profilometry with 50X microscope.

7. LIFE-TIME PREDICTION

The combination of early prototype aging, EDU-2 aging and MOPA brassboard aging [5] gave degradation pattern as the function of fluence stress. This is summarized in Table 4.

Table 4. Summary of life-aging and degradation of similar systems for ATLAS/ICESAT-2 mission.

Laser System	Fluence @ 532 nm [J/cm2]	Life (KHrs), EOL =-1dB	Notes
EDU 0 (The first Prototype)	1.4	1.2	20 mm LBO, Critical
EDU1	1.4	0.788	21 mm LBO, Critical
EDU2 Step-Stress 1	0.275	55 (*)	22 mm LBO Non-critical
EDU2 Step-Stress 2	0.93	13.5	22 mm LBO Non-critical
MOPA BB1 (@ 20KHz)	0.6	20	25 (?) mm LBO critical
MOPA 2		TBD	
ITL		on-going	30 (?) mm LBO, critical
(*) Linearly Extrapolated Value. Have rather large error. Test was too short to reveal onset of photo-contamination if any.			

The results from Table 4 are recasted on the graph in Figure 19. The curve-fitting showed slope of 1.58 (Life $\propto 1/F^{1.58}$) which is close to square law dependence expected from two absorption process. The graph suggests that fluence level as low as F~0.3 J/cm^2 maybe sufficient for mission goal. To get the survivability of the system with 90% of confidence or more, with current state of the testing and knowledge, the fluence level should be reduced to ~ 0.15 -0.2 J/cm2. This can be accomplished with pulse energies as low as ~1.5 mJ and efficiency in excess of 60% only in non-critical phase matching configuration by using crystals as long as 35-40 mm.

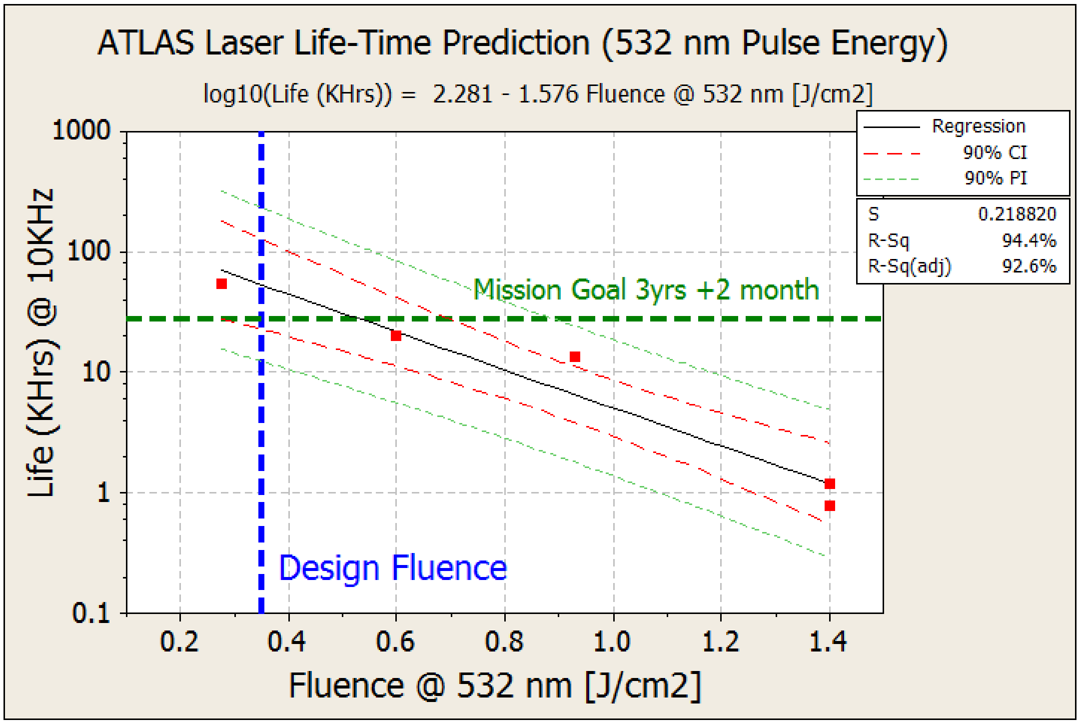

Figure 19. The life-time prediction of transmitter laser based on 532 nm power degradation. The predicted life-time is shown versus fluence level of the 532 nm radiation.

8. CONCLUSIONS

The experience acquired during three year of life-aging of EDU-2 laser with external frequency doubler revealed both reliable and (potentially) unreliable parameters of the laser system and inherent technology used. Averaged laser power at 1064 nm was stable; no substantial degradation trend was noticed. The pulse energy at 1064 nm had some degradation (but potentially restorable) that can be attributed to pre-lasing or pre-pulse build up.

A finite low-energy prepulse up to the level of 15% of total energy was developed during life-aging. This prepulse will reduce energy of second harmonics pulse.

Pulse energy @ 532 nm degradation rate depends on the stress and ambients (volatile contaminants). The issue can be mitigated by setting reasonably low fluence and controlling level of contamination in LOM

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