FIBERTEK, INC.

Single-Frequency 1 µm Laser for Field Applications

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Acknowledgments

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Program Overview

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- Phase I - Telescopic ring oscillator development
  - Self-imaging unstable ring
  - Non-imaging unstable ring
  - High repetition rate TEM_{00} ring
- Phase II – Amplifier development
  - 500 mJ, 20 Hz
- Phase III – Robust packaging
  - Low expansion optical bench
  - Oscillator/amplifier integration
  - Higher repetition rate amplifier characterization

Telescopic Ring Oscillator
Self-Imaging Unstable Design

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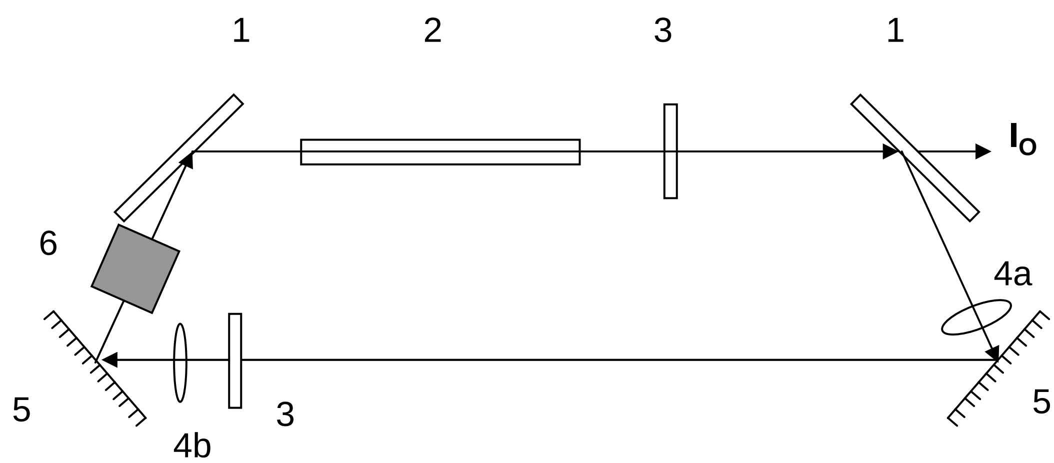
Schematic of Self-Imaging Unstable Ring Resonator



1. Thin film polarizer
2. Nd:YAG slab
3. λ/2 waveplate
4a, b. Telescope
5. High reflector
6. EO q-switch

- **>95% unidirectional operation without a feedback mirror**
- **500 µrad misalignment results in less than 5% energy loss and no observable distortion of the output beam profile**

Telescopic Ring Oscillator
Self-Imaging Ring Laser Performance

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Results of Self-Seeded, Q-Switched Resonator Tests

- M^2 measurements determined from minimum focus and the Rayleigh range after a focusing lens
  - M_x^2 is in zigzag plane
- Self-seeding was used to achieve >95% single frequency pulses
- Key performance results
  - 125 mJ/pulse output was achieved at 20 Hz with 200 µs, 60 A diode pump pulses
  - 5.8% electrical to optical efficiency
  - M_x^2 (zigzag plane) = 2.2
  - M_y^2 = 1.3
- Reduced beam quality in zigzag plane is due to previously observed distortion in that plane

Telescopic Ring Oscillator
Self-Imaging Ring Laser Performance

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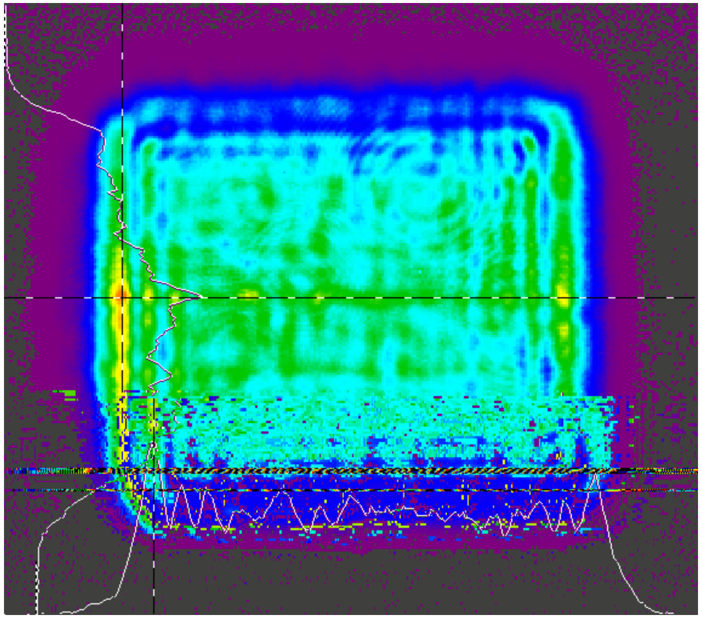
Near Field Profile of Q-switched Output

- Square beam profile more efficiently extracts stored energy from oscillator slab
- Imaging of square beam profile into amplifier in Phase II will allow efficient extraction of stored amplifier energy
- Diffraction effects are due to an intracavity limiting aperture
  - There are no excessive hot spots in the beam profile
  - The change to radially graded output coupling will reduce the spatial modulation due to diffraction effects



Telescopic Ring Oscillator
Self-Imaging Ring Laser Performance

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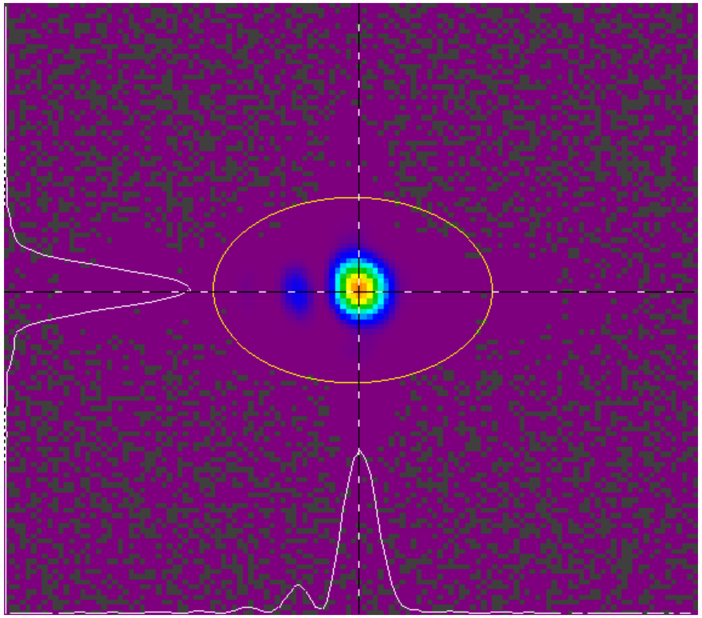
Far Field Profile of Q-switched Output

- Far field is near Gaussian in the non-zigzag plane (vertical in figure)
  - Qualitatively consistent with M_y^2 of 1.2
- Far field in zigzag plane (horizontal in figure) has a near Gaussian primary lobe with a small side lobe
  - Side lobe is source of M_x^2 of increased to 2.2



Telescopic Ring Oscillator
Unstable Non-Imaging Ring Design

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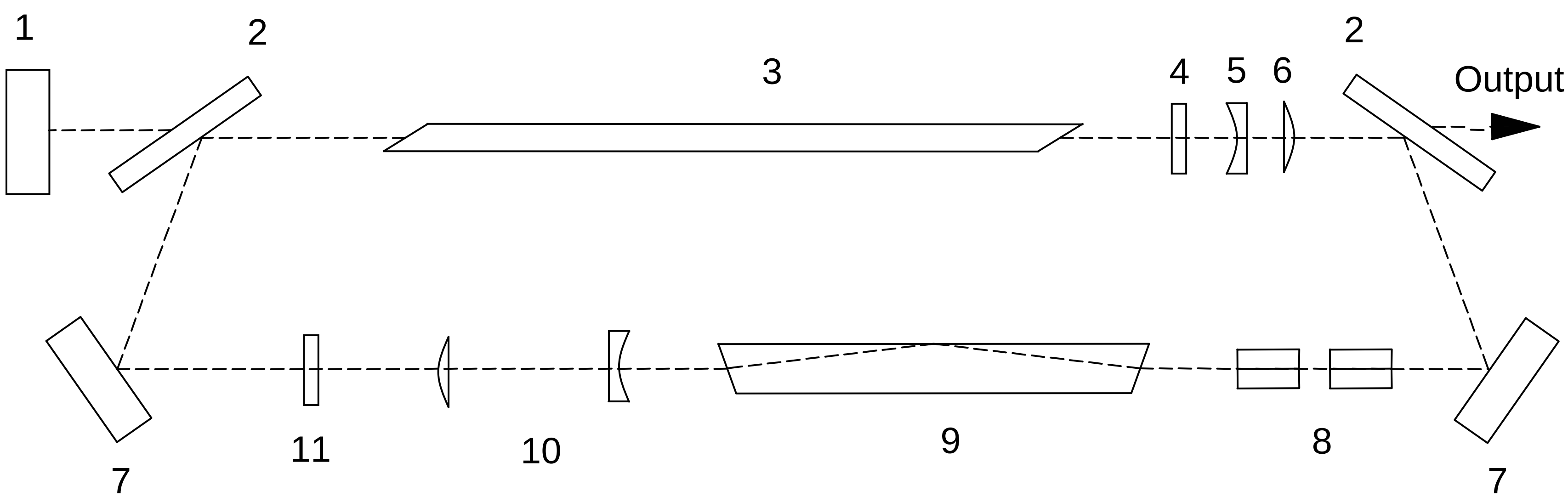
Non-Imaging Ring Resonator Layout



1) 85% R Mirror
2) Polarizer
3) Slab
4) Reflectivity Waveplate
5) Curved Waveplate
6) Compensating Lens
7) Turning Mirror
8) RTP Q-switch
9) Dove Prism
10) Telescope
11) Hold-Off Waveplate
12) Turning Mirror

Telescopic Ring Oscillator
Unstable Non-Imaging Ring Performance

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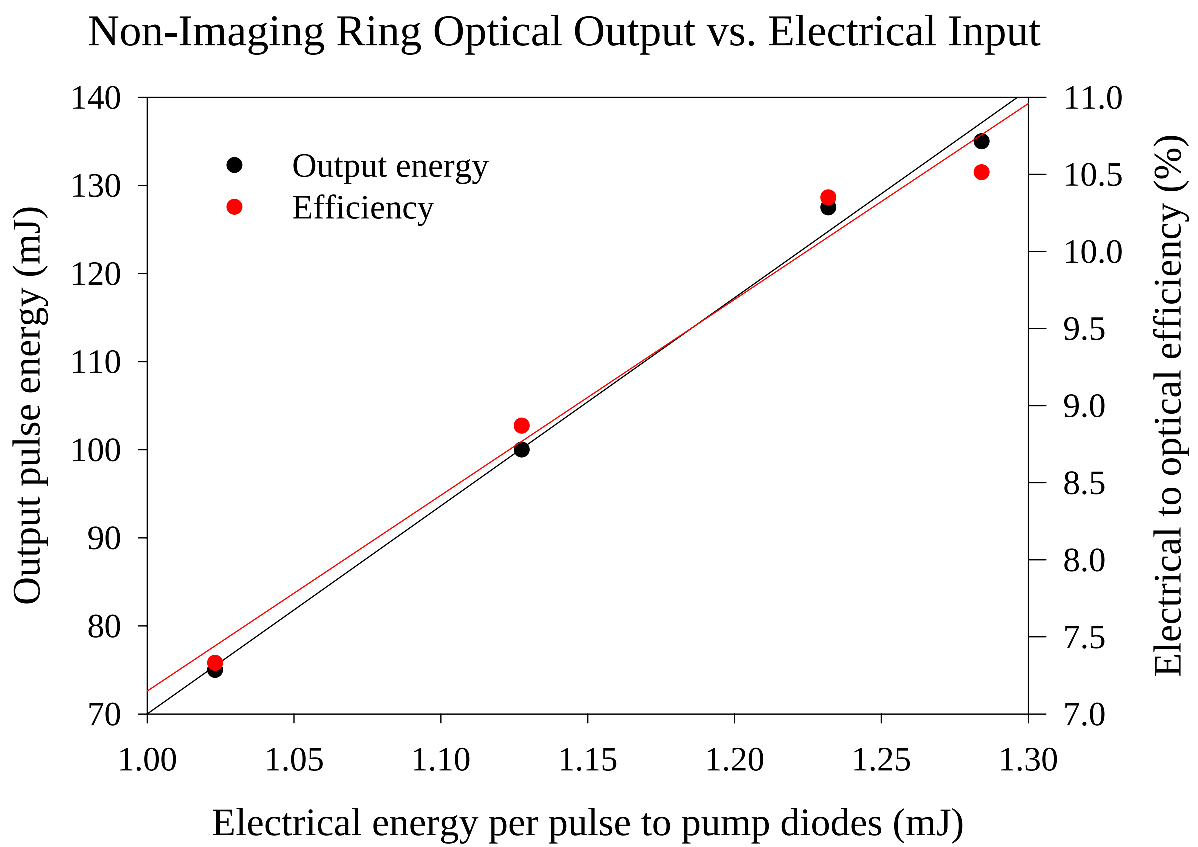
135 mJ/pulse Q-switched with 10.5 % electrical to optical efficiency at 20 Hz



Telescopic Ring Oscillator
Unstable Non-Imaging Ring Performance

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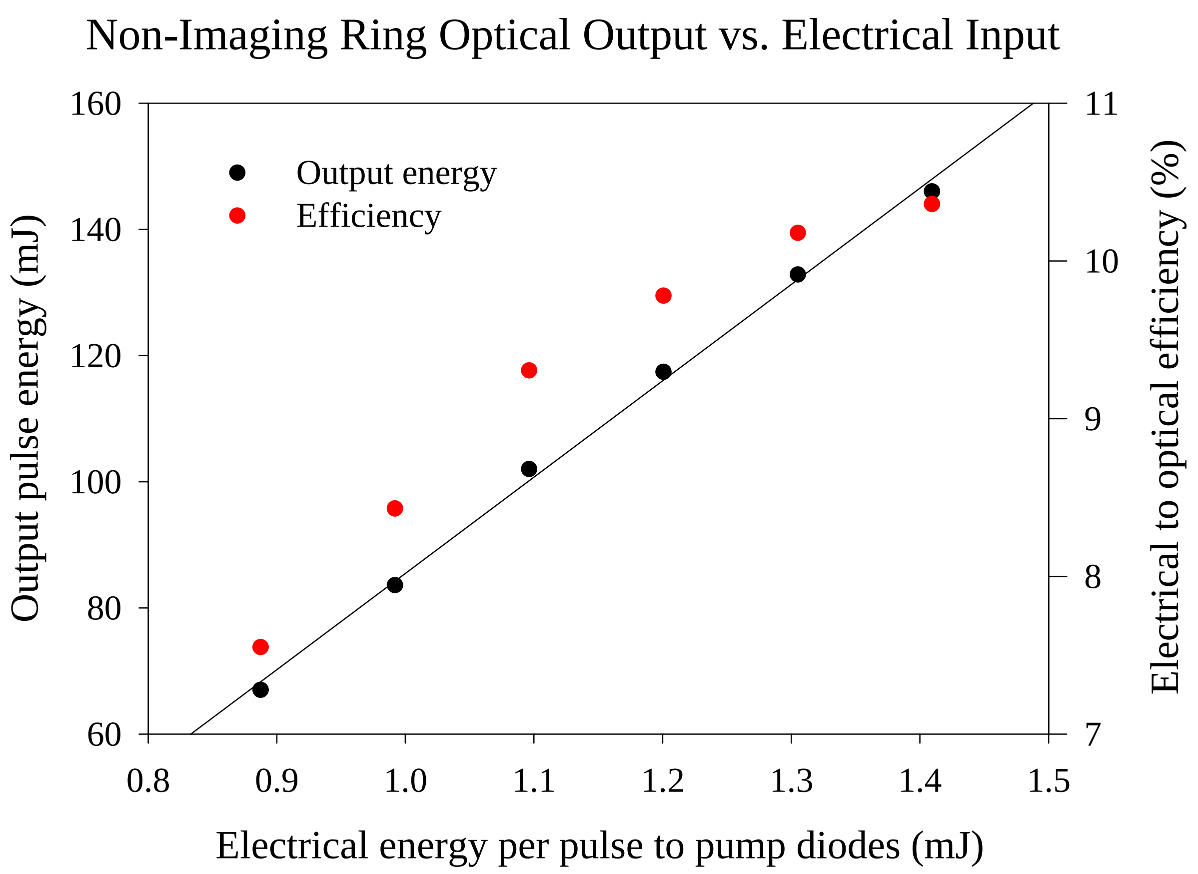
146 mJ/pulse Q-switched with 10.4% electrical to optical efficiency at 50 Hz



Telescopic Ring Oscillator
Unstable Non-Imaging Ring Performance

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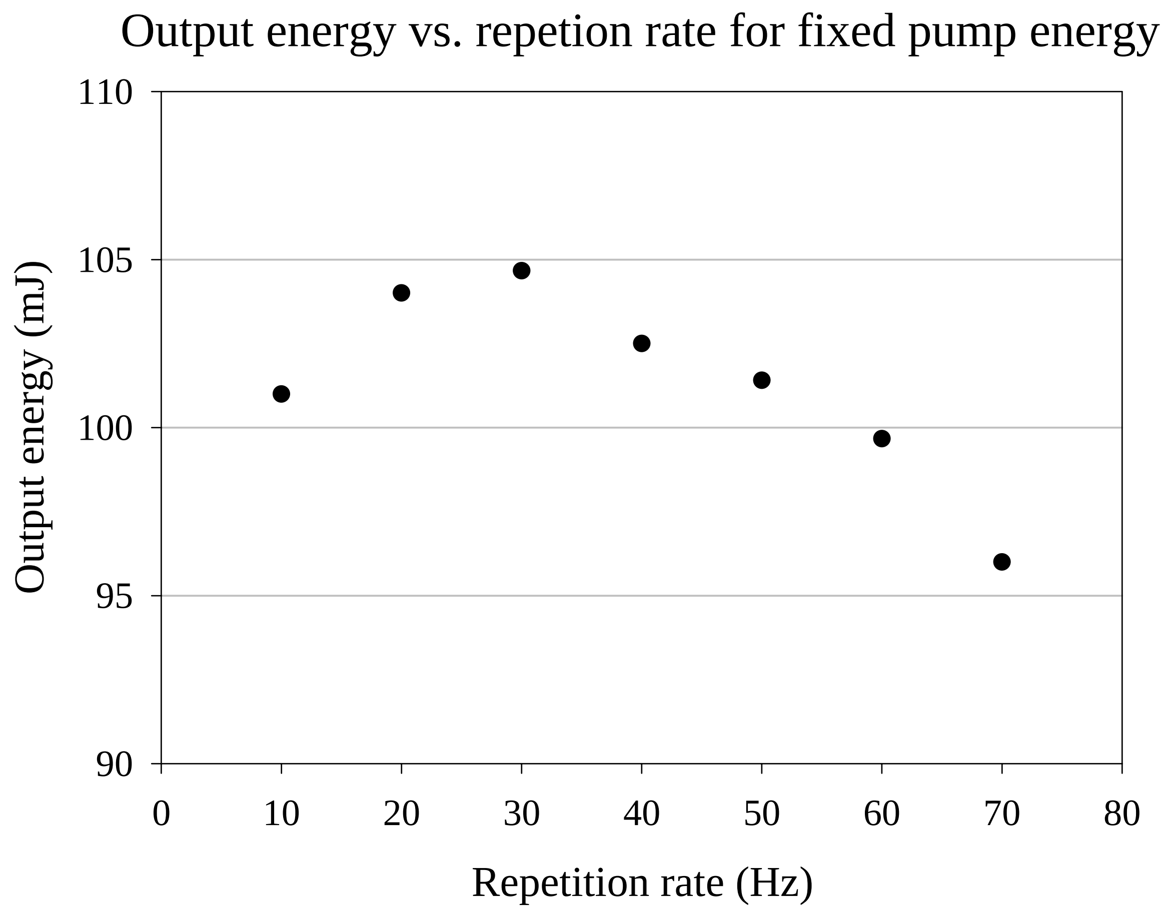
- Demonstrated 100 mJ from 10-70 Hz with ~ +/- 5% energy variation



Telescopic Ring Oscillator
Unstable Non-Imaging Ring Performance

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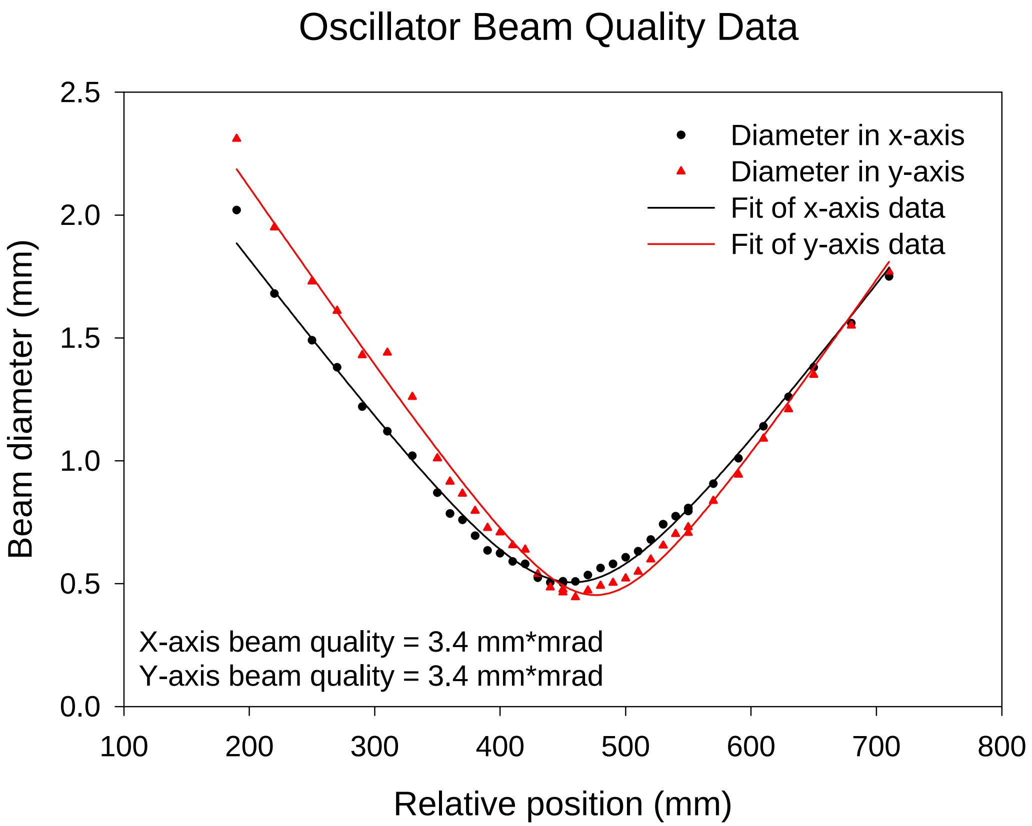
- Use of Dove prism improved output beam symmetry
  - Beam quality is 3.4 mm*mrad (2.5 times diffraction limit) in both axes



Summary of Results With Unstable Non-Imaging Telescopic Ring

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- Over 130 mJ/pulse demonstrated at 20 Hz and 50 Hz
- Over 10% electrical to optical efficiency demonstrated at 20 Hz and 50 Hz
- Pulse energy of 100 +/- 5 mJ achieved at 10 Hz to 70 Hz for a fixed pump energy
- Use of Dove prism at 45° improved beam symmetry
  - Beam quality is 2.5 x diffraction limit in both axes
- Efficient, but unlocked, seeding as ring cavity drifts in and out of resonance with the seed laser shows we would not have difficulty achieving stabilized seeding

Telescopic Ring Oscillator
TEM$_{00}$ Ring Design

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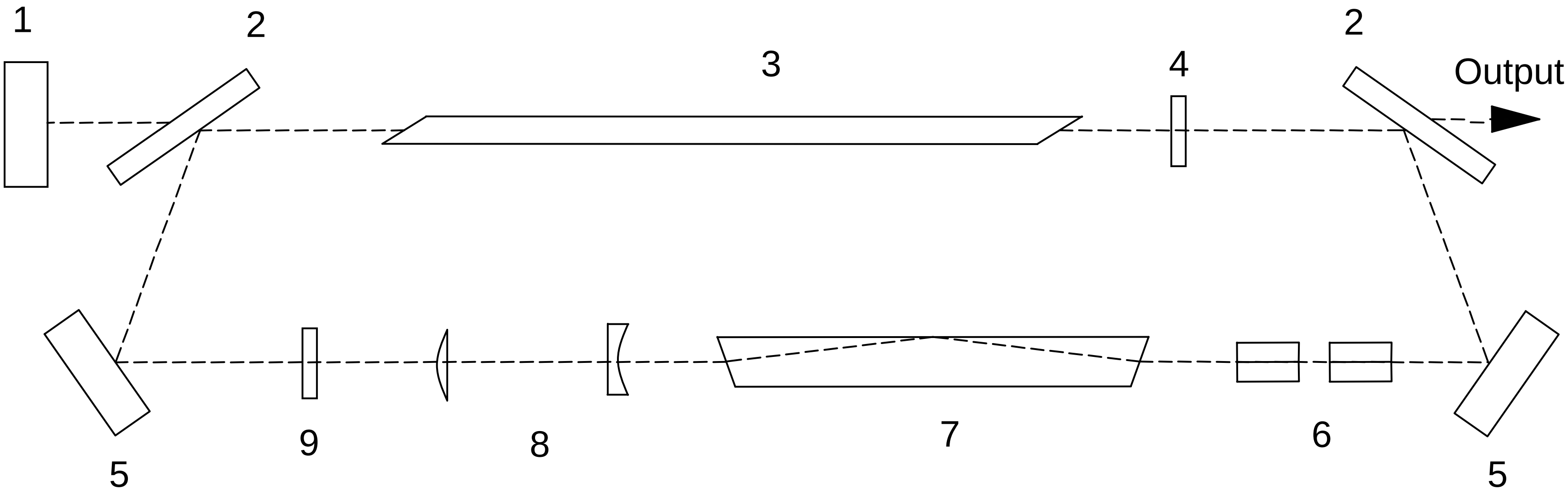
TEM$_{00}$ Ring Resonator Layout



1) 50% R Mirror
2) Polarizer
3) Slab
4) Output-Coupling Waveplate
5) Turning Mirror
6) RTP Q-switch
7) Dove Prism
8) Telescope
9) Hold-Off Waveplate

Telescopic Ring Oscillator TEM$_{00}$ Ring Results

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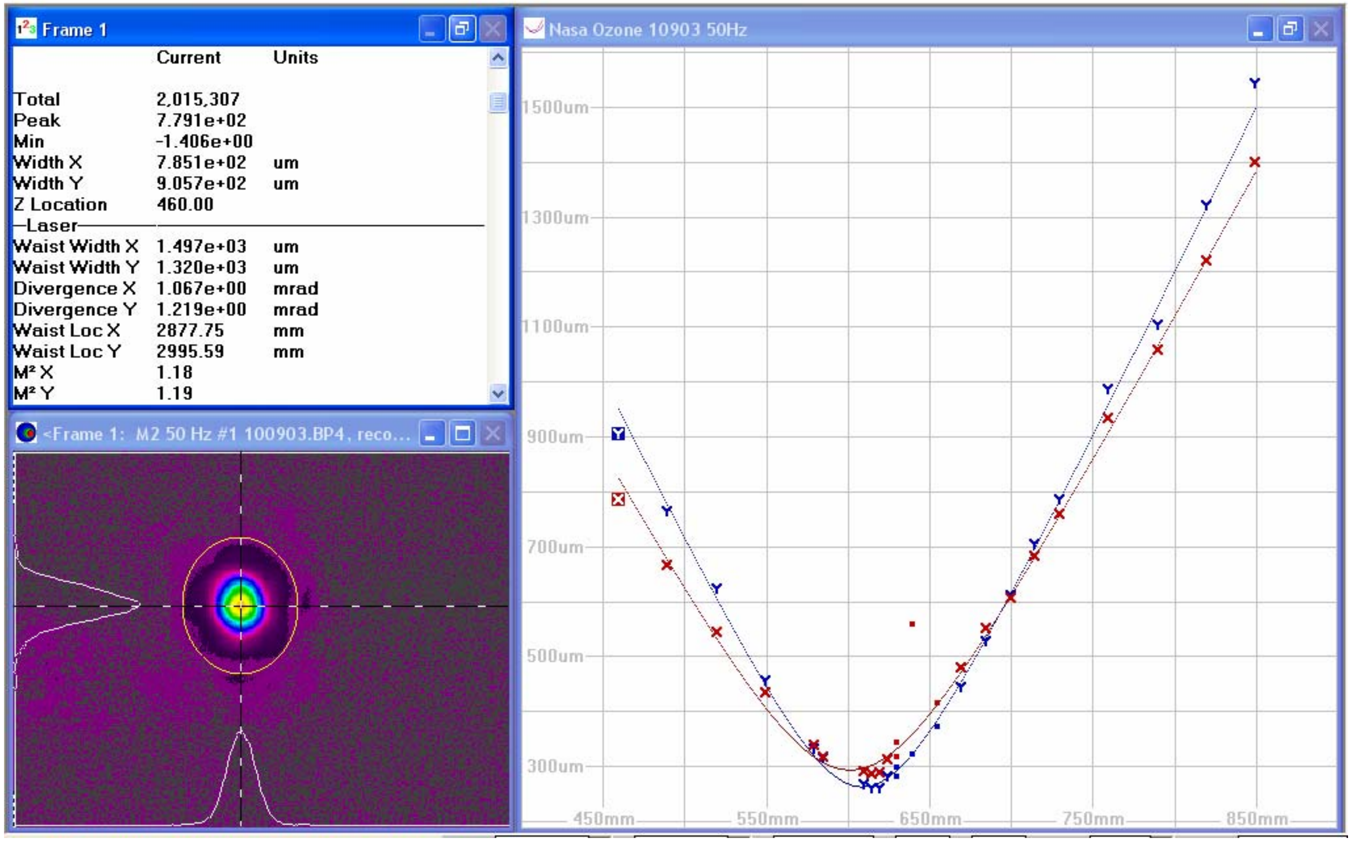
50 Hz Oscillator Beam Quality Measurements

- Ring oscillator was configured as a 30 mJ, TEM$_{00}$ oscillator
- M^2 was 1.2 in both axes



Telescopic Ring Oscillator TEM$_{00}$ Ring Results

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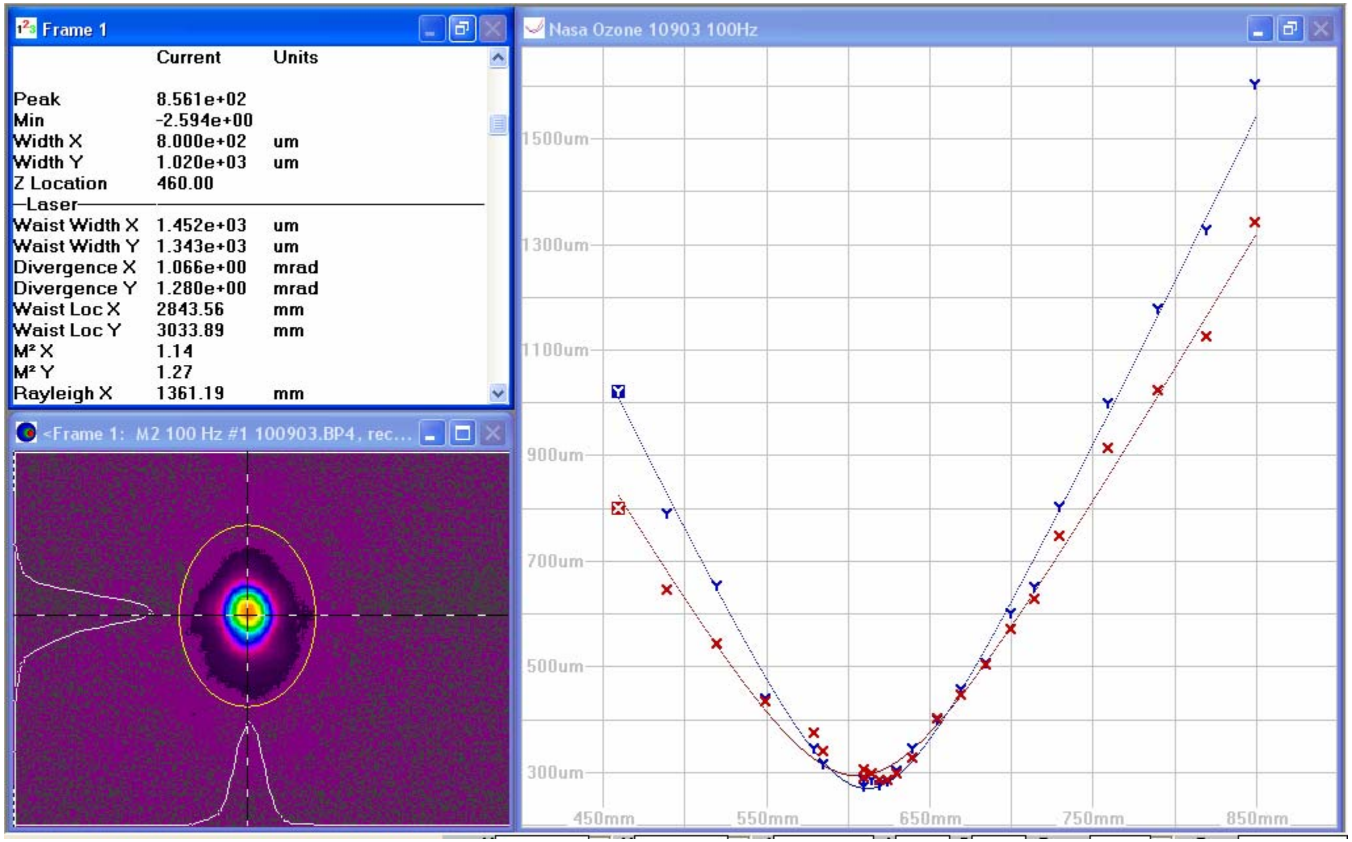
100 Hz Oscillator Beam Quality Measurements

- Ring oscillator was configured as a 30 mJ, TEM$_{00}$ oscillator
- M^2 was 1.2 in non-zigzag axis, 1.3 in zigzag axis



Telescopic Ring Oscillator TEM_{00} Ring Design

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- Summary of TEM_{00} Ring Results
  - Demonstrated 30 mJ, 50 Hz operation with M^2 of 1.2
  - Demonstrated 30 mJ, 100 Hz operation with M^2 of 1.3
  - At both 50 Hz and 100 Hz the stable oscillator beam quality is significantly higher that the M^2 of 2.5 achieved with the unstable ring
    - Improved graded reflectivity design may improve beam quality of unstable ring
    - Modeling of unstable resonators for other Fibertek programs has shown that an M^2 of 1.5 should be achievable with an unstable resonator

Phase II
Amplifier Design

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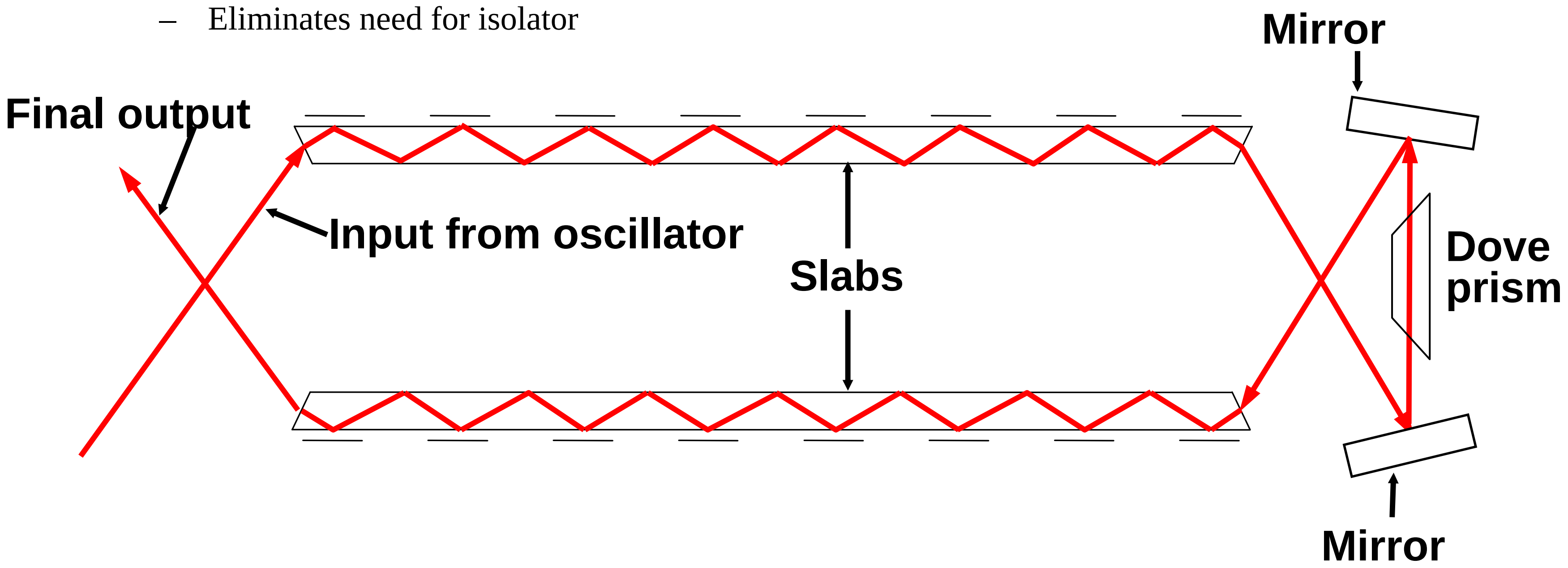
Schematic of Dual Slab Amplifiers

- The output beam from the oscillator enters the first slab near normal to the slab face and executes a 15-bounce path
- A mirror pair folds the output of the first slab through a Dove prism into the second slab for 15-bounce path through it
  - Dove prism symmetrizes gain thermal lensing
- The output of the second slab is well spatially separated from the original input beam
  - Eliminates need for isolator



Phase II
Amplifier Design

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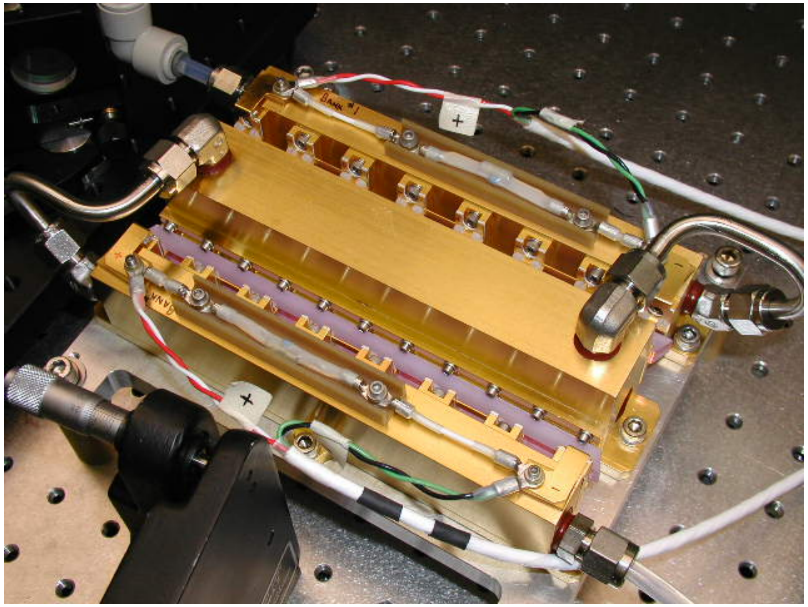
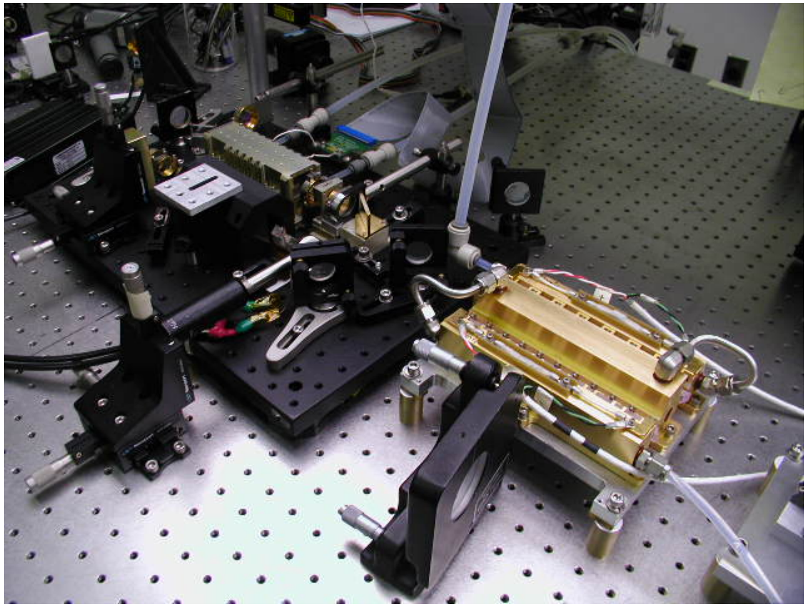


Amplifier Close Up



Oscillator/Amplifier System

Amplifier Results
Extraction With Non-Imaging Unstable Ring

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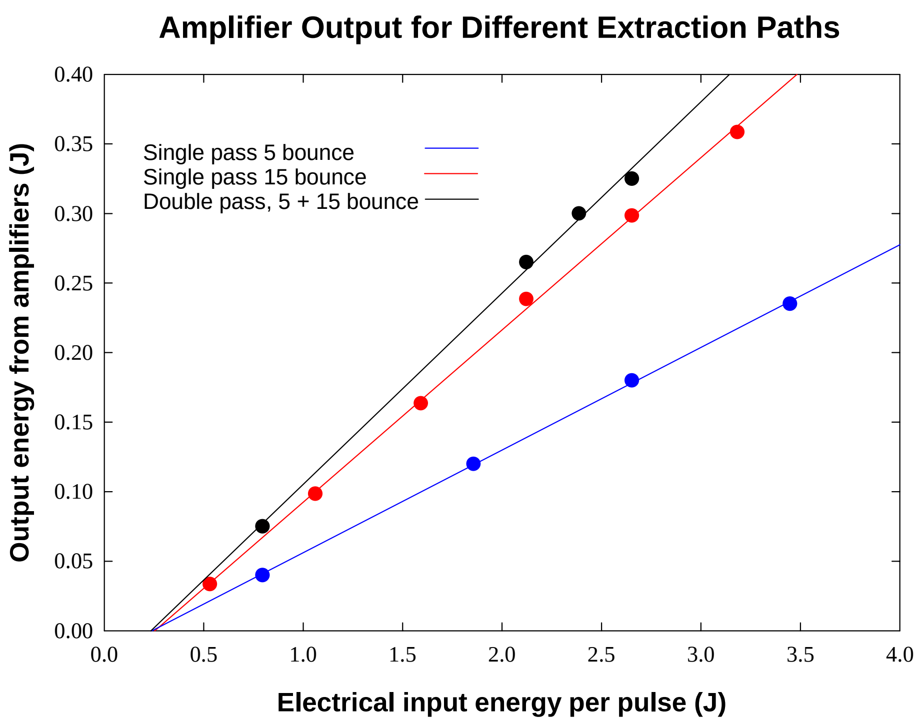
Output Energies of Alternate Extraction Geometries

- Single pass 15-bounce amplifier extraction gives >95% of the peak double pass total energy (oscillator + amps) and eliminates beam overlap damage
- **Single pass 15-bounce amplifier electrical to optical efficiency of 11.3% exceeds program goal of 10%**



Amplifier Results
Extraction With Non-Imaging Unstable Ring

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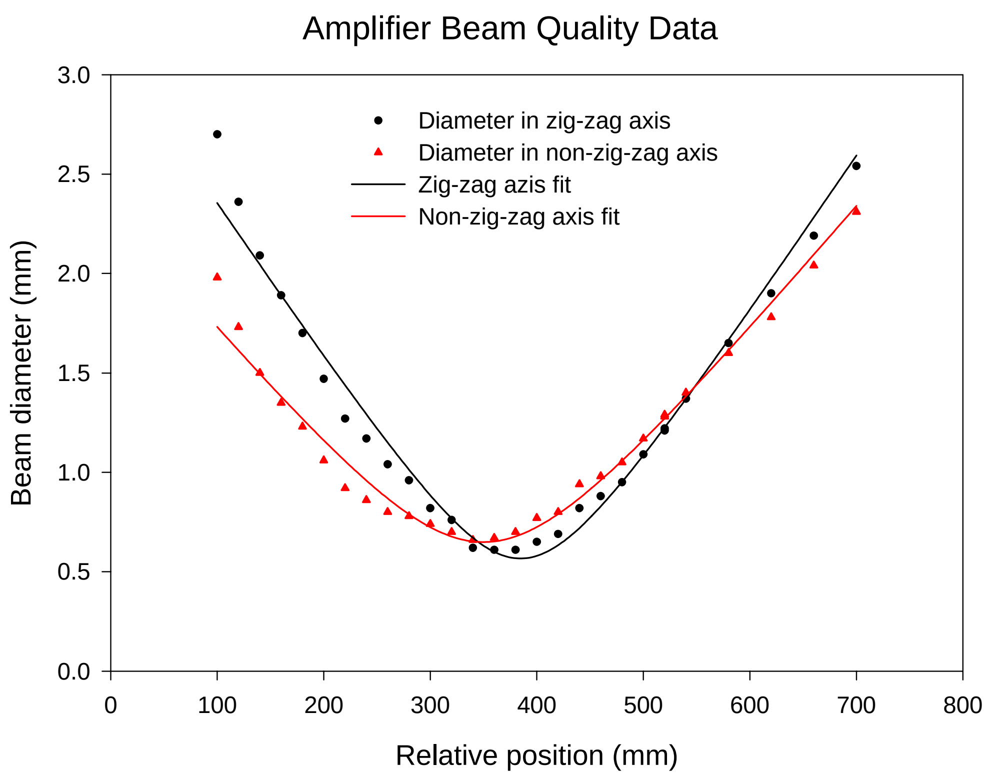
Single Pass 15-Bounce Beam Quality Data

- Beam quality in zig-zag axis is 3.4 x diffraction limit for an input beam with 2.5 x diffraction limit
- Beam quality in non-zig-zag axis is 3.1 x diffraction limit for an input beam with 2.5 x diffraction limit



Phase III - Improved Packaging & Higher Repetition Rate

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- Develop robust ring oscillator packing
  - Based on low expansion ceramic materials

- Evaluate higher repetition rate amplifier performance
  - Higher repetition rate operation is required for Doppler Wind Lidar and High Spectral Resolution Lidar systems

Phase III – Improved Ring Oscillator Packaging

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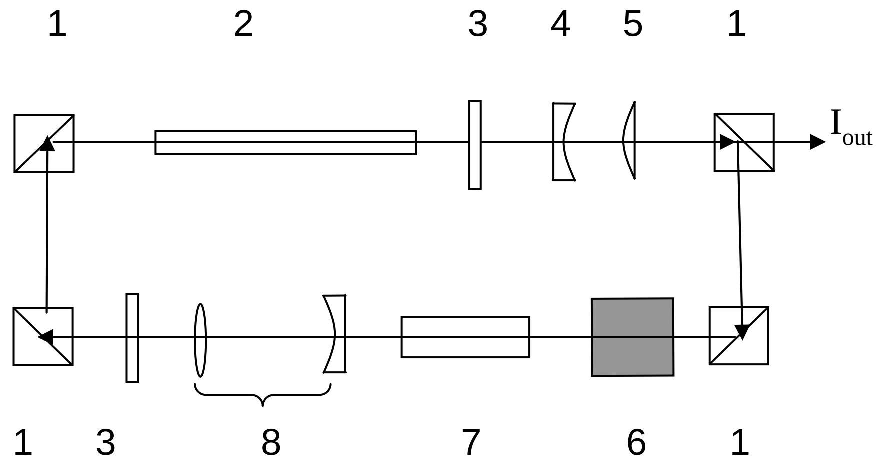
Optical Layout for Zerodur Bench Design

Schematic showing optical layout for ring



1. Cube polarizer
2. Odd bounce slab
3. λ/2 waveplate
4. Compensating lens
5. Curved waveplate
6. RTP q-switch
7. 45° Dove prism
8. Non-imaging telescope

- 90° cube polarizers replace thin film polarizers and HR mirrors to reduce cost and package size
  - Cube polarizers are spin-off of telecom industry
- Intracavity focal point of the negative branch unstable ring which limits scaling to higher powers is eliminated

Phase III – Improved Ring Oscillator Packaging

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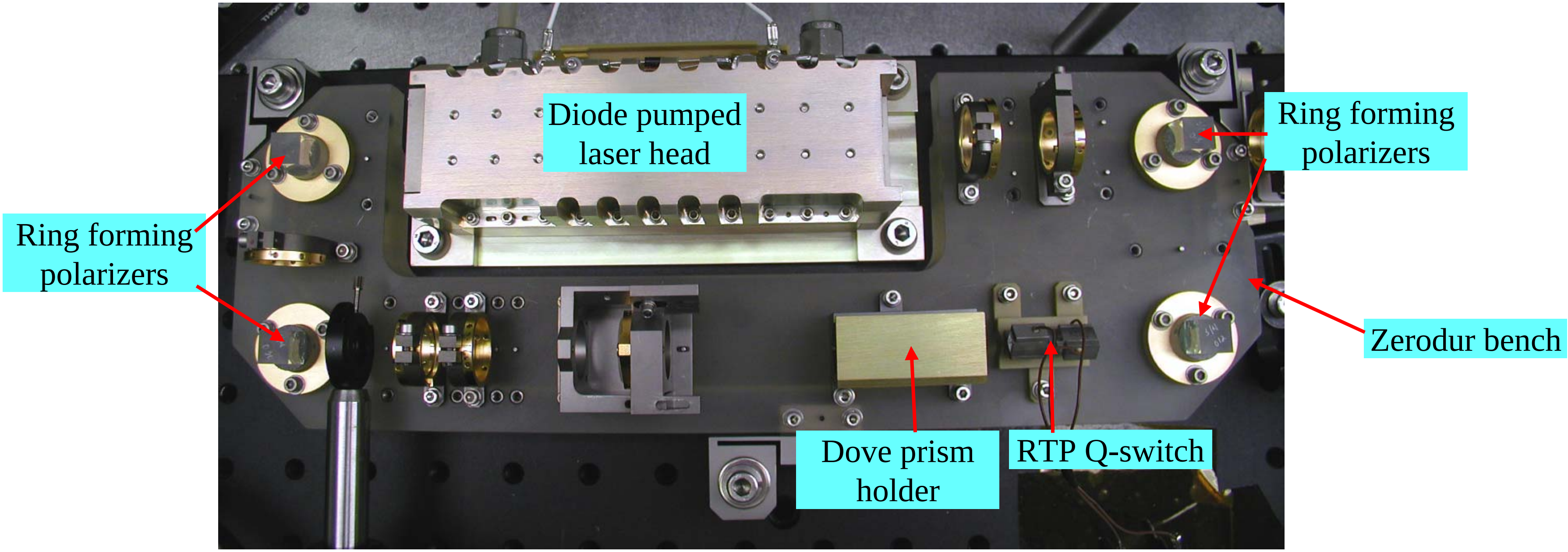
- Zerodur optical bench for the ring oscillator was been built and tested
  - 30 mJ/pulse at 50 Hz demonstrated with M^2 of 1.2
  - High beam quality oscillator will allow us to achieve goal of $M^2 < 2$ out of amplifiers



Phase III
Oscillator/Amplifier Integration

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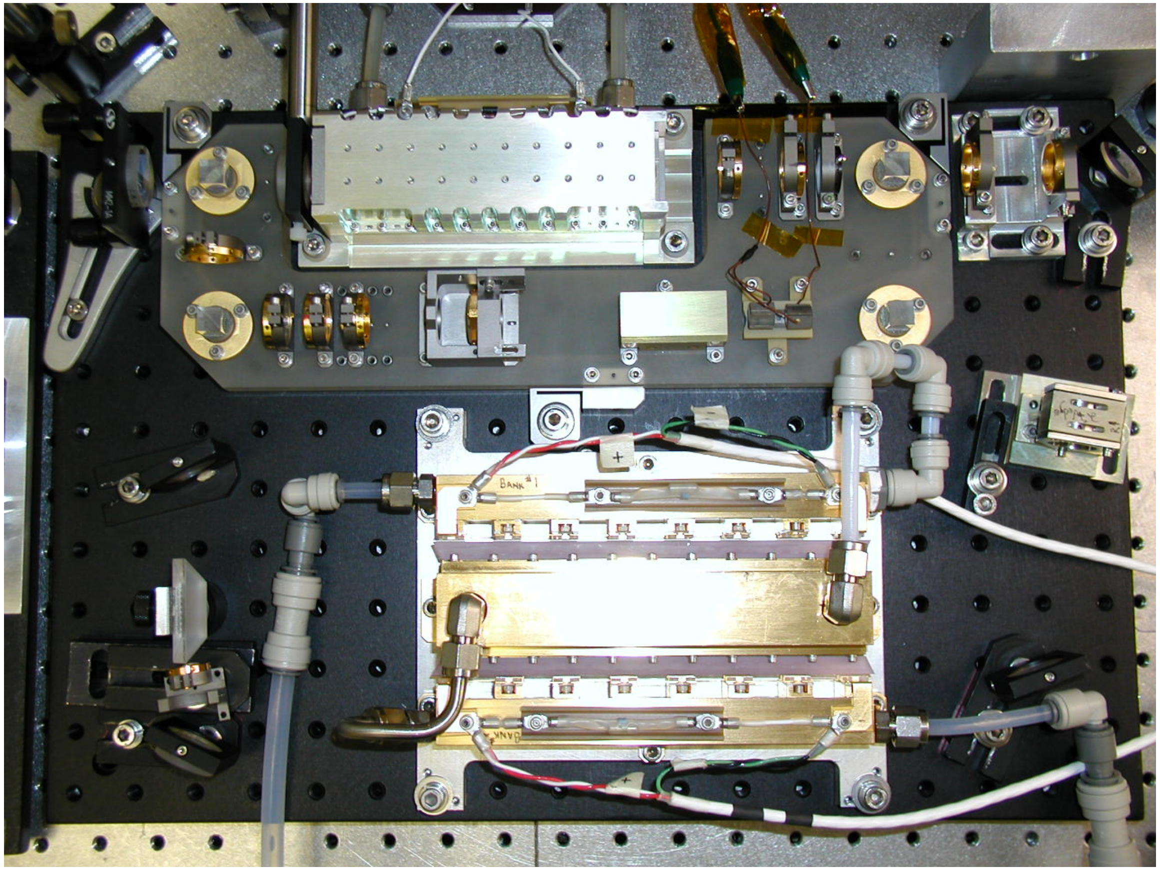
- The ring oscillator and dual stage amplifier have been successfully integrated onto a semi-hardened brass board configuration
  - All turning mirrors are lockable, no gimbal mounts
  - Position insensitive wedge prisms are used for fine steering



Phase III - Higher Repetition Rate Amplifier Characterization

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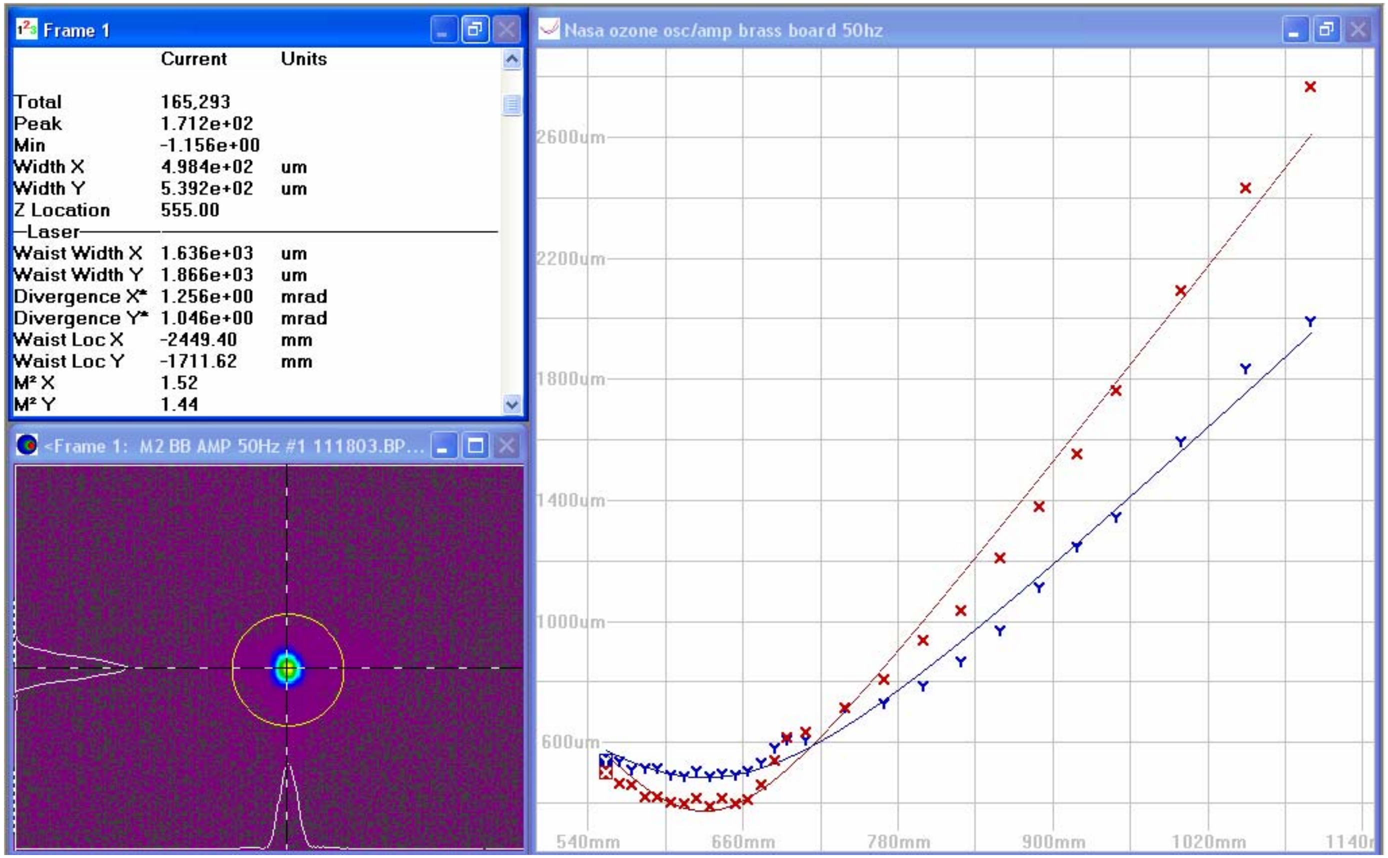
50 Hz Amplifier Beam Quality Measurements

- Input was 30 mJ, near diffraction limited
- Output was 300 mJ, $M^2 = 1.5$



Phase III - Higher Repetition Rate Amplifier Characterization

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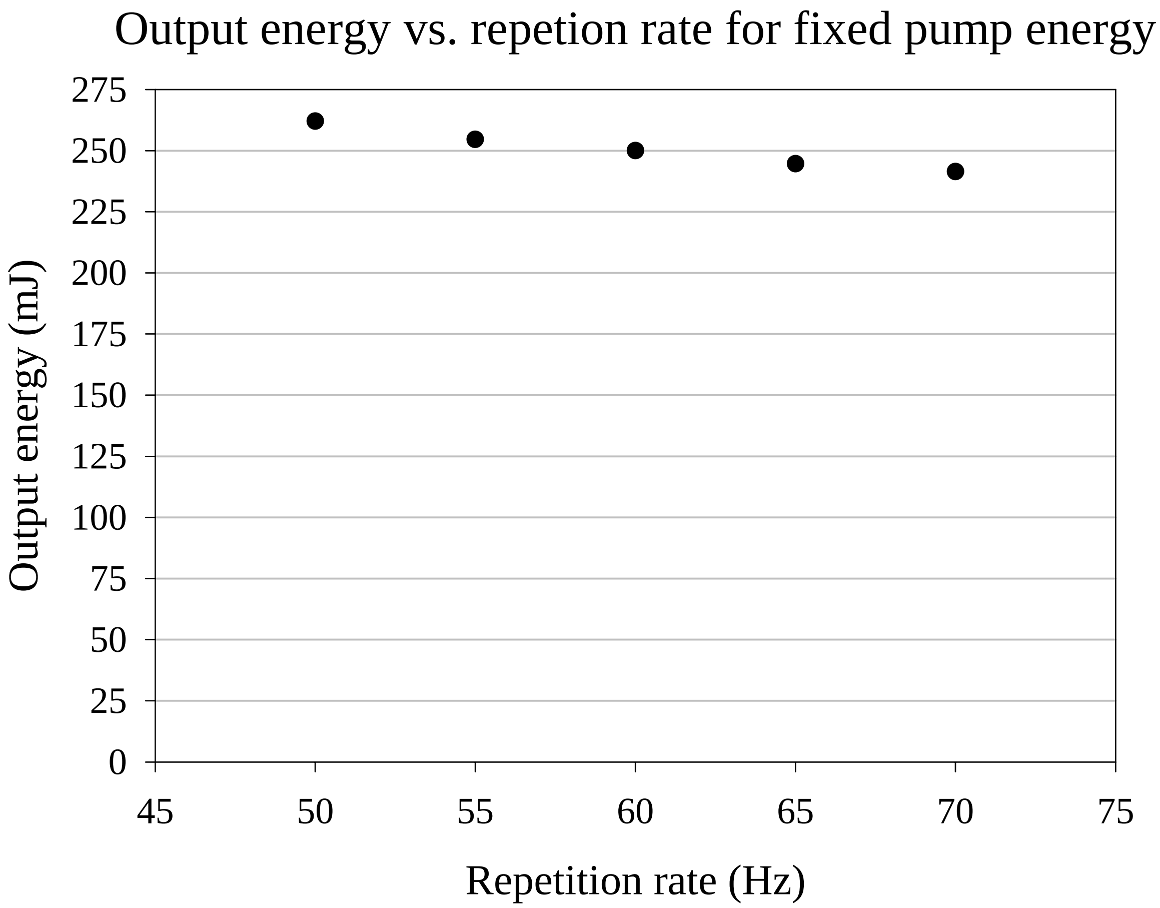
- Demonstrated 250 mJ from 50-70 Hz with ~ +/- 4% energy variation



Phase III - Higher Repetition Rate Amplifier Characterization

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– **Summary**
  - Demonstrated 300 mJ, 50 Hz operation with M^2 of 1.5
  - Operated at 250 mJ/pulse from 50 Hz to 70 Hz at +/-4% pulse energy stability

Summary of Technical Accomplishments
Ring Oscillator

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- High efficiency unstable ring laser design developed and demonstrated
  - Over 130 mJ/pulse at 20 Hz and 50 Hz
  - 10% electrical to optical efficiency at 20 and 50 Hz
  - 100 +/- 5 mJ achieved at 10 Hz to 70 Hz
  - M^2 of 2.5

- High beam quality stable ring laser demonstrated
  - 30 mJ/pulse at 50 Hz with M^2 of 1.2
  - 30 mJ/pulse at 100 Hz with M^2 of 1.3

- Designed and fabricated optical bench made from low expansion ceramic
  - All mounts are hardened designs
  - Ring oscillator using this bench is ready for transition to field use

Summary of Technical Accomplishments Oscillator/Amplifier

- Oscillator/Amplifier results with unstable ring configuration
  - Output pulse energy of 500 mJ at 20 Hz, goal was 500 mJ
  - Amplifier electrical-to-optical efficiency of 11.3%, goal was 10%
  - Beam quality of 3.4 x diffraction limit in zig-zag axis and 3.1 in non-zig-zag axis, goal was 2

- Oscillator/Amplifier results with stable ring configuration
  - This development was beyond the scope of the original contract
  - Output energy of 300 mJ/pulse at 50 Hz with an M^2 of 1.5