Solid state multi-wavelength laser development for planetary science laser mass spectrometer

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January 28 2024

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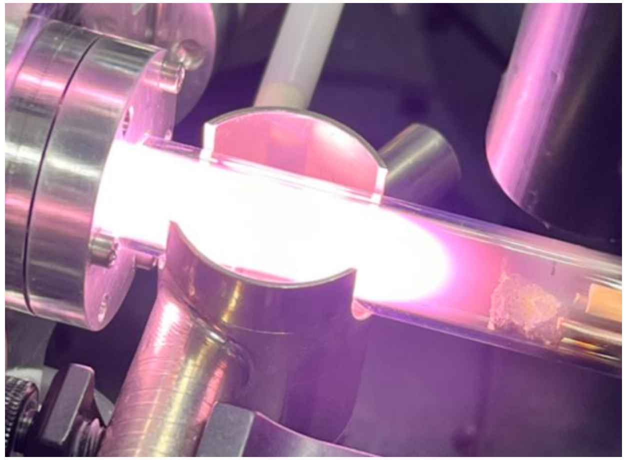
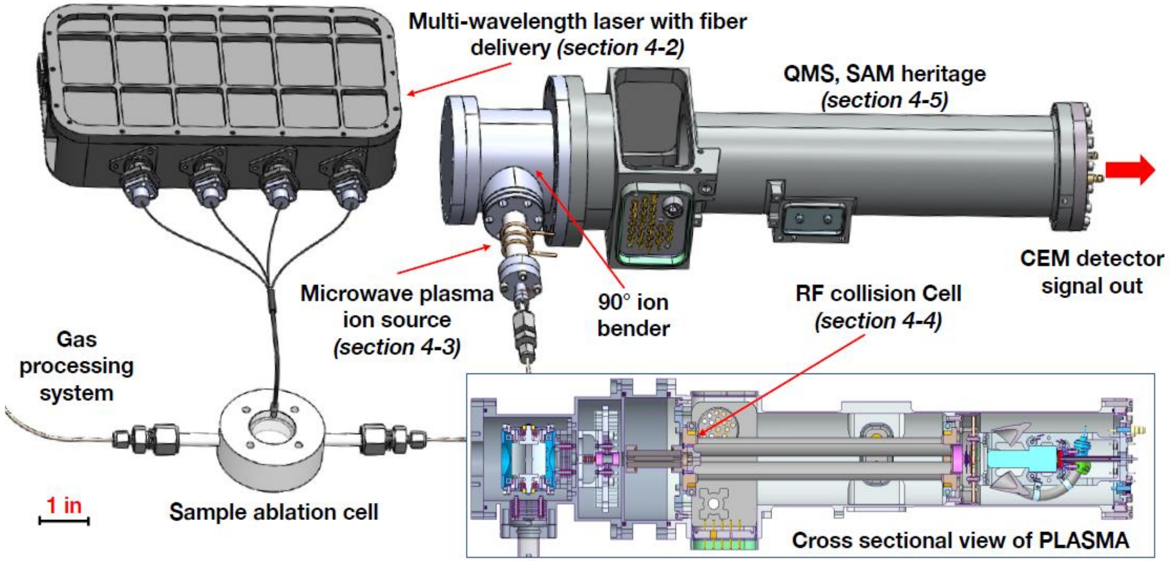
Outline

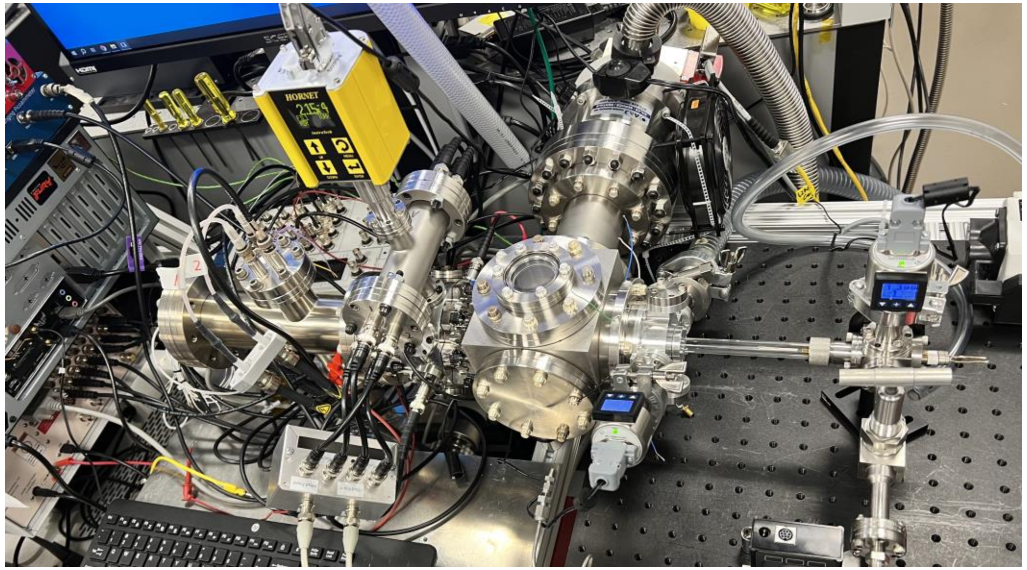
- Introduction
- Laser Requirements
- Fundamental laser - 1064 nm
- Nonlinear frequency conversion – modelling and experimental results
  - Second harmonic generation
  - Fourth harmonic generation
  - Fifth harmonic generation
- Engineering test unit (ETU) design
- Summary and future work

PLASMA instrument

- PLASMA: Pulsed Laser Ablation Sampling and Mass Analysis
- NASA DALI (Development and Advancement of Lunar Instrumentation)
- Multi-wavelength laser - 1064 nm, 532 nm, 266 nm, 213 nm
- Plasma source: low power (<25 W), low gas flow (<0.2 L/min), efficiently atomizing and ionizing input material
- Collision cell: RF only quadrupole ion guide, designed to separate Rb and Sr for radiometric dating
- Quadrupole mass spectrometer – flight proven TRL 9 unit (SAM QMS)
- Mass (i.e., 11.8 kg CBE), Power (86 W peak), and Gas flow (<200 SCCM)







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PLASMA instrument

- Multiwavelength laser: different materials have distinct absorption characteristics, thus the emission of multiple wavelengths enhances photon-substrate coupling with a range of targets.

Wavelength	Photon Energy	Function
1064 nm	1.2 eV	Analysis of water-bearing phases
532 nm	2.3 eV	Complementary Raman spectroscopy
266 nm	4.7 eV	Desorption of aromatic hydrocarbons
213 nm	5.8 eV	Ablation of silicates and oxide minerals

- **Instrument will deliver in situ analyses via**
- Spatially resolved sampling, 2D chemical imaging of lunar materials, and emission of multiple wavelengths for enhanced photon-substrate coupling
- Quantitative analysis of major, minor, and trace elements across the periodic table (6Li to 238U) to higher precision and accuracy than previous spaceflight investigations
- Discrimination of isobaric interferences via collision cell technology to separate competing elemental and isotopic signals and enable Rb-Sr radiometric dating

PLASMA laser requirement

Parameter	PLASMA	
Program	DALI	
Period of Performance	3 Years	
Targeted Mission	Moon	
Mission Lifetime	1M Shots	
Frequency Conversion	2^{nd}, 4^{th}, & 5^{th} Harmonic of 1064 nm	
Pulse Width	< 6 ns	
Beam Spot Size	50 – 200 µm diameter all wavelengths Spot overlap YES AOI for each wavelength 0 degree Distance from sample 2 – 3 “	
Output Wavelengths/ Peak flounce	213 nm 266 nm 532 nm 1064 nm	5.0 ± 1.0 J/cm^2 5.0 ± 1.0 J/cm^2 0.1 ± 0.05 J/cm^2 5.0 ± 1.0 J/cm^2
Pulse Rate	10 Hz	

Ceramic Nd:YAG oscillator: 1064 nm

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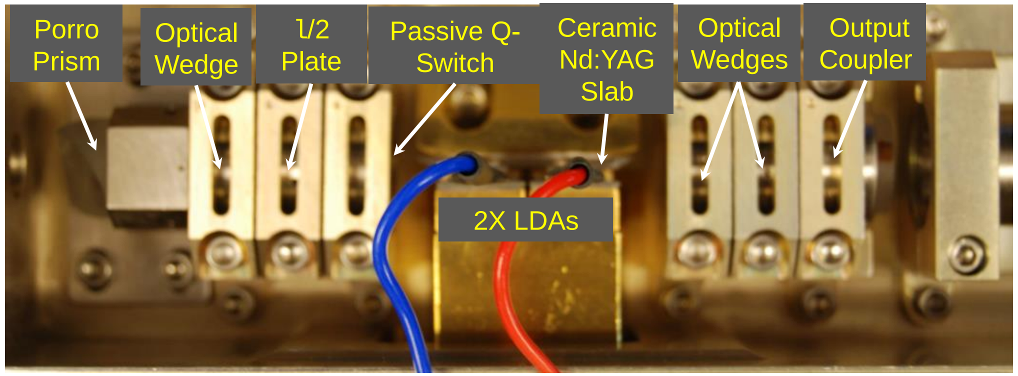
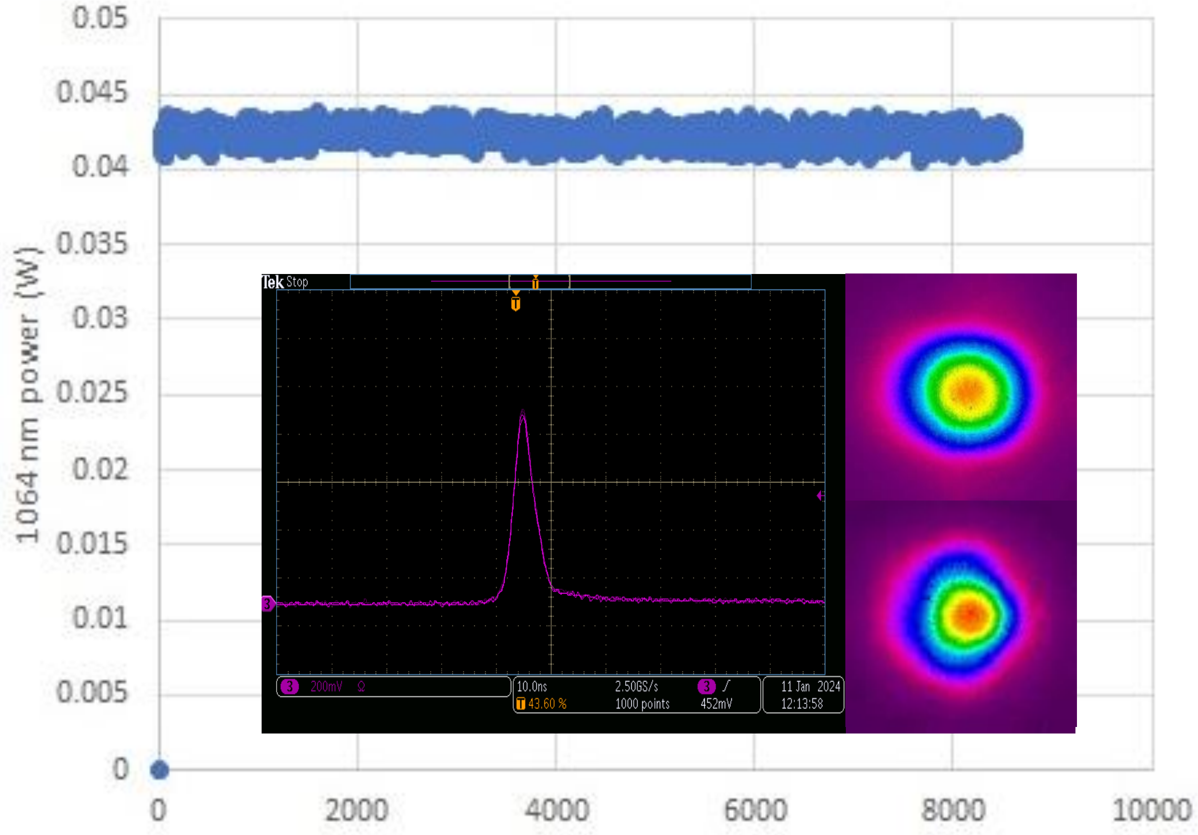
- TRL9 heritage system GLAS MLA LOLA/LOLA QS design
- 4-at% Nd ceramic Nd:YAG slab gain medium
- 11-bounce, Brewster cut zig-zag slab
- 885 nm laser diode array (LDA) (Northrop Grumman)
- Passive Q-switching with 0.3 O.D. Cr:YAG
- 30 % reflectivity output coupler
- 100 µs pump duration
- ~ 4 mJ, ~5 ns, 10 Hz PRF
- The switch-out time is ~ 93 µs and
- the Q-switch threshold current is ~ 101 A.





- Anthony W. Yu, et. al., "885-nm laser diode array pumped ceramic Nd:YAG master oscillator power amplifier system," Proc. SPIE 7686, Laser Technology for Defense and Security VI, 76860G (4 May 2010); doi: 10.1117/12.849596

Second harmonic generation

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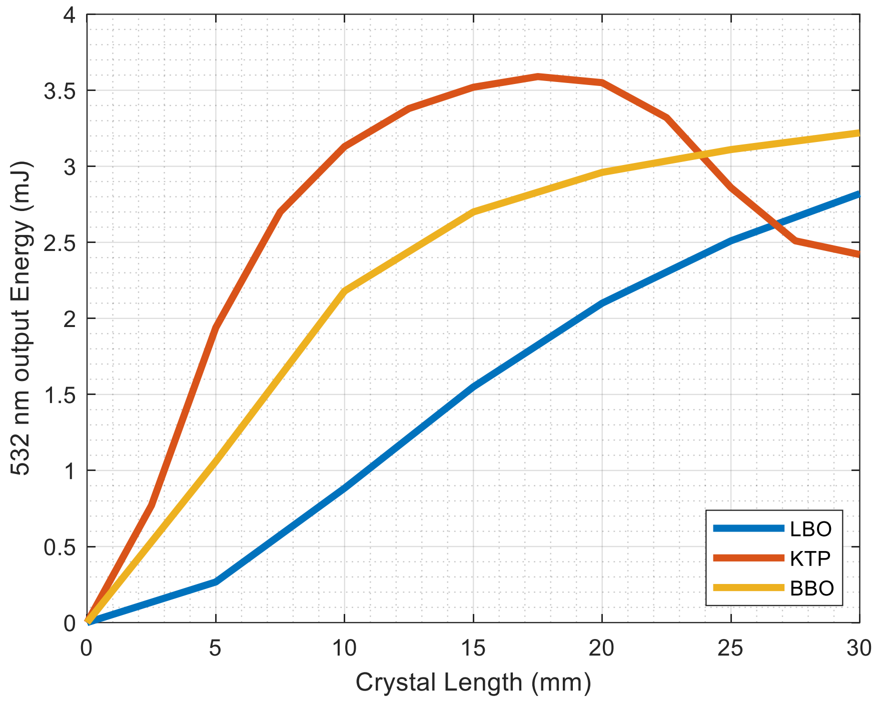
- 1064 nm to 532 nm
- 1064 nm input parameter

  : 4 mJ, 5 ns, 1 mm $1/e^2$ beam diameter, collimated beam
- Type II KTP (potassium titanyl phosphate) – max. conversion around 15 – 20 mm length
- Type I LBO (lithium triborate) - increase the conversion with longer crystal length
- 6 mm, 10 mm, and 15 mm KTP crystals and 20 mm and 30 mm LBO crystals were experimentally tested.



Crystal	θ (°) at 300 K	ϕ (°) at 300 K	Walk-off angle (mrad)	D_{eff} (pm/V)	Crystal angle tolerance (mrad/cm)	Temperature tolerance (K/cm)
KTP	90.0	23.6	4.16	3.58	11.42	25.45
LBO	90.0	11.3	6.88	0.832	4.82	7.04
BBO	22.9	-	55.85	2.01	0.58	40.67

Fourth harmonic generation

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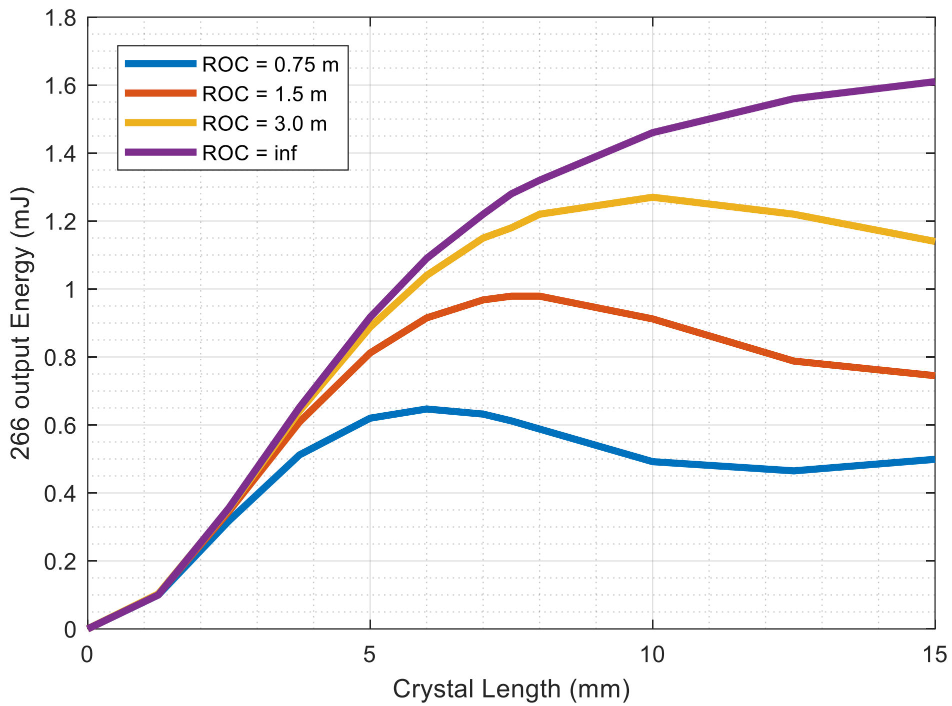
- 532 nm to 266 nm
- Type I BBO
- 532 nm input parameters: are 2.5 mJ, 5 ns, 1.0 mm $1/e^2$ diameter
- Radius of curvature from 0.75 m to infinity
- Absorption coefficients included
- ±0.5 mm crystal length change at maximum conversion for 2.3 mJ and 2.7 mJ and 0.8 - 1.2 mm $1/e^2$ diameter

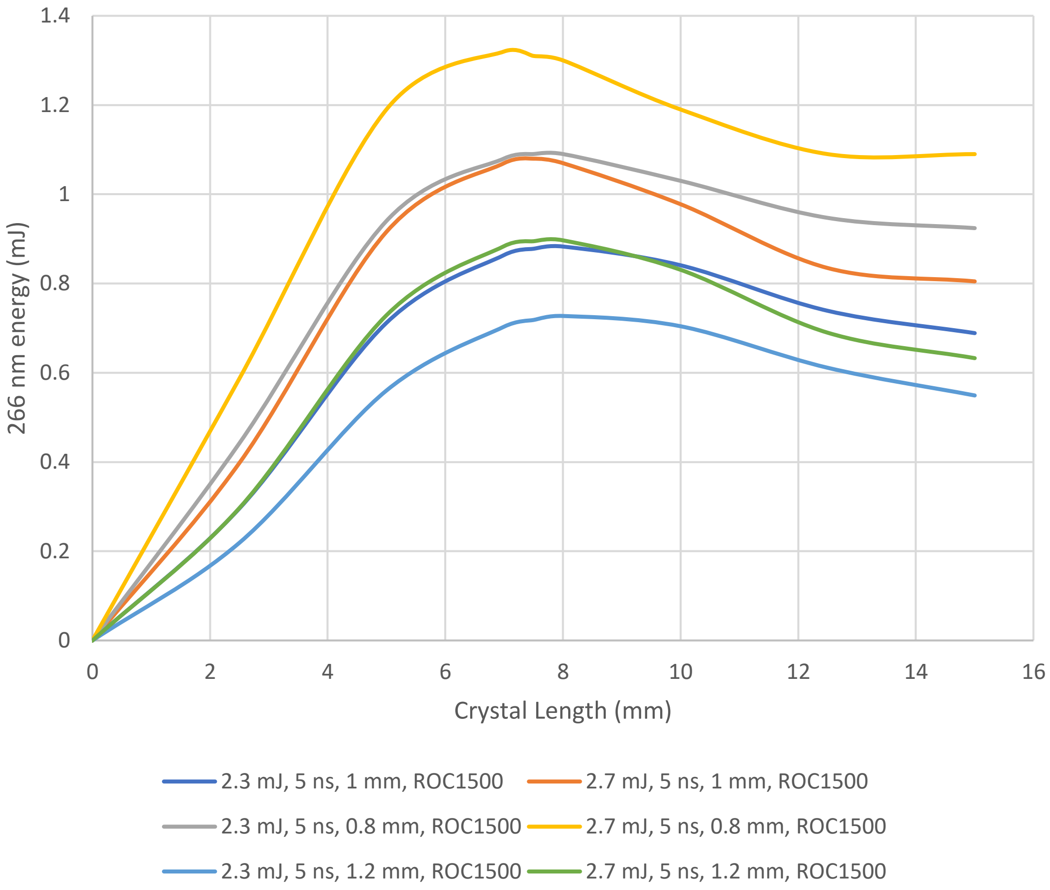


	1064 nm	532 nm	266 nm	213 nm
Linear absorption coefficients (1/cm)	~ 0	~ 0	0.01	0.025
Nonlinear refractive index n2 (cm2/W)	5.6E-16	6.5E-16	2.38E-17	N/A
Two photon absorption coefficients (cm/W)	N/A	N/A	9E-10	2.45E-9

Harmonic generation	Crystal	θ (°) at 300 K	Walk off angle (mrad)	D_{eff} (pm/V)	Crystal angle tolerance (mrad/cm)	Temperature tolerance (K/cm)
4HG Type I	BBO	47.7	85.30	1.75	0.19	6.02
	CLBO	61.5	32.96	0.788	0.54	6.80
	KBBF	36.6	62.14	0.413	0.29	N/A
	KDP	76.7	14.18	0.463	1.24	2.55

Fourth harmonic generation

	2.3 mJ, 5 ns, 1 mm, ROC1500	2.7 mJ, 5 ns, 1 mm, ROC1500	2.3 mJ, 5 ns, 0.8 mm, ROC1500	2.7 mJ, 5 ns, 0.8 mm, ROC1500	2.3 mJ, 5 ns, 1.2 mm, ROC1500	2.7 mJ, 5 ns, 1.2 mm, ROC1500
0	0	0	0	0	0	0
2.5	0.296	0.398	0.442	0.587	0.219	0.297
5	0.712	0.916	0.94	1.19	0.56	0.729
7	0.864	1.07	1.08	**1.32**	0.703	0.884
7.5	0.878	**1.08**	**1.09**	1.31	0.718	0.895
8	**0.883**	1.07	**1.09**	1.3	**0.727**	**0.897**
10	0.841	0.978	1.03	1.19	0.704	0.831
12.5	0.739	0.835	0.947	1.09	0.611	0.69
15	0.689	0.805	0.924	1.09	0.549	0.633



Fifth harmonic generation

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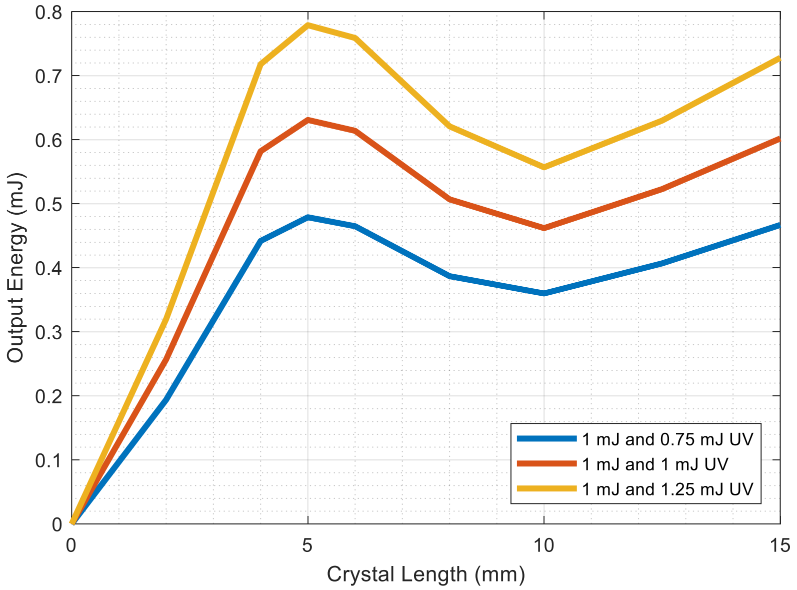
- Sum frequency generation: 1064(o) + 266(o) = 213(e)
- 1064 nm input energy: 1.0 mJ
- 266 nm input energy: 0.75 mJ and 1.25 mJ
- 5 ns, 1 mm 1/e^2 diameter, and 1.5 m ROC

- Varied input energy 1064 nm: 0.7 mJ – 1.3 mJ
  266 nm: 0.75 mJ - 1.3 mJ



Harmonic generation	Crystal	θ (°) at 300 K	Walk off angle (mrad)	D_{eff} (pm/V)	Crystal angle tolerance (mrad/cm)	Temperature tolerance (K/cm)
5HG Type I	BBO	51.2	96.15	1.95	0.13	4.35
	CLBO	67.6	30.07	0.949	0.46	4.14
	KBBF	37.0	65.95	0.452	0.21	N/A

Fifth harmonic generation

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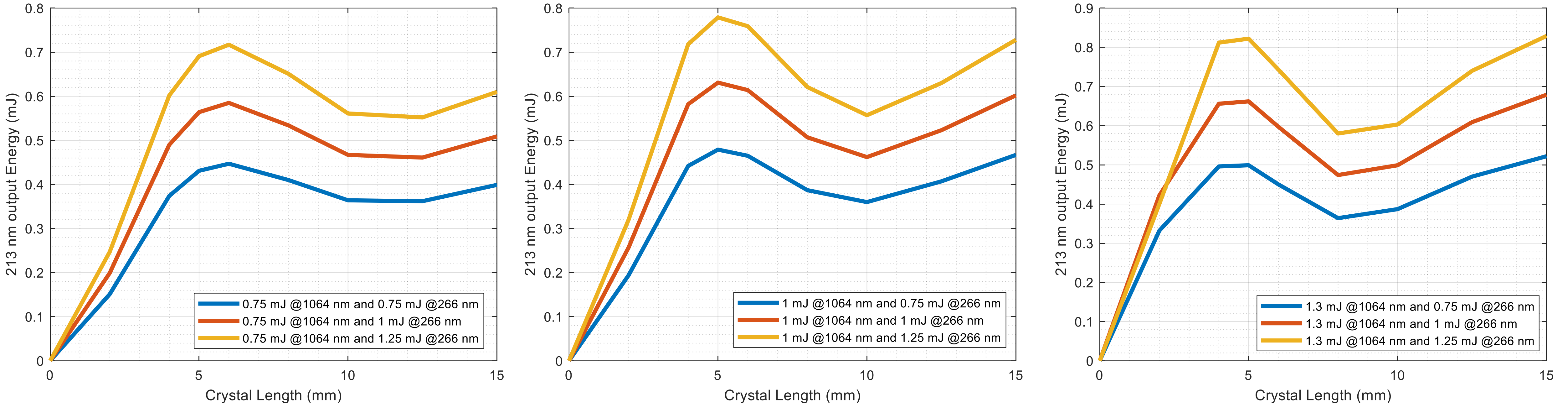
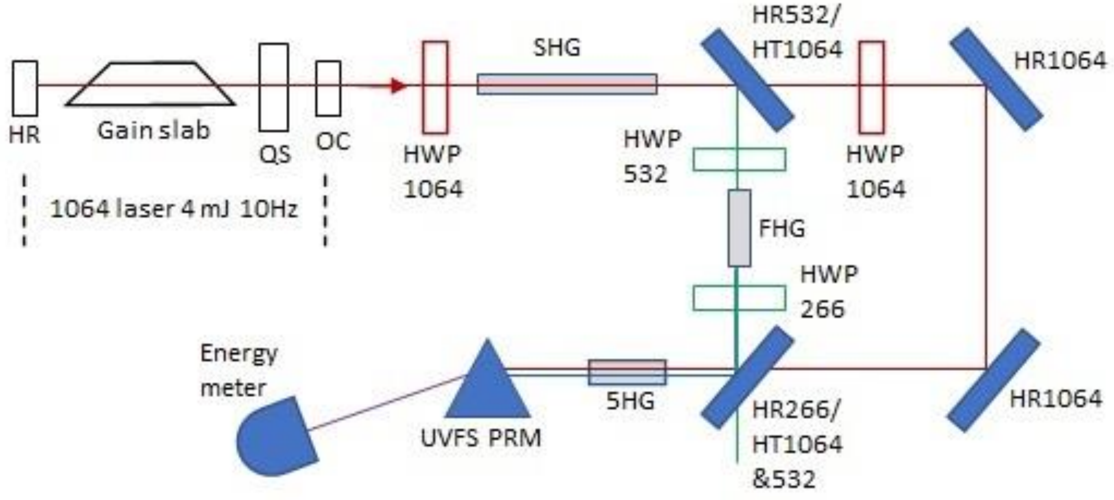
- 5 ns, 1 mm 1/e^2 diameter, and 1.5 m ROC

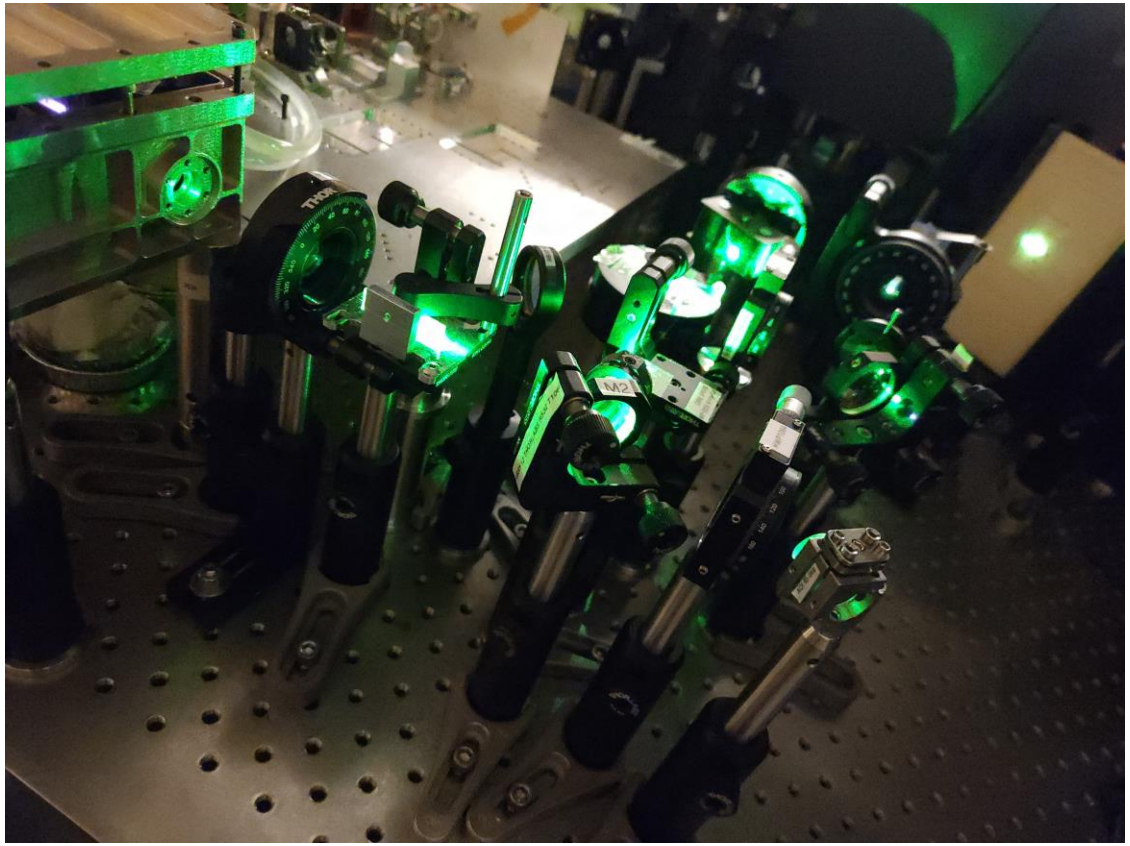


	0.7 mJ @1064 nm		1 mJ @1064 nm		1.3 mJ @1064 nm	
0.75 mJ @266 nm	0.447 mJ	6 mm	0.479 mJ	5 mm	0.499 mJ	5 mm
1 mJ @266 nm	0.585 mJ	6 mm	0.631 mJ	5 mm	0.662 mJ	5 mm
1.25 mJ @266 nm	0.717 mJ	6 mm	0.779 mJ	5 mm	0.822 mJ	5 mm

Experimental Setup

- The fundamental 1064 nm breadboard laser
- Output coupler to SHG crystal : ~ 100 mm
- 532 nm beam path from SHG to FHG: ~ 100 mm
- FHG to 5HG crystal: 532 nm 250 mm 1064 nm 300 mm (Δt = 0.16 ns)
- Uncoated UV grade fused silica prism





Experimental results

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Conversion	Crystal	Input wavelength (nm)	Input energy (mJ)	Converted wavelength (nm)	Converted energy (mJ)	Conversion efficiency (%)
SHG	LBO 20 mm	1064	4.02	532	1.67	41.5
SHG	LBO 30 mm	1064	4.0	532	2.39	59.8
SHG	KTP 6 mm	1064	3.96	532	2.15	54.3
SHG	KTP 10 mm	1064	3.97	532	2.59	65.2
SHG	KTP 15 mm	1064	3.97	532	3.1	78.1
FHG	BBO 5 mm	532	2.54	266	0.98	38.9
FHG	BBO 5 mm	532	3.1	266	1.21	39
FHG	BBO 7 mm	532	2.36	266	0.92	39
FHG	BBO 10 mm	532	2.45	266	1.01	41.2
FHG	BBO 15 mm	532	2.5	266	0.9	36
5HG	BBO 4 mm	1064/266	1.31/0.98	213	0.215	9.4
5HG	BBO 6 mm	1064/266	1.07/1.02	213	0.445	21.3
5HG	BBO 8 mm	1064/266	1.19/1.02	213	0.384	17.3

- SHG: 15 mm KTP - 78 % conversion efficiency and 30 mm LBO - 60 % conversion efficiency
- FHG: BBO 5 – 10 mm length ~ 39 % conversion efficiency
- 5HG: 6 mm BBO crystal - 21 % conversion efficiency.

Engineering test unit

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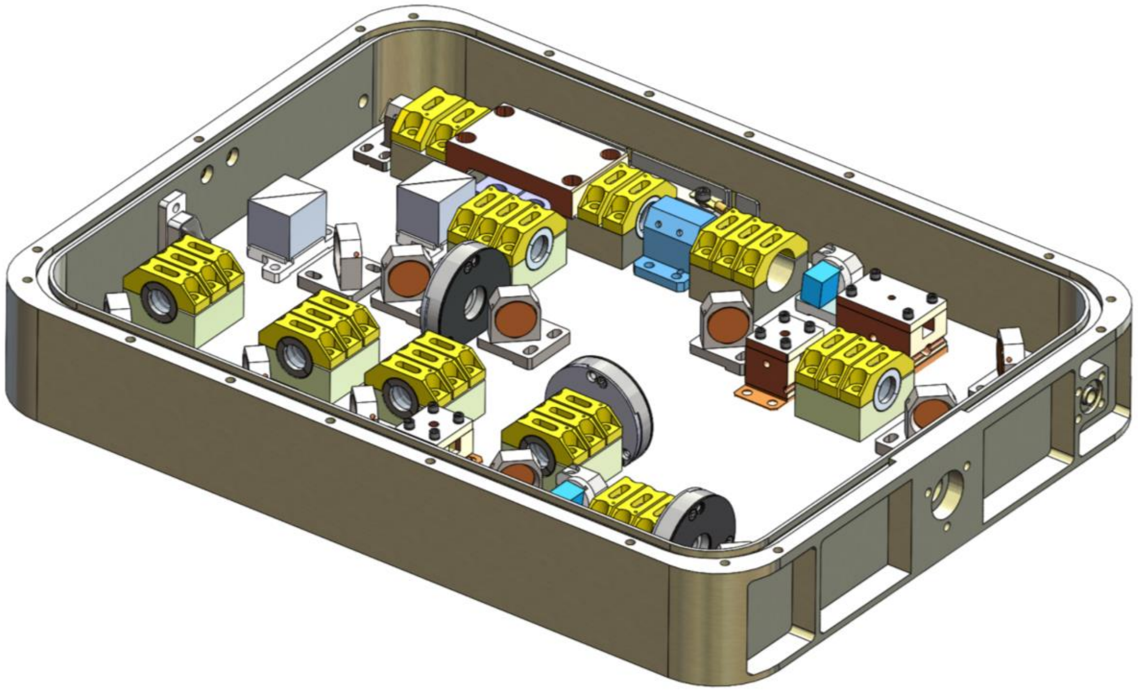
- The laser oscillator - based on proven spaceborne TRL9 laser design flown successfully on GLAS (Geoscience Laser Altimeter System), MLA (Mercury Laser Altimeter), and LOLA (Lunar Orbiter Laser Altimeter)
- Porro prism as a resonator mirror
- Intracavity Risley pairs and polarizer
- Passive Q-switch with Cr:YAG saturable absorber
- Output coupler
- Risley pairs and half wave plate in front of each nonlinear crystals
- Wavelength selection



Summary and future work

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- The progress of developing the multi-wavelength pulsed laser system based on the ceramic Nd:YAG oscillator with 885 nm pumping and nonlinear frequency conversion was discussed.
- We are developing a multi-wavelength laser system capable of emitting wavelengths from IR (1064nm) to green (532 nm) to deep UV (266 and 213 nm) for chemical/isotopic analysis for the PLASMA instrument.
- The PLASMA engineering test unit (ETU) design is currently in progress and targeting to meet the TRL6 (technology readiness level) instrument requirements.

- All laser components will be prepared according to the approved processes for flight.
- Vibration/shock and thermal vacuum chamber (TVAC) testing
- Integration onto the PLASMA collision and mass spectrometer analyzer
- Instrument level performance testing
- Hollow core fiber as beam delivery system is under evaluation

BACK UP

Science Objectives

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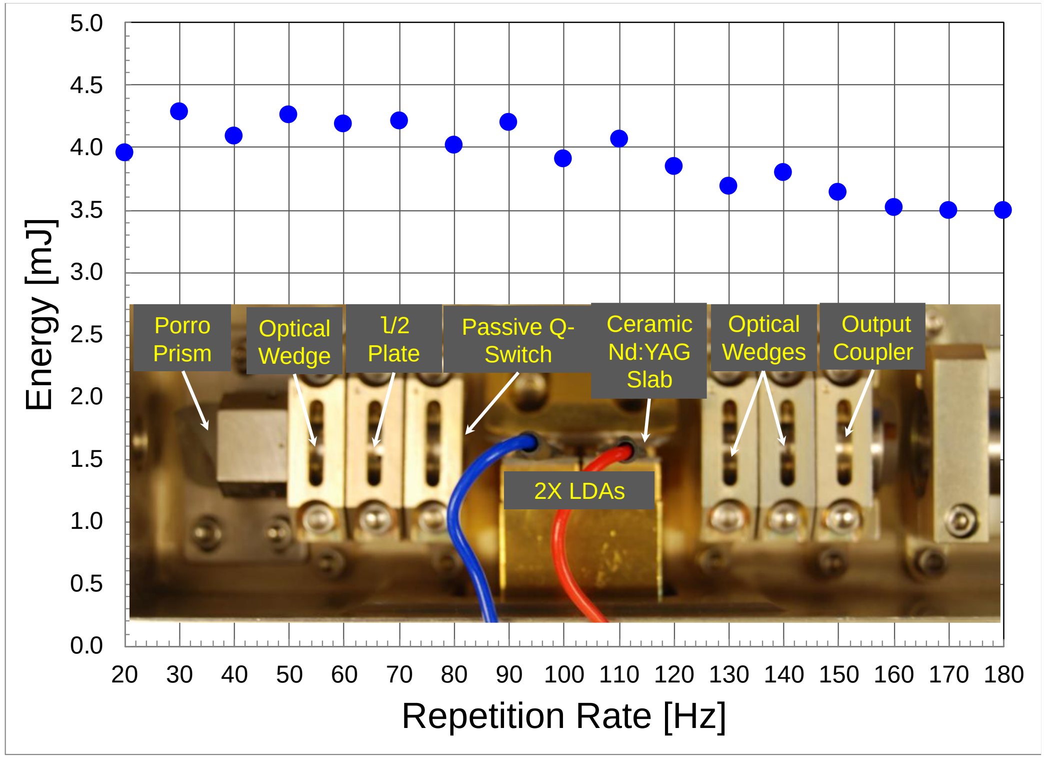
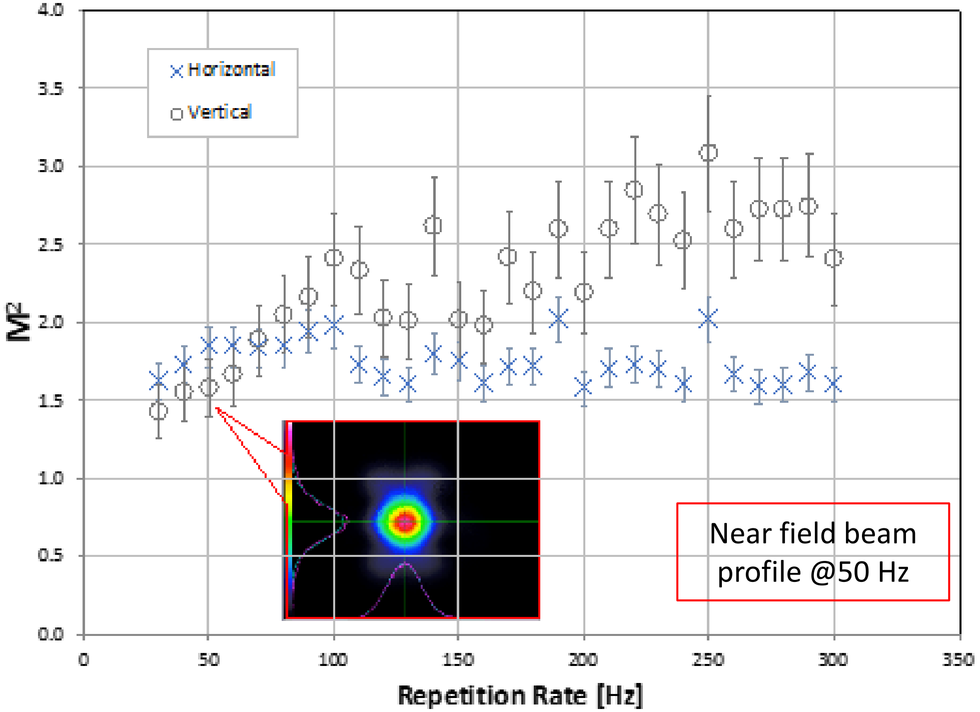
PLASMA Lunar Science Objectives	
Objective 1	Characterize the depletion of moderately volatile elements (MVEs) and putative enrichment of refractory elements, particularly heat-producing K, Th, and U, in lunar surface materials to inform on the dynamics of the Moon's formation and thermal evolution.
Objective 2	Quantify absolute and relative abundances of Al & first row transition elements (FRTEs) to discern mare source mineralogy and melting depths and produce a stratigraphic cross section of the farside mantle.
Objective 3	Determine absolute ages via the Rb-Sr isotopic system to constrain the timing of farside crust formation and document the secular evolution of mare basalt compositions.
Objective 4	Investigate the veracity of the Late Heavy Bombardment (LHB) by dating materials sourced from the SPA basin via in situ Rb-Sr chronometry.
Objective 5	Quantify elemental abundances down to ppmw levels and identify economically viable deposits of raw materials and precious metals (e.g., REEs) to support human exploration.

Ceramic Nd:YAG MOPA system (2010)

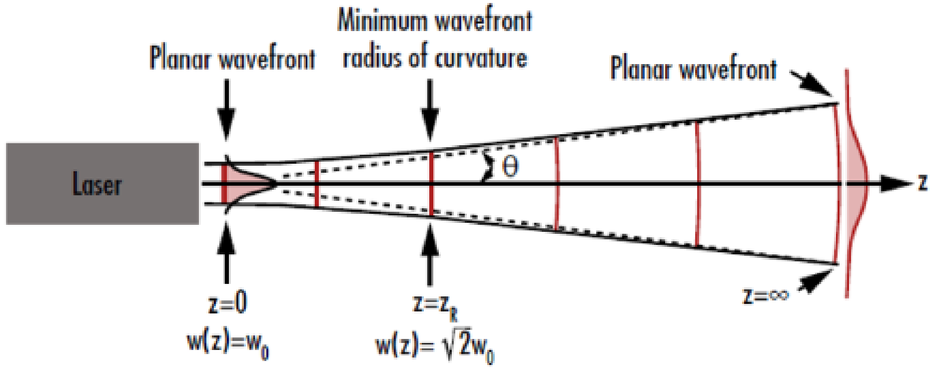


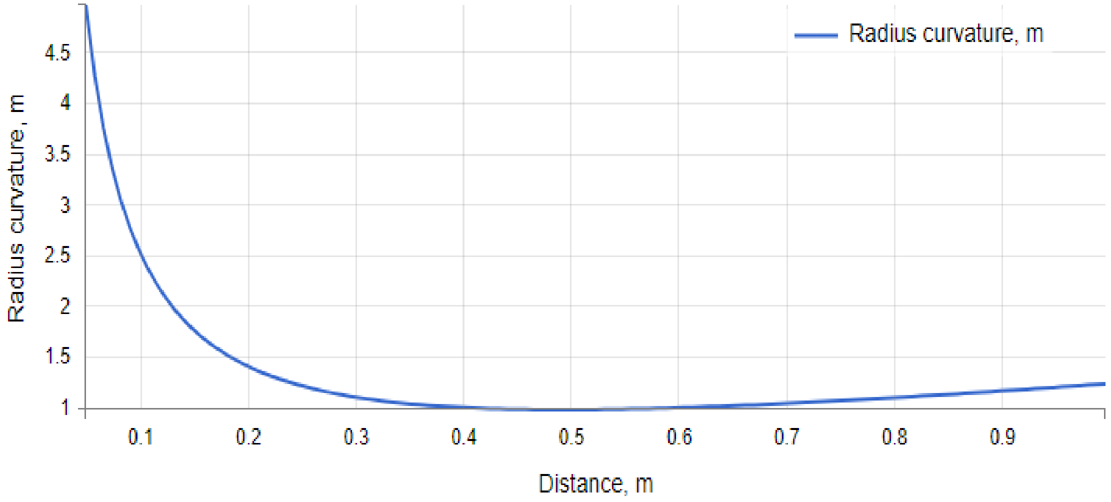


[1]A.W. Yu, S.X. Li, M. A. Stephen, A. Seas, E. Troupaki, A. Vasilyev, H. Conley, T. Filemyr, C. Kirchner, A. Rosanova, "885-nm laser diode array pumped ceramic Nd:YAG master oscillator power amplifier system," Proc. SPIE 7686, Laser Technology for Defense and Security VI, 76860G (4 May 2010); https://doi.org/10.1117/12.849596

Nonlinear frequency conversion

- With $M^2 = 1.5$, 1 mm $1/e^2$ diameter 1064 nm beam, Rayleigh range Z_R is ~ 0.49 m
- Radius of curvature varies toward the minimum value in the compact engineering test unit (ETU) design
- All nonlinear crystal locations are within the Rayleigh range of the fundamental laser

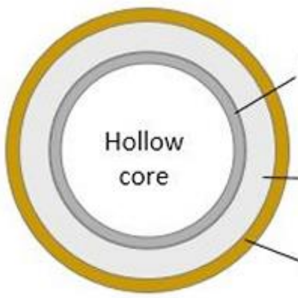




https://www.edmundoptics.com/knowledge-center/application-notes/lasers/gaussian-beam-propagation/
https://toolbox.lightcon.com/tools/gaussianbeampropagation

Beam Delivery System

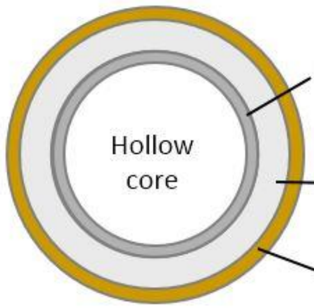
Hollow Core Fiber Designed for UV



Internal Diameter (ID)	320 µm	700 µm	1000 µm
Typical Loss† (straight)	2 dB/m	1 dB/m	0.5 dB/m
Max Energy* (λ = 193 nm ArF)	1 mJ	5 mJ	10 mJ
Maximum Power (average)*	0.5 W	1.0 W	2.0 W
Minimum Bend Radius	10 cm	20 cm	50 cm
Patch Cable Length	0.1 - 1.0 m		

† Additional loss on bending, which scales with radius (R) as 1/R.
* Assuming proper coupling. Initial alignment should always be done at reduced power.

Hollow Core Fiber Designed for VIS/NIR



	Glass			Plastic
Internal Diameter (ID)	500 µm	750 µm	1000 µm	1500 µm
Typical Loss† (straight)	0.5 dB/m	0.4 dB/m	0.3 dB/m	2.0 dB/m
Max Energy* (λ = 532 nm; 5 ns)	20 mJ	50 mJ	75 mJ	100 mJ
Maximum Power (average)*	30 W	50 W	100 W	30 W
Minimum Bend Radius	10 cm	20 cm	50 cm	5 cm
Patch Cable Length	0.1 - 5.0 m			

† Additional loss on bending, which scales with radius (R) as 1/R.
* Assuming proper coupling. Initial alignment should always be done at reduced power.

Hollow core fiber beam delivery

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- Experiment: coupling efficiencies – **All test fibers are 0.5 m length**

A. 320 µm: showed ~ 27 % coupling efficiencies in IR, VIS, and UV. It attributed to the micro-irregularity on the internal wall of the glass capillary of 320 um ID hollow core fiber caused the micro bending scatter off the propagating beam.

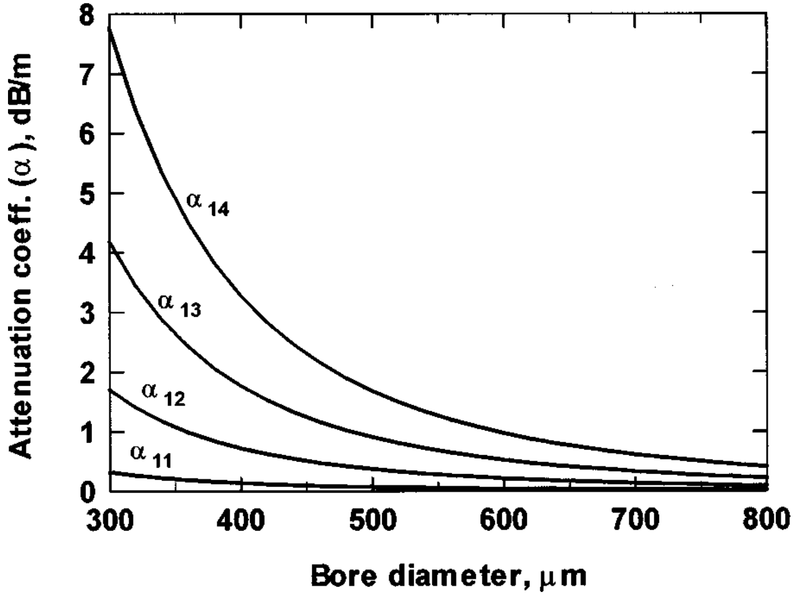
B. 1000 µm: Showed ~91 % coupling efficiencies but not flexible due to large bend radius of large core HCF.

C. 700 µm:

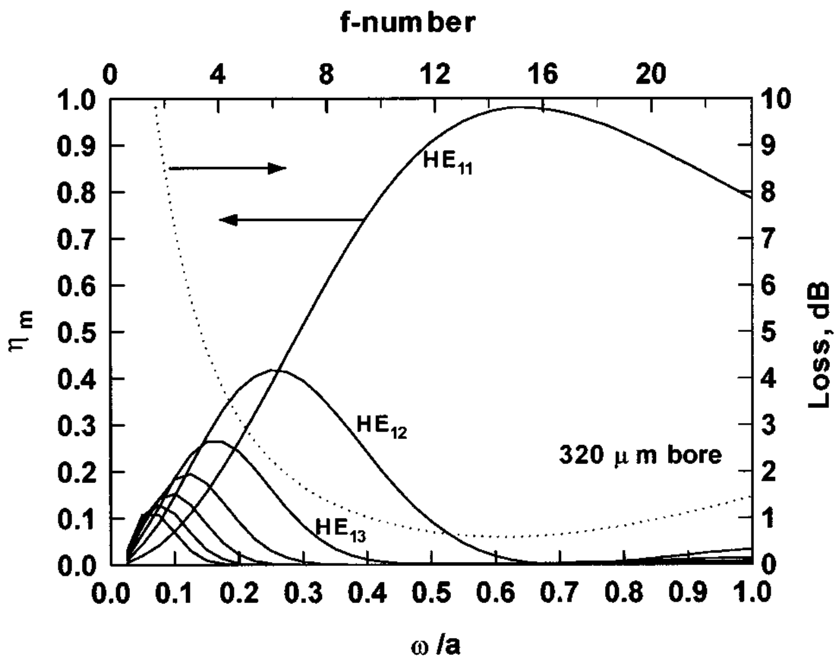
	1064 nm	**532 nm**	**266 nm**	**213 nm**	**NOTE**
Coupling efficiency	59%	63%	72%	79%	Fiber held straight

- The loss for the single fiber with the UV coating to be 1 to 2 dB/m at 532 nm and 1064 nm

Beam coupling to hollow core fiber



Calculated attenuation coefficients of the first four HE_{1m} modes in hollow-glass waveguides.



Calculated coupling coefficients (solid curves) and total loss (dotted curve) of a 1-m-long, 320-mm-bore, hollow-glass waveguide.

Rick K. Nubling, et. al., “Launch conditions and mode Coupling in hollow glass Waveguides”, Opt. Eng. 37(9) 2454–2458 (1998)

Solarization resistant fiber – 600 µm ID

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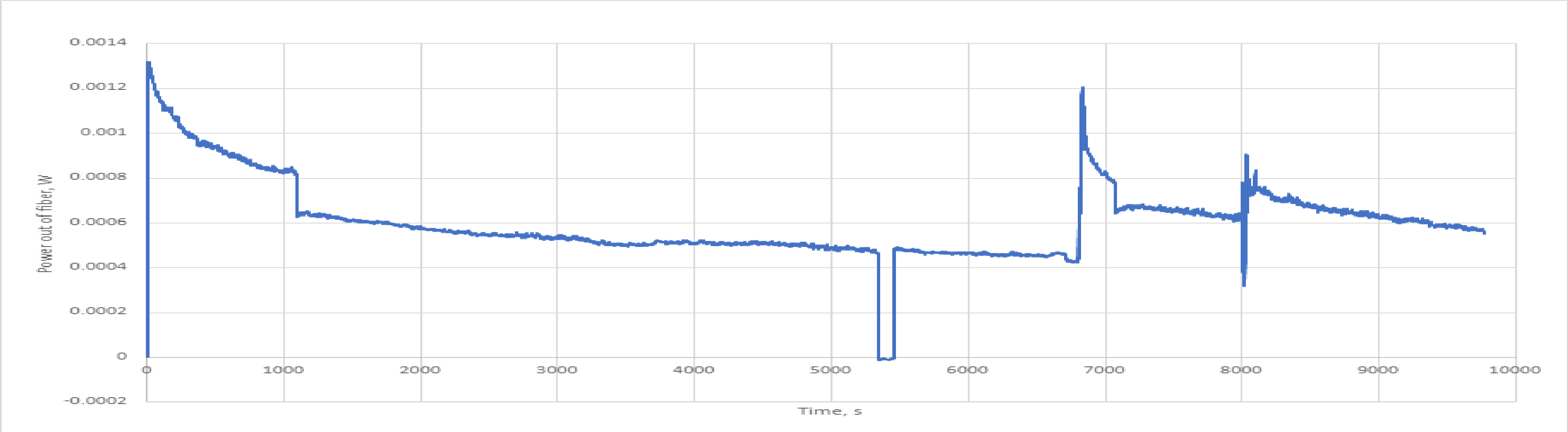
135 µJ input of 266 nm beam input



75 µJ input of 266 nm beam input