High energy, single-mode, all-solid-state and tunable UV laser transmitter

Narasimha S. Prasad[a], Upendra N. Singh[a], Floyd Hov

[a]NASA Langley Research Center,

5 N. Dryden St., MS 468, Hampton, VA 23681

[b]Fibertek, Inc.,

510 Herndon Parkway, Herndon, VA 20170

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Laser Risk Reduction Program (LRRP)

- **NASA began Laser Risk Reduction Program (LRRP) in 2002 to develop reliable, robust, and compact laser technologies for lidar applications from space based platforms**
  - ***Program:*** **Joint operation of Langley Research Center and Goddard Space Flight Center**
  - ***Goal:*** **1 micron and 2 micron lasers and wavelength conversion technology**
  - ***Applications:*** **Four Lidar Techniques-altimetry, Doppler, Differenctial Absorption Lidar (DIAL), backscatter lidar**
  - ***Measurements:*** **6 priority Earth Science measurements:**

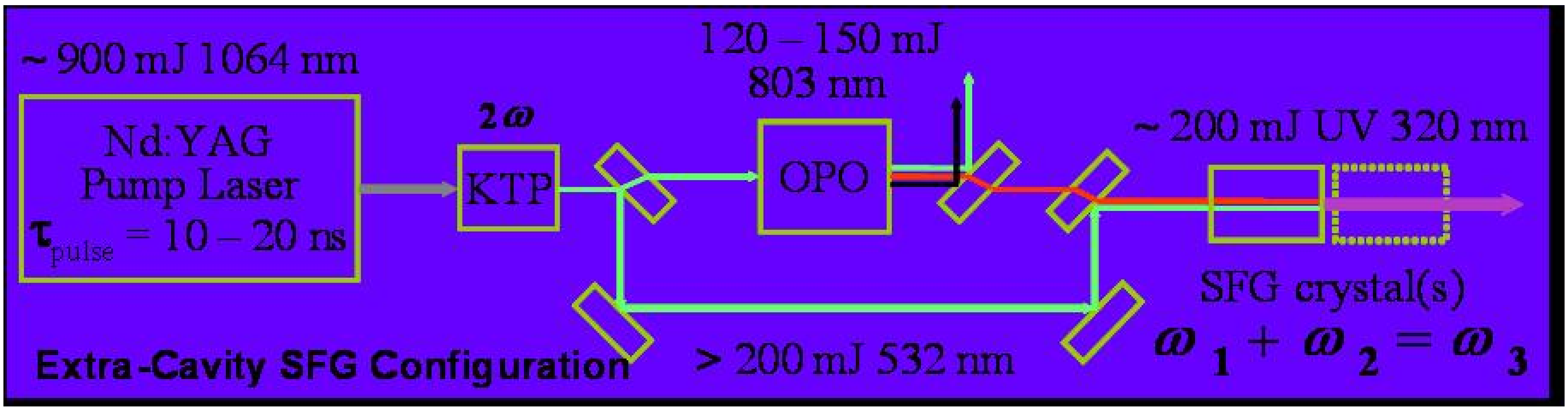
    (1) Surface and ice mapping, (b) Horizontal vector wind profiles (3) Carbon-di-oxide (CO_2) profiles (4) Ozone (O_3) profiles(5) Aerosol/clouds and (6) River currents

UV Task Objectives

- **The objective of the UV Task is to develop an efficient, all-solid-state, diode pumped, conductively cooled, single longitudinal mode and high energy 1-micron to UV wavelength conversion technology**
- **The emphasis is to generate UV wavelengths of 308 nm and 320 nm for ozone sensing using DIfferential Absorption Lidar (DIAL) technique from space**
- **Performance Goals:**
  - **Output energy at UV wavelengths:** **$\geq$ 200 mJ**
  - **Pulsewidth:** **10 - 25 ns**
  - **PRF:** **50 Hz**
- **High pulse energy allows enhanced performance during strong daylight conditions**
- **UV Task is a collaborative effort among Sandia National Labs, Fibertek, and NASA LaRC**

Technical Approach to UV generation

- **Basic Scheme comprises of a Nd:YAG laser pumped nonlinear optics based converter comprising of a second harmonic generation (SHG), optical parametric oscillator, (OPO) and sum frequency generation (SFG) processes**



1064 nm → SHG → 532 nm

532 nm → OPO → 803 nm +1576 nm; 731.5 nm + 1950 nm

532 nm + 803 nm → SFG → 320 nm

532 nm + 731.5 nm → SFG → 308 nm

UV Wavelength Conversion
-Experimental Results-

- The nonlinear optics based technology to efficiently generate UV wavelengths has been established using a flash lamp pumped Nd:YAG laser
- The scheme utilizes a novel (Rotated Image Singly Resonant Twisted RectAngle) RISTRA OPO to generate 803 and 731.5 nm wavelengths pumped using a 532 nm pump source
- A type-I BBO crystal is used in the RISTRA OPO and a LBO crystal is used for SFG
- Single mode operation is obtained through pulsed seeding technique with temporally matched pump and idler pulse profile
- Pulse idler seeding is obtained by a tunable laser diode and RISTRA OPO in tandem as seed sources
- **For 803 nm**
    - **A small or low energy RISTRA OPO that is locked by Pound-Drever-Hall (PDH) technique and seeded by New Focus tunable diode laser operating at 803 nm**
    - **The 1.5x scaled big RISTRA OPO that is pulse seeded at 1576 nm from the small OPO and locked by energy stabilization technique**

Latest Results on the UV conversion

- **State-of-the-art conversion efficiencies have been demonstrated using a flash lamp pumped Nd:YAG laser with a round top-hat profile**

- **Greater than 90 % pump depletion obtained**
- **At 320 nm, >200 mJ extra cavity SFG with good beam Quality**
  - **IR to UV efficiency > 21% (27% for 1 mJ seed)**
- **At 320 nm , up to 160 mJ intra-cavity SFG**
  - **IR to UV efficiency up to 24%**
- **Fluence ≥1 J/cm^2 for most beams**

RISTRA OPO Module

Solid-State Nd:YAG Pump laser

- For future space applications, an all solid-state, diode pumped Nd:YAG pump laser has been developed in collaboration with Fibertek, Inc.
  - The pump laser is an upgrade of ~300 mJ/pulse Nd:YAG laser developed under NASA funded ATIP program
  - Two amplifiers have been added to the NASA ATIP laser to achieve up to 1.2 J/pulse

Nd:YAG Pump Laser

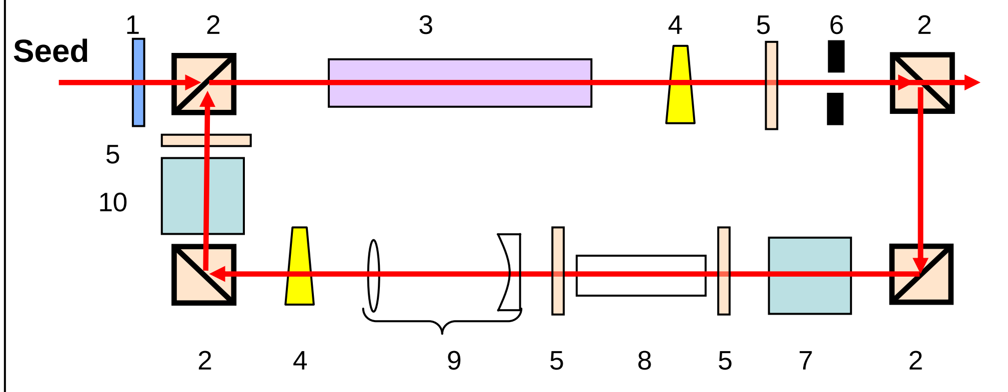
-Summary of Technical Approach-

An all solid-state diode-pumped laser transmitter featuring:

• **Injection seeded ring laser**	**Improves emission brightness (M^2)**
• **Diode-pumped zigzag slab amplifiers**	**Robust and efficient design for use in space**
• **Advanced E-O phase modulator material**	**Allows high frequency cavity modulation for improved stability injection seeding**
• **Alignment insensitive / boresight stable 1.0 μm cavity and optical bench**	**Stable and reliable operation over environment**
• **Conduction cooled**	**Eliminates circulating liquids w/in cavity**
• **Space-qualifiable component designs**	**Establishes a path to a space-based mission**

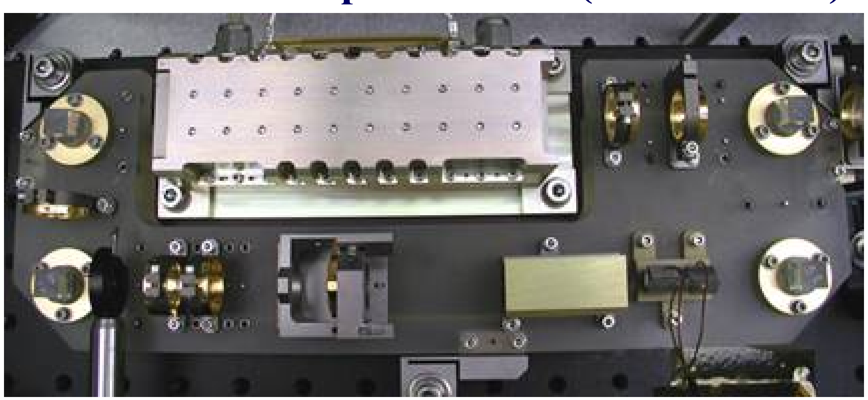
Single Frequency Laser Ring Laser Design

Optical Schematic



1. **Reverse wave suppressor**
2. **Cube polarizer**
3. **Odd bounce slab**
4. **Steering wedge**
5. **λ/2 waveplate**
6. **Mode limiting aperture**
7. **RTP phase modulator**
8. **45° Dove prism**
9. **Non-imaging telescope**
10. **RTP q-switch**

Final Zerodur Optical Bench (12cm x 32cm)



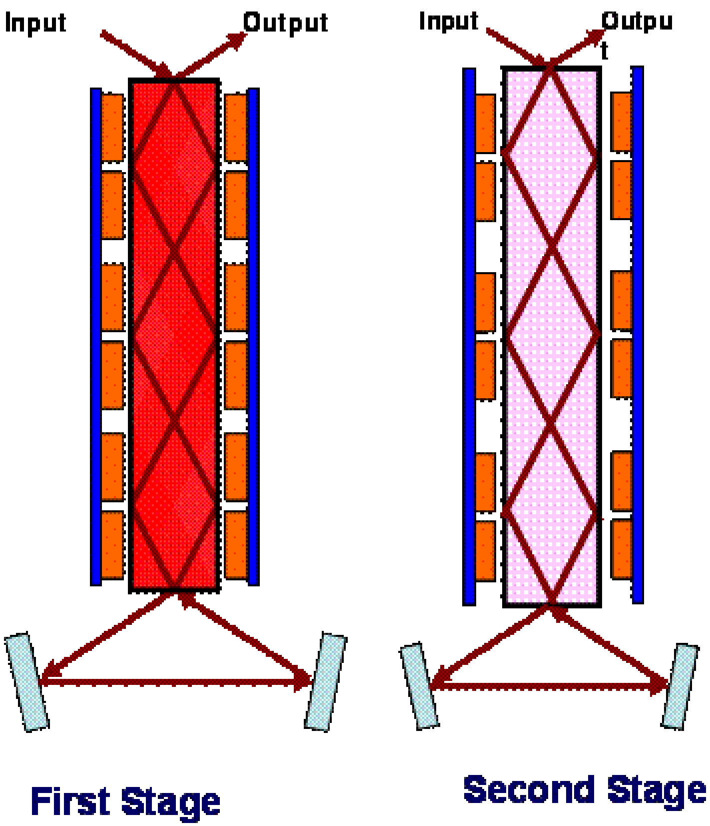
Design Features

- Near stable operation allows trading beam quality against output energy by appropriate choice of mode limiting aperture
  - –30 mJ TEM_{00}, M^2 =1.2 at 50 Hz
  - –30 mJ TEM_{00}, M^2 =1.3 at 100 Hz
  - –50 mJ square supergaussian, M^2 = 1.4 at 50 Hz
- Injection seeding using an RTP phase modulator provides reduced sensitivity to high frequency vibration
- PZT stabilization of cavity length reduces sensitivities to thermal fluctuations
- Zerodur optical bench results in high alignment and boresight stability

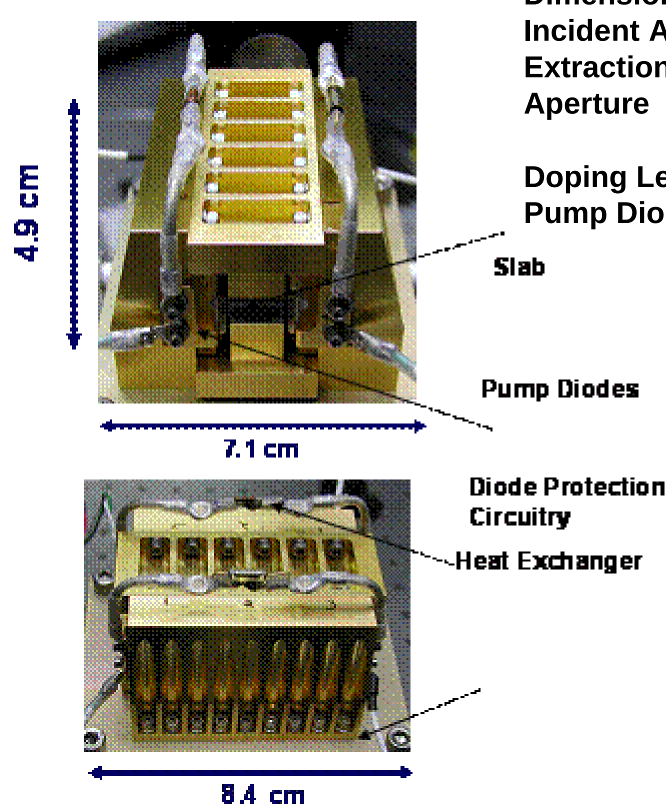
Amplifier Design Configuration

3 Bounces-Rectangular Shape-2 sided pumping in the TIR axis,
2 sided conduction cooling, Pump faces uncoated (~10%loss)

2-Sided Pumped & Cooled Amplifier



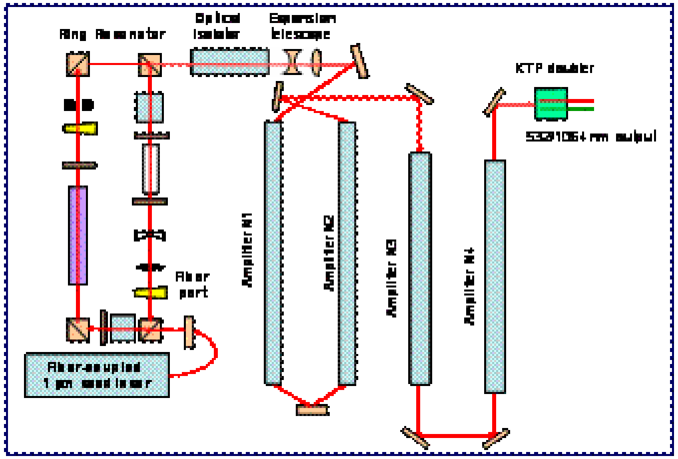
Prototype Two-Sided Pumped and Cooled Head Design



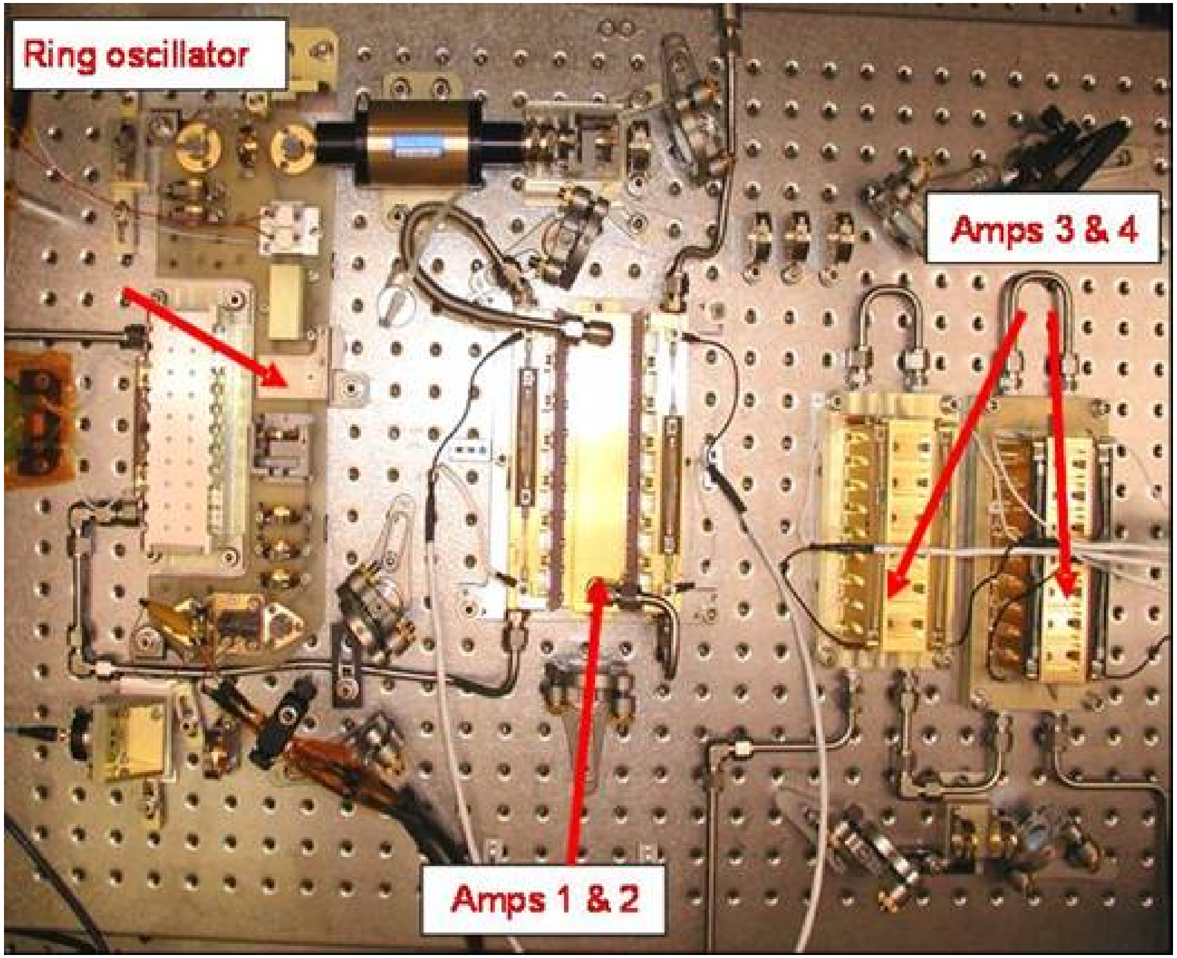
Dimensions	6.8 x 13.0 x 75.3 mm3
Incident Angle	Near Brewster (*57°*)
Extraction	100% at full aperture
Aperture	11.5 x 6.8 mm2 (*internal*)
	7.1 x 6.8 mm2 (*external*)
Doping Level	0.5 ± 0.1 % Nd3+
Pump Diodes	192 ea. 50 watt QCW bars
	(12 ea. 16 bar arrays)

Final System Configuration

Optical layout



Breadboard layout



Diode Bars and slabs are conductively coupled to the heat sink.

For space applications, one can use heat pipes or radiators

Amplifier Upgrade
2-Sided Pumped & Cooled Amplifier

Dual Stage Amplifier Modeling

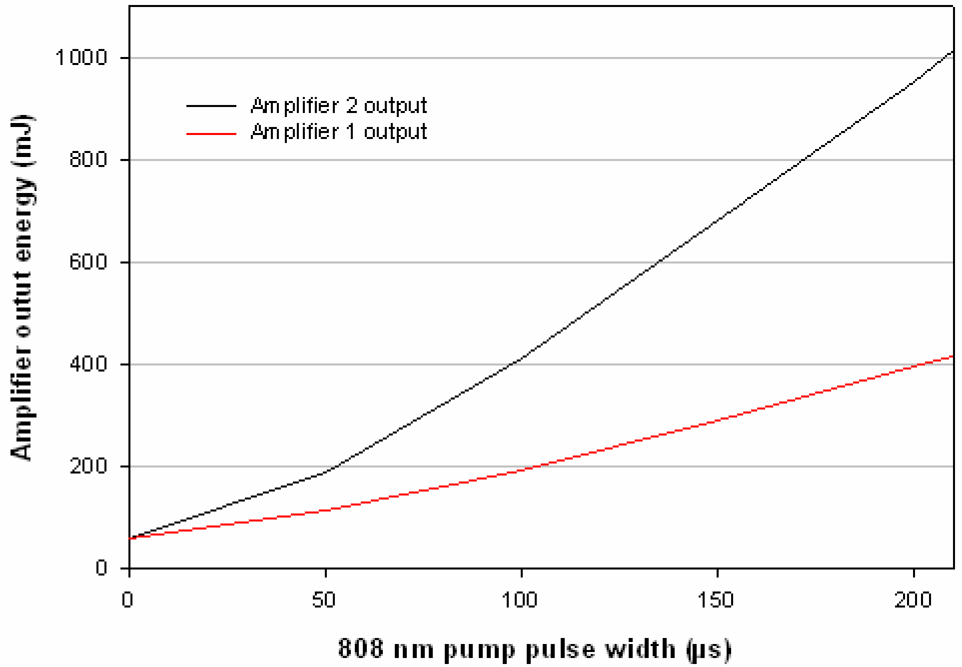
Model is based on Franz-Nodvic result for a amplifying a square (in time) pulse

Model includes all key parameters explicitly

- Number of pump diodes (192)
- Peak diode power (75 W)
- Diode pulse width
- Input oscillator pulse energy (60 mJ)
- Input beam diameter
- Gain path length in amp
- Slab volume

Accounts for reduced gain for second pass

1 J per pulse output is predicted for 210 μs diode pump pulses

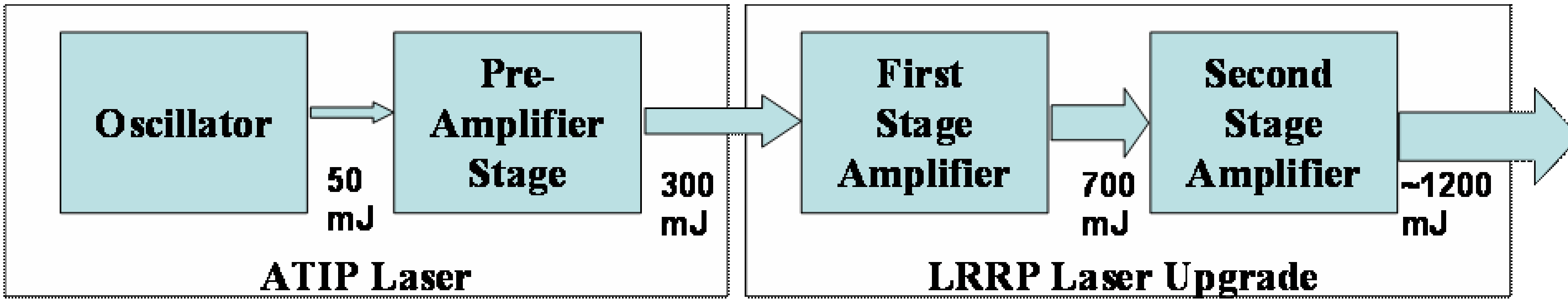


Modeled output of dual 2-sided pumped and cooled amplifiers for 60 mJ input to first stage

Dual 2-sided pumped amplifiers meet the requirements of most space-based direct detection wind lidars designs

Pump Laser Performance

- The laser is now operational at 50 Hz PRF with maximum pulsewidths around 22 ns
- The output beam profile is rectangular super gaussian



Oscillator Configuration
- 100 μs pump pulse
- 55 W/bar
- 100 bars

Oscillator Output
- 50 mJ/pulse
- PRF = 50 Hz
- 0.41 cm x 0.41 cm square beam
- $M^2 = 1.2$

Amplifier Configuration
- Vary pump pulse width
- 55 W/bar
- 112 bars/amp

Peak Dual Amplifier Output
- 350 mJ/pulse
- $M^2 = 1.6$

Input = 280 mJ
First Stage Output > 700 mJ
PRF = 50 Hz
Pulsewidth = ~16 ns
Spatial Mode =Rect. Super Gaussian
M2 ~ 2
Optical Eff. >11%
Wall Plug Eff. >7%

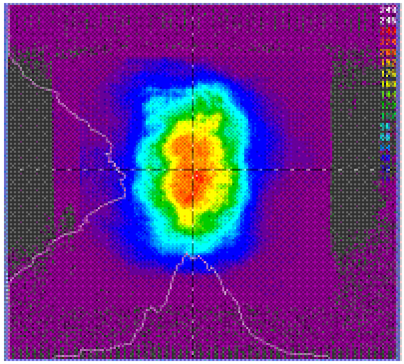
Input = 700 mJ
Second Stage O/P > 1100 mJ
PRF = 50 Hz
Pulsewidth 22 ns
Spatial Mode SG
M2 2.5
Optical Eff. 11%
Wall Plug Eff. 7%

Nd:YAG Pump Laser

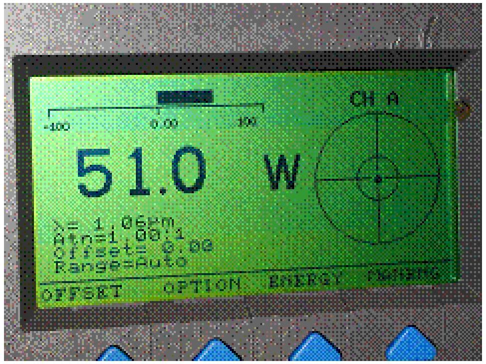
- Typical Output Characteristics -

Parameter	Specification	Goal	Design/Performance
Pulse Energy (mJ)	900	1200	1040
M^2	NA	2	2.5
Laser head package	Single breadboard	NA	Single breadboard in custom enclosure
Cooling	Conductive to diodes and slabs	NA	Conductive to diodes and slabs
Seeding	Ramp & fire	NA	Ramp & fire
Electronics	Separate custom module	NA	Separate custom module

Typical pulsewidth = 22 ns. Max. Pulse Energy achieved = 1.2 J. Electrical to optical efficiency >7% was achieved with only 58 W peak power per diode bar pumping the amplifiers.



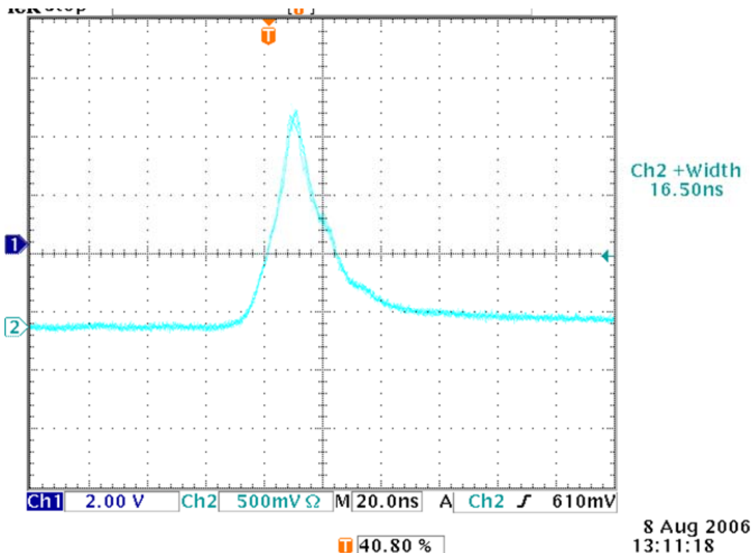
Near field beam profile of final amplifier output



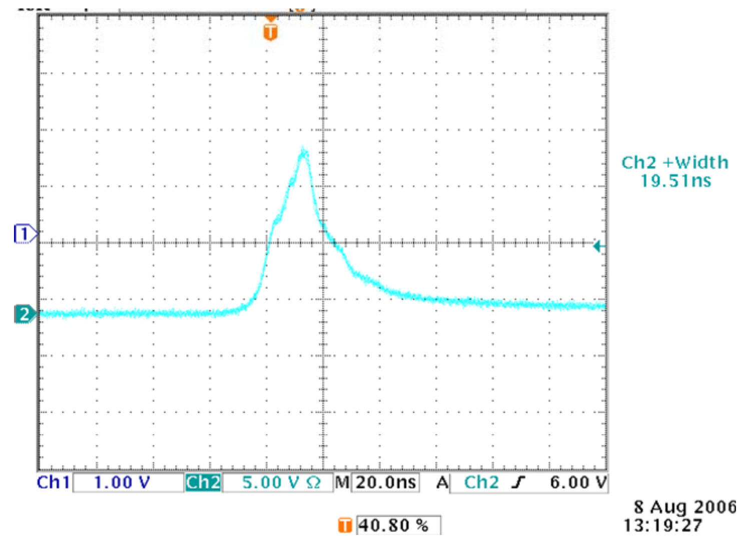
Average power at 50 Hz of 51.0 W (1020 mJ/pulse)

Temporal Characteristics

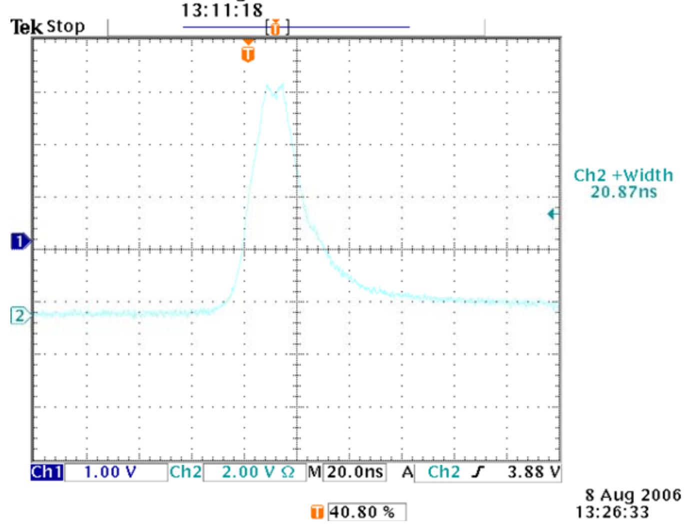
Oscillator Only: 16.5 ns



Oscillator + Preamp 1 + Preamp 2 : 19.5 ns



Oscillator + Amp 1 + Amp 2 : 20.9 ns

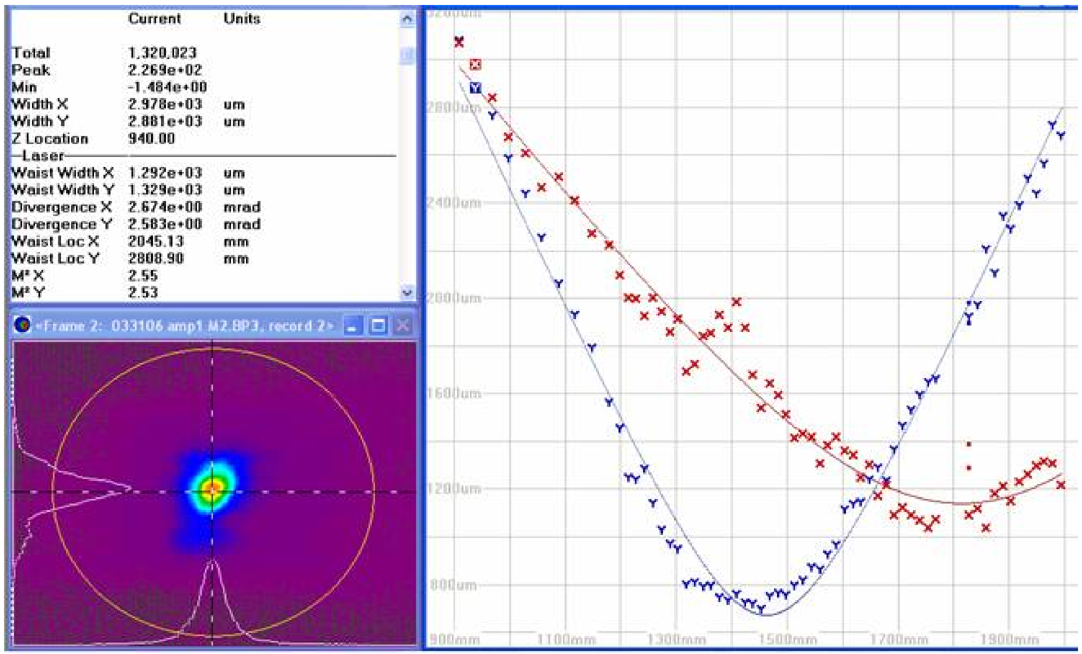


Full System:
Pulsewidth ~ 22 ns

Full System Results Beam Quality

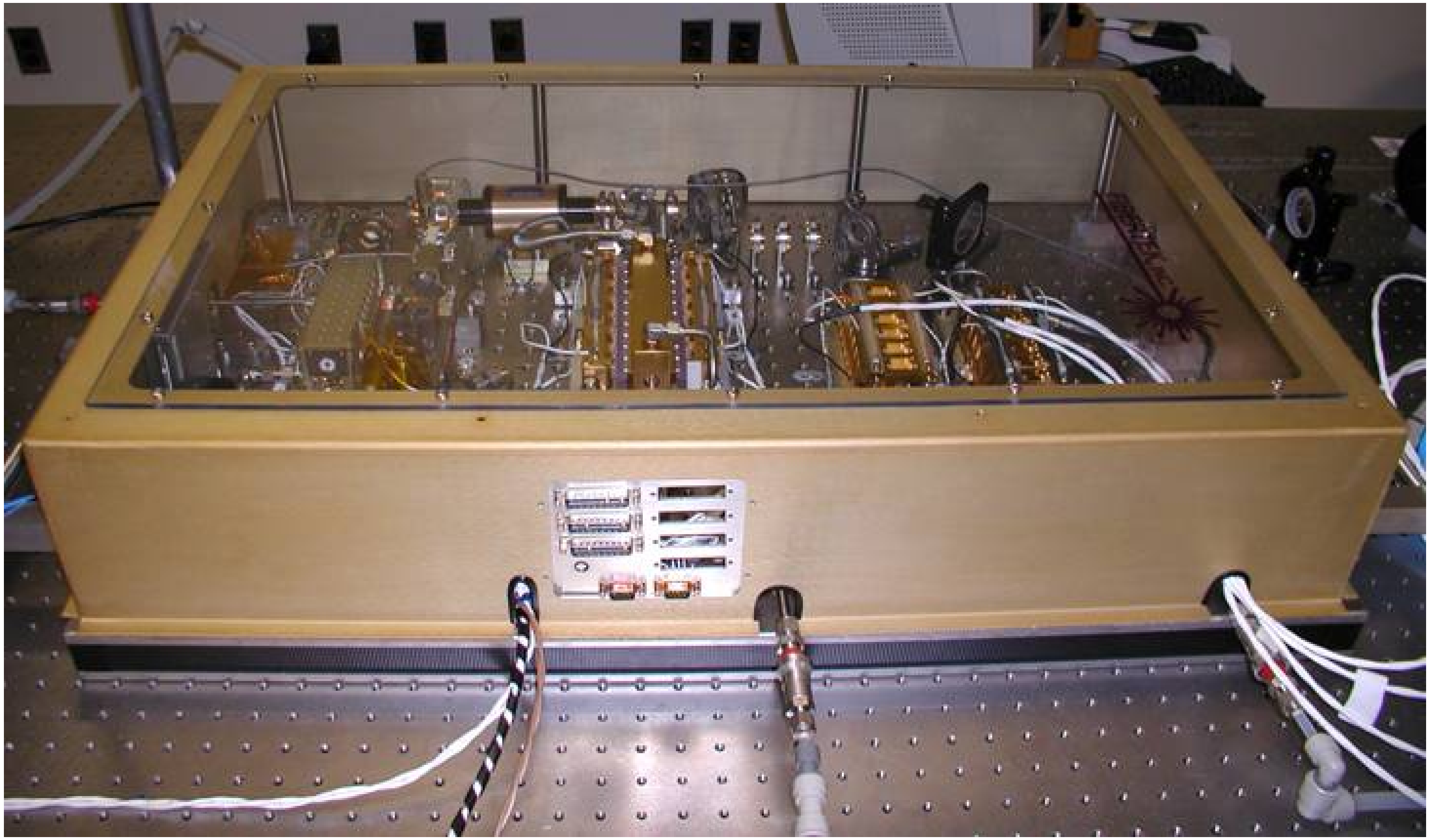
50 Hz, Full Power Beam Quality Measurements

$$\mathbf{M_x^2 = 2.5,\ M_y^2 = 2.5,}$$



M^2 data

Full Nd:YAG Laser Unit



- The dimensions of this laser unit, including a SHG module, is 34” x 22” x 8”
- With latest diode bars and modified opto-mechanical components, the above package can be reduced to less than a quarter of its size

Final System
Control and Power Electronics

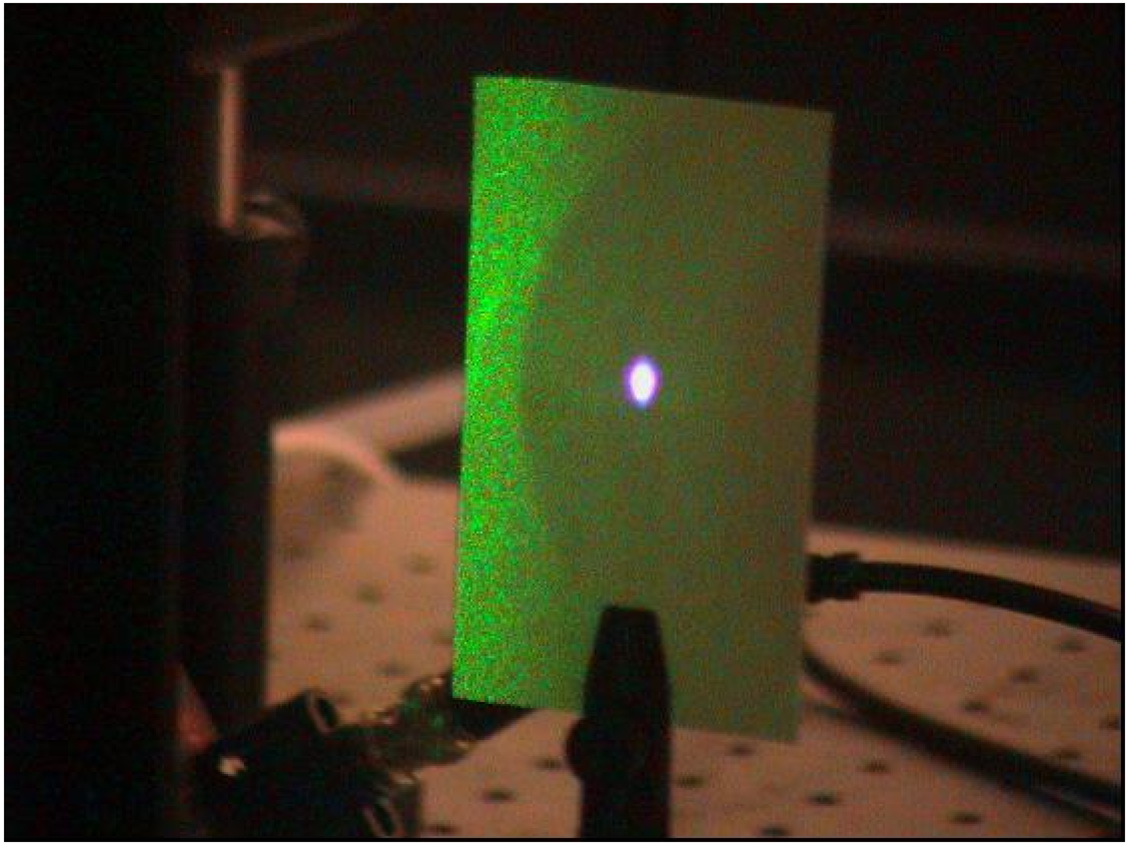
Custom power supplies and control electronics for the upgrade have been built

- **Control electronics consists of two 19"rack mountable boxes**
- **All power supplies are contained in two 19" rack mountable power supply modules**
- **Each amplifier can be individual set between high power and low power operation to allow the user to achieve a wide range of output powers at 50 Hz**

Single Power Supply Module

Control electronics

320 nm UV generation



- **Currently, we are generating a few mJ with limited pump energy of 280 mJ/pulse**
  - The elliptical beam allows reduced overlap inside the nonlinear crystal of RISTRA module hence reduces the conversion efficiency

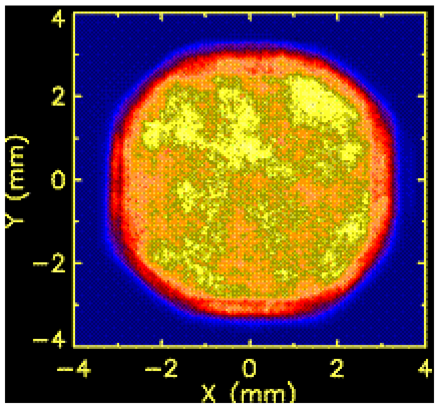
Spatial fluence profile & RISTRA

- RISTRA OPO requires round, top-hat spatial pump profile -

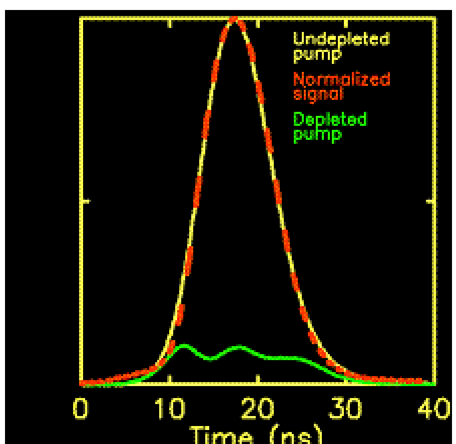
Flat pump profiles have facilitated high pump depletion &hence high OPO conversion efficiency

Results Using refined Flash Lamp pump laser

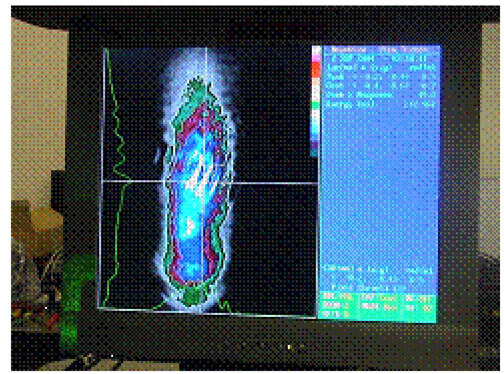
OPO signal near-field spatial fluence profile, Fresnel Number > 450



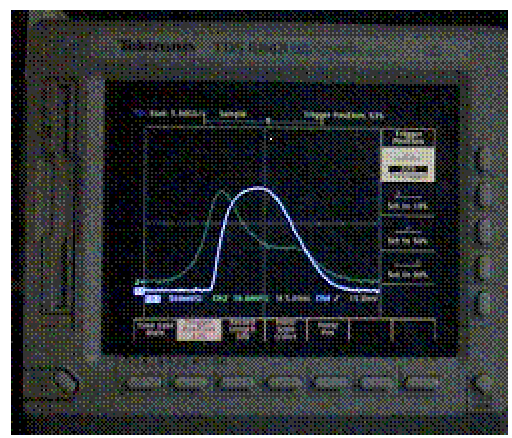
Self-seeded oscillation in two-crystal RISTRA ~85% pump depletion



Results Using Diode pumped Nd:YAG laser



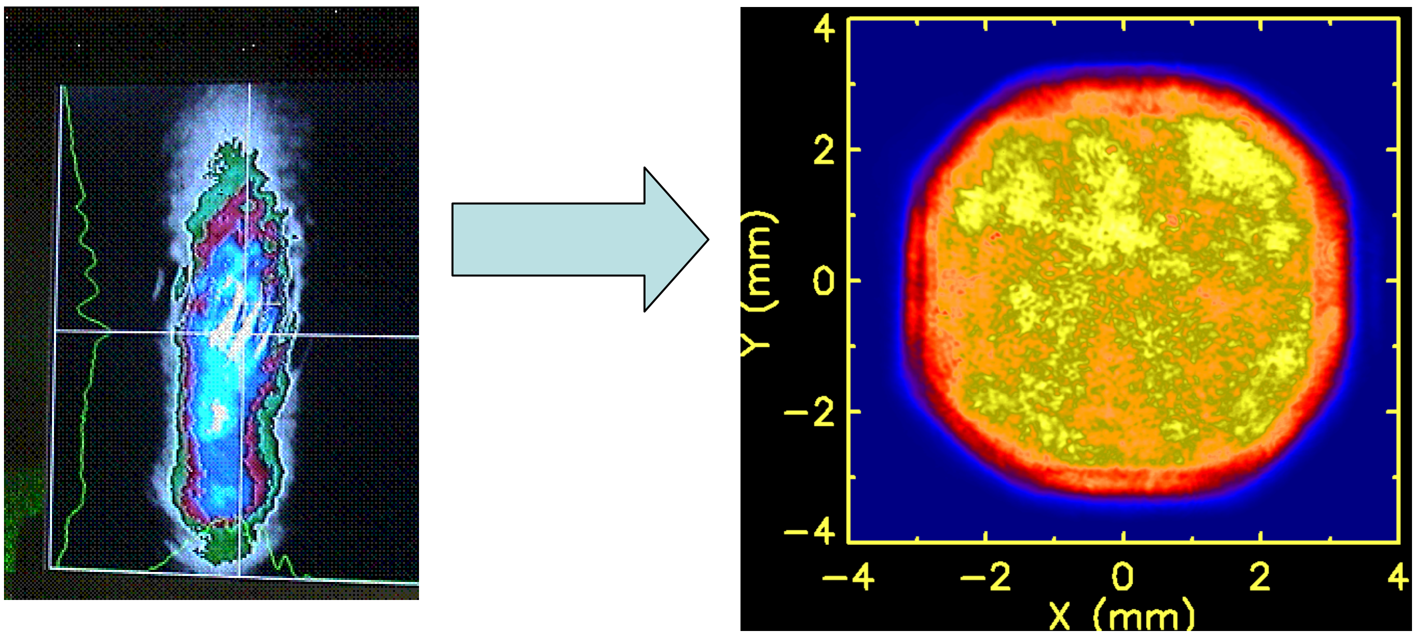
Pump Beam at the Big OPO



Reduced Pump Depletion

On-Going Work

- Improve the Beam Quality of the Diode Pumped Nd:YAG Laser
  - The goal is to achieve a Round, Top Hat spatial fluence profile with wavefront aberration less than 0.5



- Refinements to the ring oscillator cavity, pre amplifiers and amplifiers of the diode-pumped Nd:YAG laser to improve beam quality and reduce pulsewidth is nearing completion

Summary and Conclusions

- A high energy, single mode, all solid-state Nd:YAG laser primarily for pumping an UV converter is developed
- Greater than 1 J/pulse at 50 HZ PRF and pulsewidths around 22 ns have been demonstrated
- Higher energy, greater efficiency may be possible
  - Refinements are known and practical to implement
- Technology Demonstration of a highly efficient, high-pulse-energy, single mode UV wavelength generation using flash lamp pumped laser has been achieved
  - Greater than 90% pump depletion is observed
  - 190 mJ extra-cavity SFG; IR to UV efficiency > 21% (> 27% for 1 mJ seed)
  - 160 mJ intra-cavity SFG; IR to UV efficiency up to 24%
  - Fluence $\leq 1\ J/cm^2$ for most beams
- The pump beam quality of the Nd:YAG pump laser is being refined to match or exceed the above UV converter results
- Currently the Nd:YAG pump laser development is a technology demonstration
  - System can be engineered for compact packaging