Progress in the Development of Solid-State Disk Laser*

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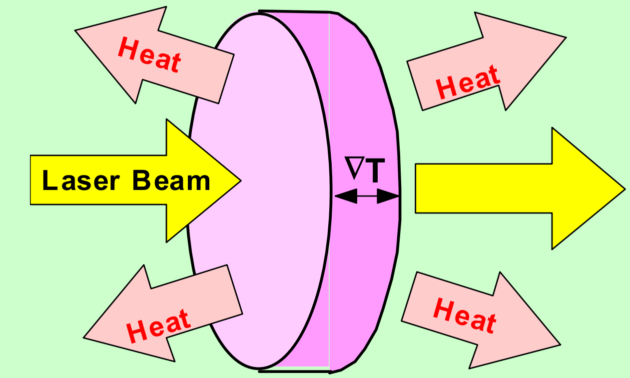
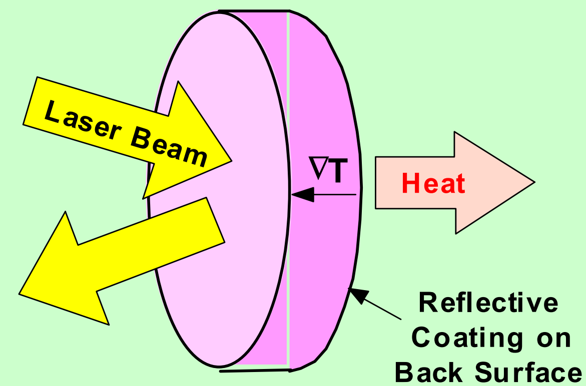
Introduction

- **Disk lasers have low susceptibility to ther. aberrations**
  - ∇T || **k**
  - Large round aperture ⇒ good mode fill
  - Large surfaces available for cooling
  - Configurations:
    - > Pass-through disk and active mirror



Pass-through configuration

- **Compact Active Mirror Laser (CAMIL): Disk laser for ultra-high-average power**
  - Active mirror configuration
  - Large-size composite disk
  - Edge-pumping by close-coupled diodes
  - Microchannel heat exchanger
  - Shows excellent scalability



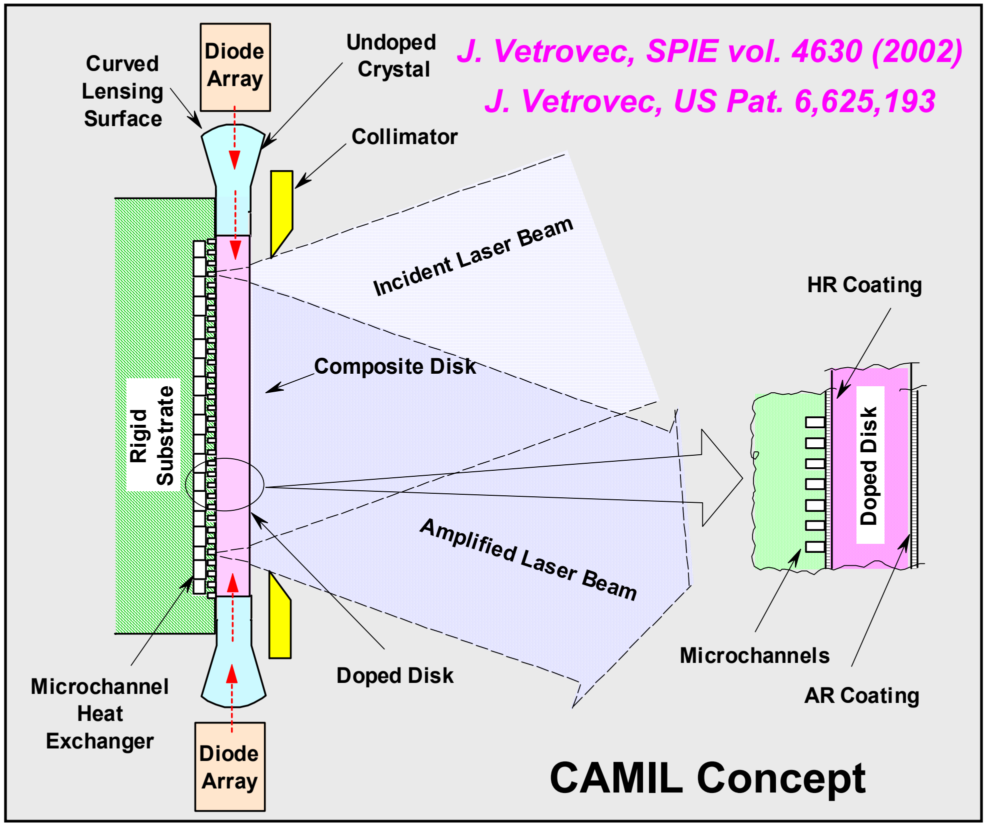
Active mirror configuration

- **Development testing**
  - Uniform pump density
  - Ultra-low optical distortions at operational heat load

Compact Active Mirror Laser (CAMIL)

- **Diode-pumped disk laser in "active mirror" configuration**
  - Composite disk: Nd^{3+} or Yb^{3+} ion doped into YAG, GGG, or glass
  - Eliminates thermal focusing
  - Edge-pumping for uniform gain
- **Continuous & uniform cooling by microstructure heat exchanger**
- **Optical figure maintained by attachment to a rigid "strong back"**

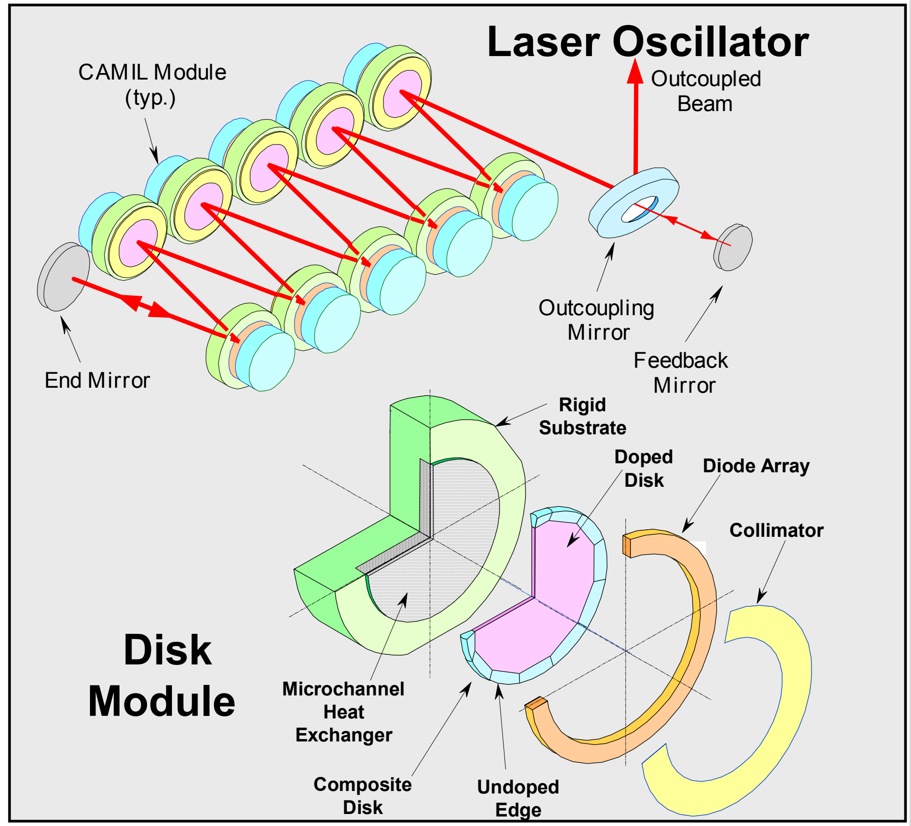
Premise for good BQ



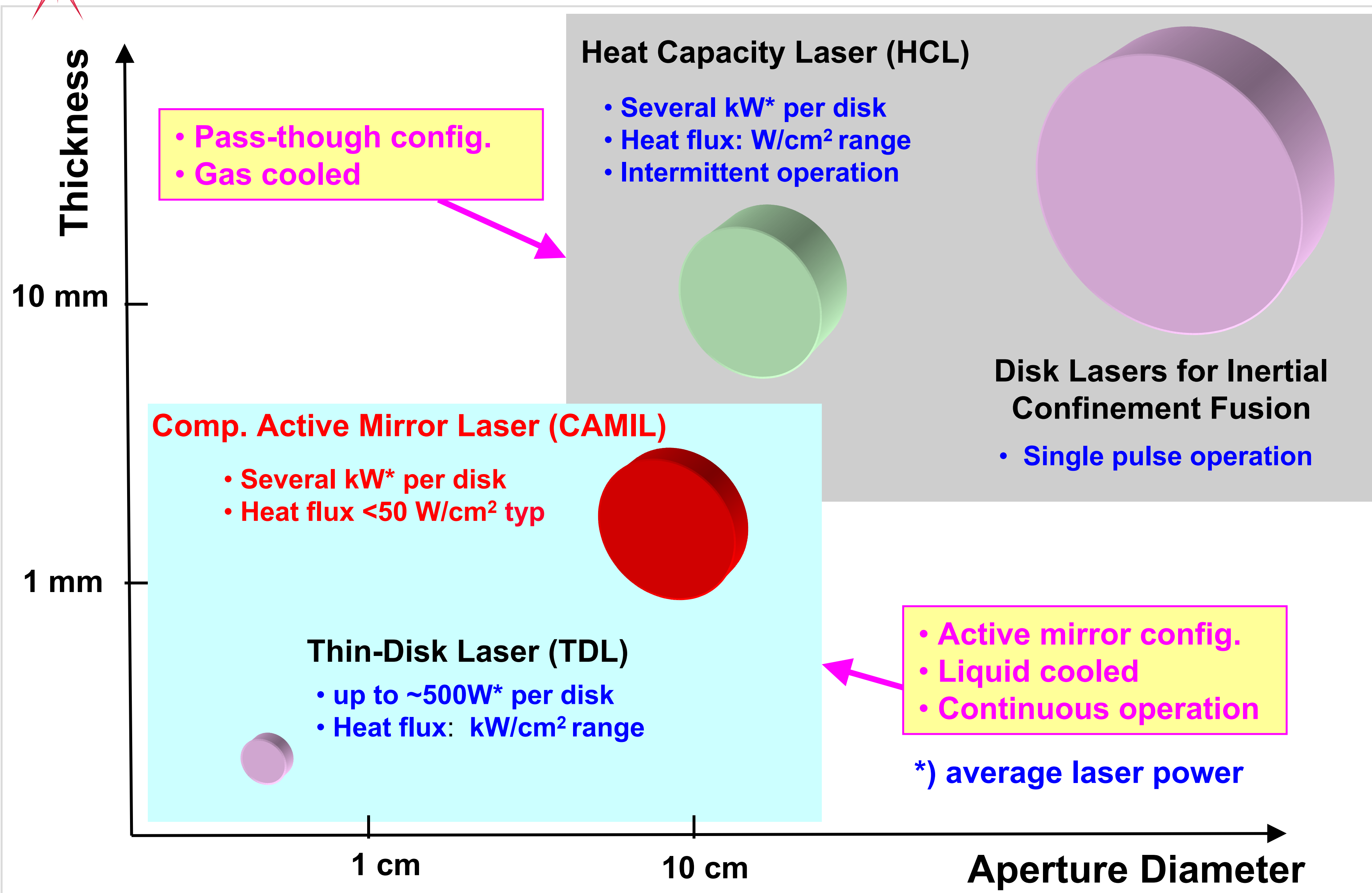
J. Vetrovec, SPIE vol. 4630 (2002)

J. Vetrovec, US Pat. 6,625,193

CAMIL Concept

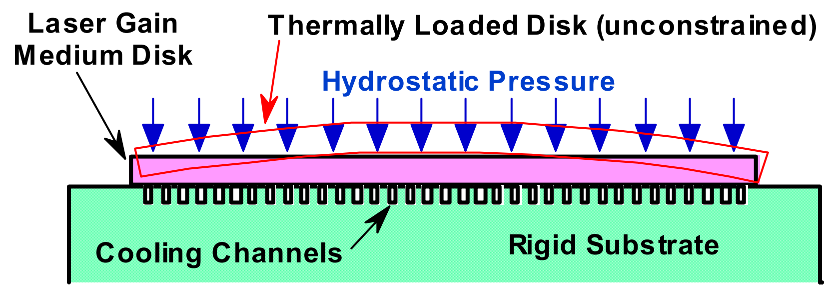


Comparisons of Selected Disk Laser Concepts



"Pressure Clamping" of the Disk to Substrate Mitigates Thermally-Driven Distortions

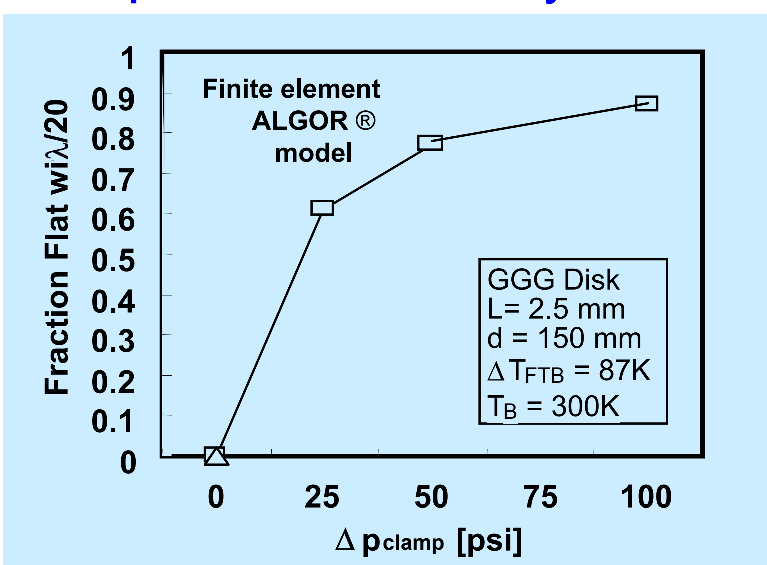
- Optical flatness can be achieved with only modest pressures
- Stresses can be reduced with pre-forming



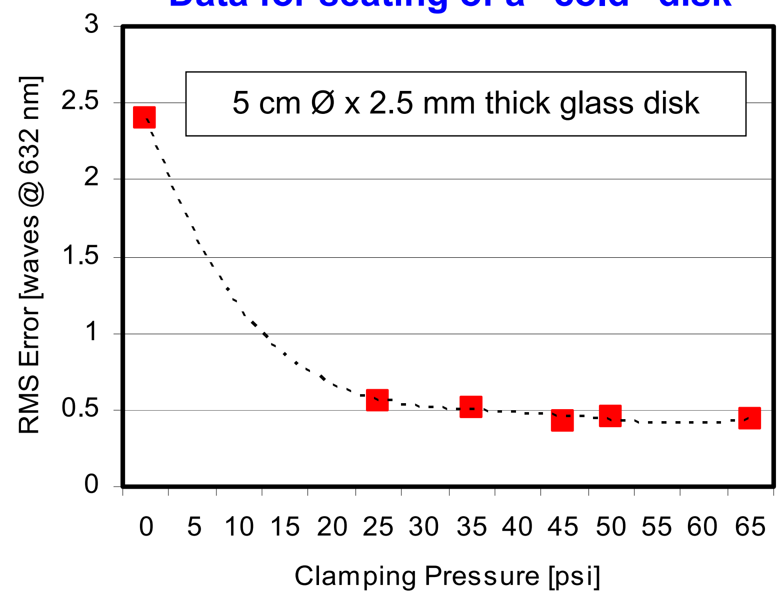
J. Vetrovec, US Pat. 6,339,605

J. Vetrovec, SPIE vol. 4270 (2001)

Model predictions for thermally loaded disk

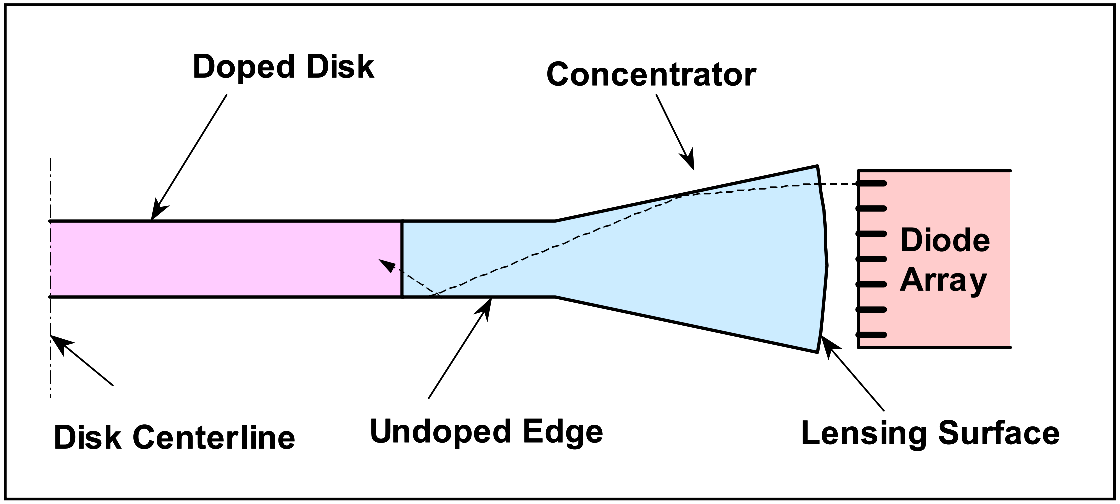


Data for seating of a "cold" disk



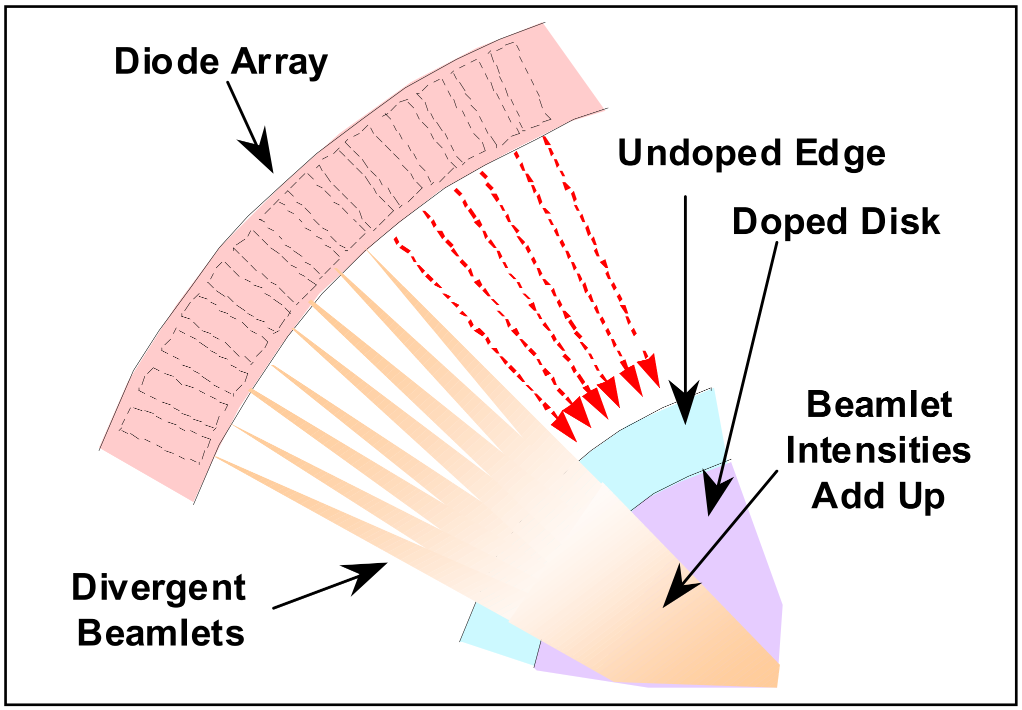
Edge-Pumping Permits Efficient Operation

- **Edge-pumping permits close-coupling diodes to the disk ($\eta_{transport} \rightarrow$ 95%)**
- **Pump light experiences TIR and is wave-guided between disk surfaces**
- **Long absorption path (~ disk Ø) ⇒ can design for ~ 95% absorption**
  - Permits reduced doping & allows using dopants with low absorption cross-section
- **Composite construction (doped + undoped media)**
  - Tapered profile & curved inlet surface can be used to concentrate pump power
  - Undoped edge traps ASE rays and reduces feedback to parasitics
    - > Conducts heat away from the gain section
    - > Avoids transverse ∇T and associated phase-front distortion near disk edge
- **Nearly 100% of pumped volume is available for power extraction**

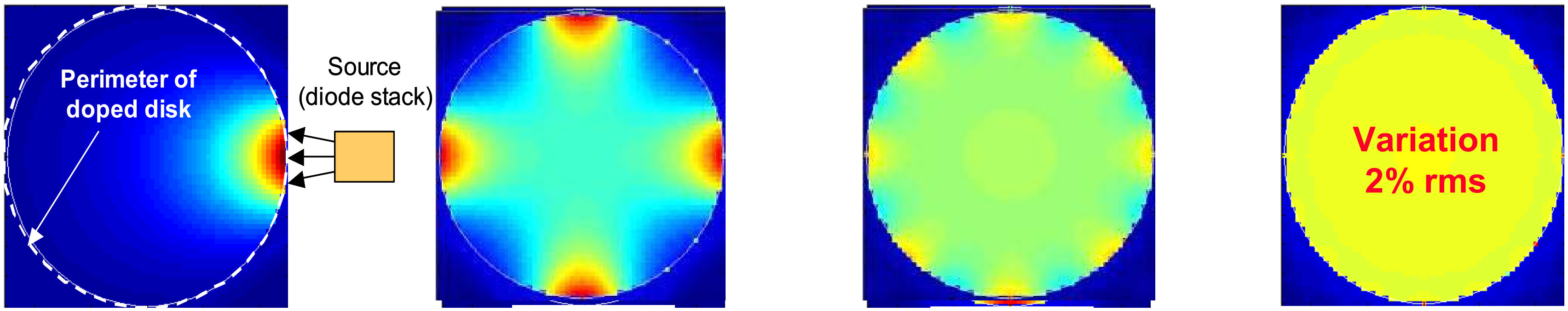


Diode Placement & Divergence Are Exploited for Uniform Pumping

- Natural divergence of diodes leads to gradual reduction of beamlet intensity with distance
- Circular geometry causes the diode beamlets to overlap inside the disk and and their intensities to add up
- Beamlet superposition can be balanced by absorption to produce uniform pumping
- Both diode placement (orientation orientation and pointing) and divergence must be taken into consideration

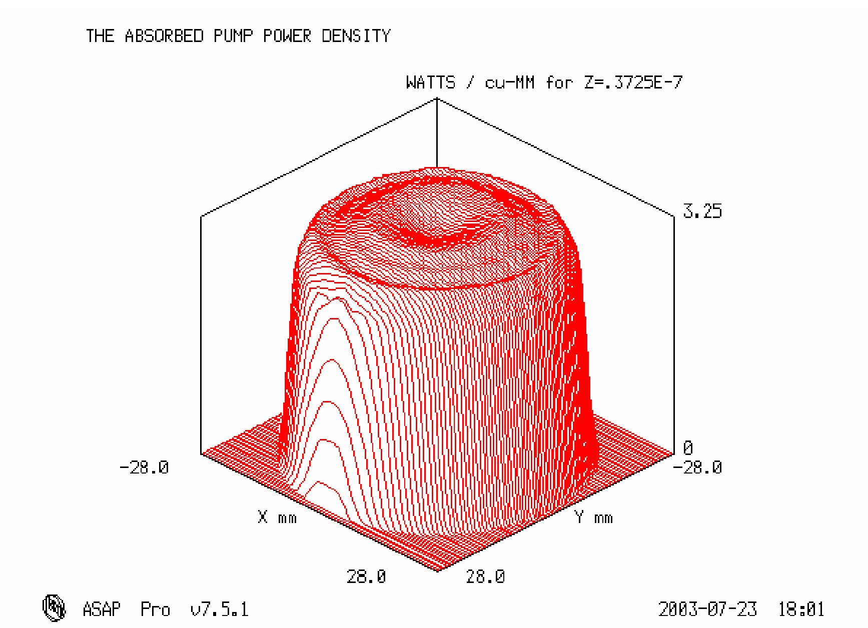


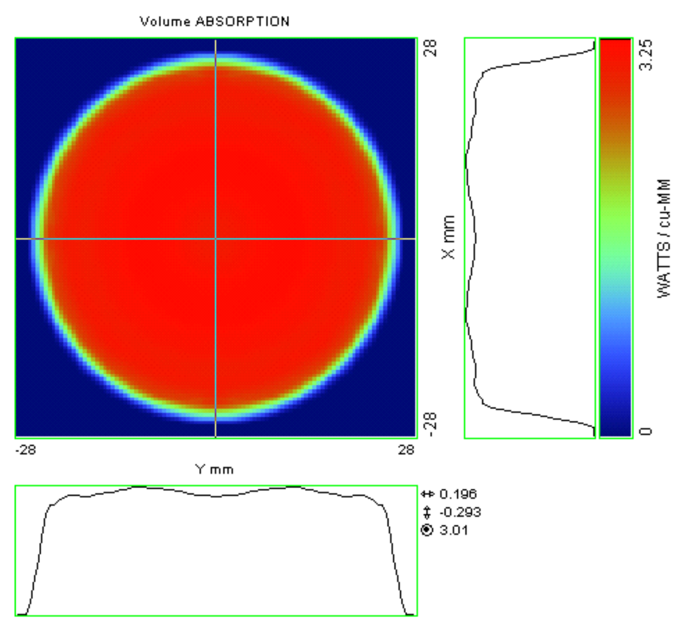
Examples of Uniform Pump Density in a Disk with a Hexadecagonal Diode Array



1 Source | 4 sources | 8 sources | 16 Sources

J. Vetrovec et al., SPIE 4968-06

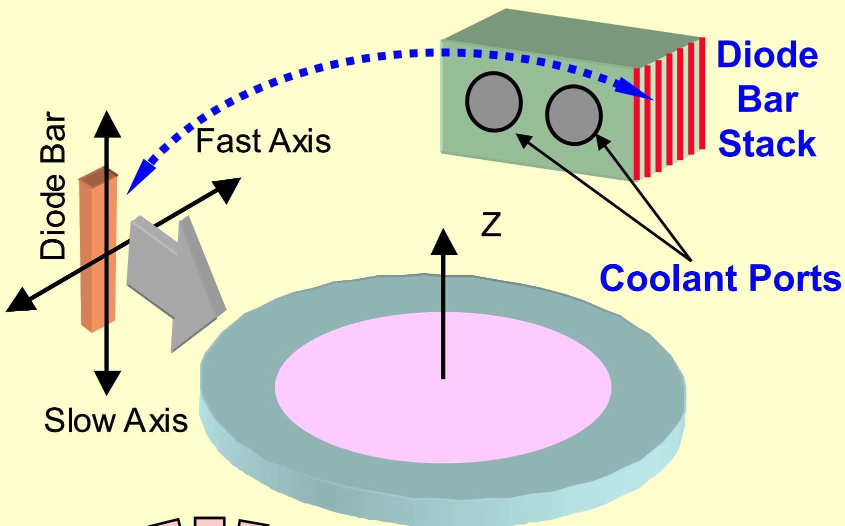


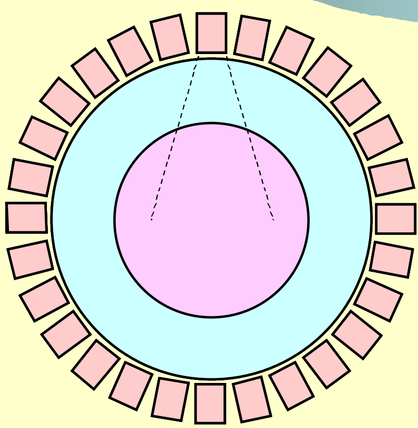


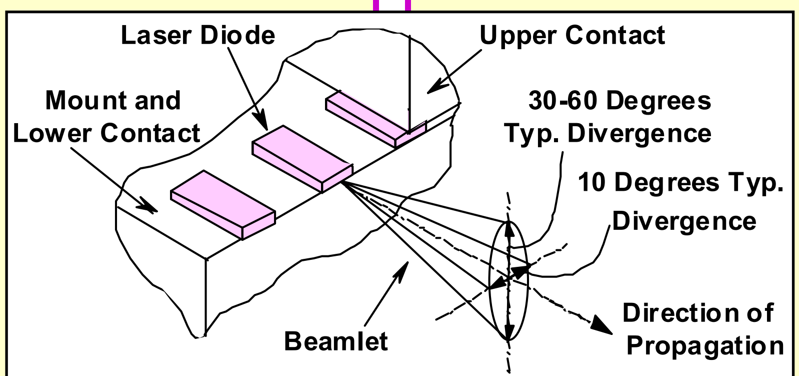
M. Bass et al., UCF-CREOL, communications

Two Diode Bar Orientations

Fast Axis || to Disk Surface

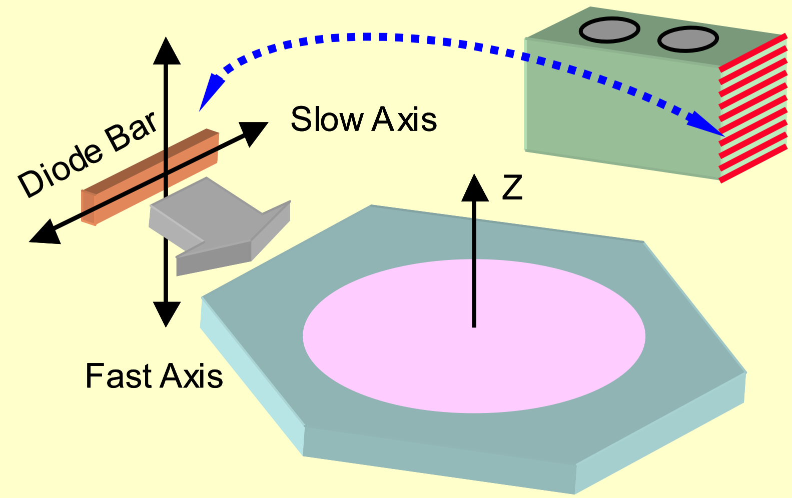


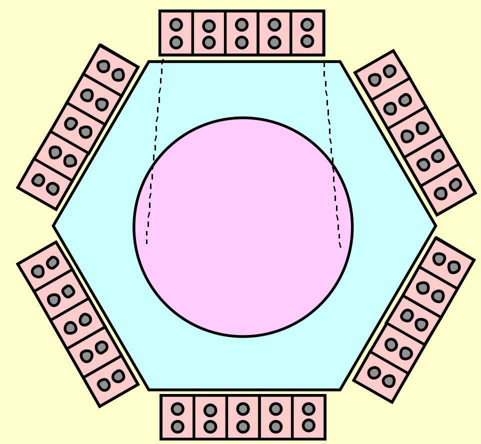




- **Fast axis divergence fortuitously meets a criterion for uniform gain**
- **…but…electrical & coolant connections are a challenge**

Fast Axis ⊥ to Disk Surface





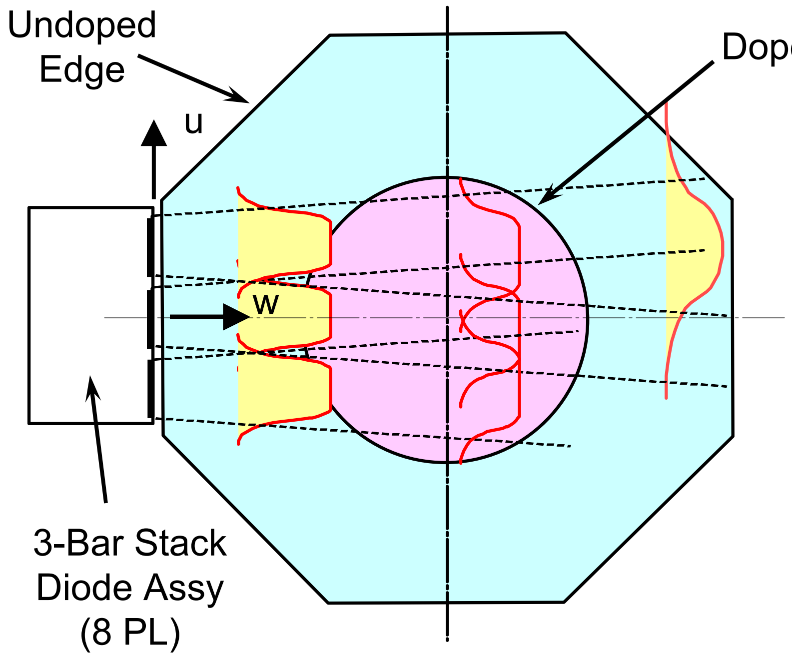
- **Easy electrical & coolant connections**
- **…but…diode placement must be carefully planned**

J. Vetrovec et al., proc. SSDLTR 2003

Pump Architecture

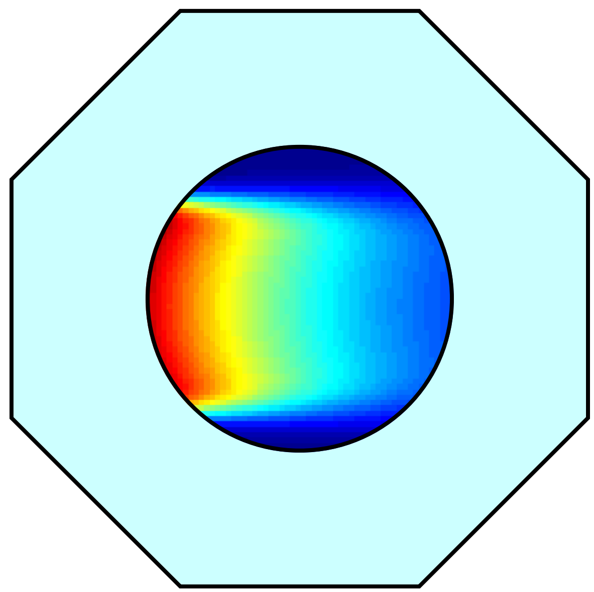
Segment Architecture

Individual beams diverge and overlap to generate a uniform intensity field

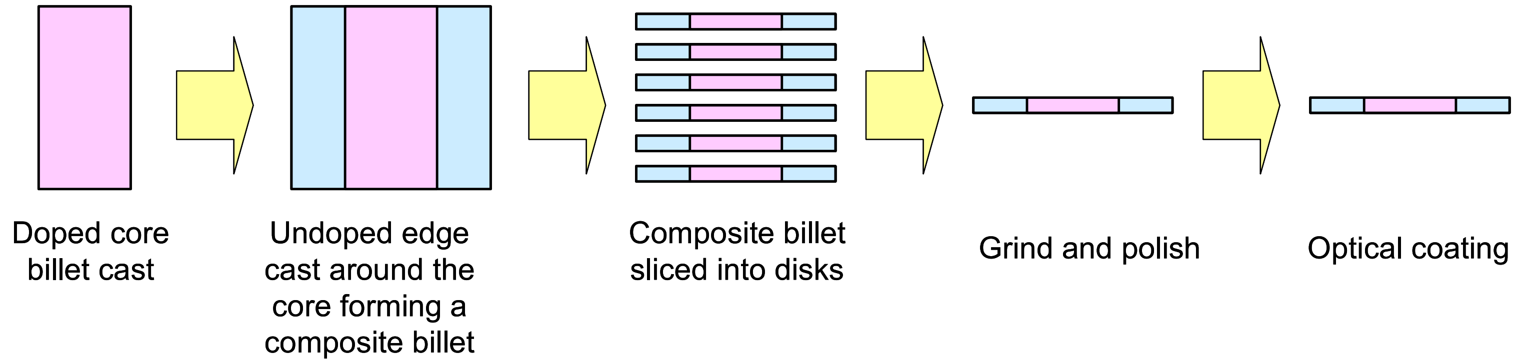


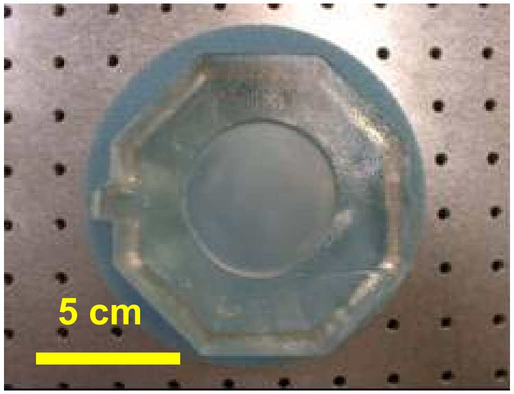
Computer Simulations of Absorbed Power

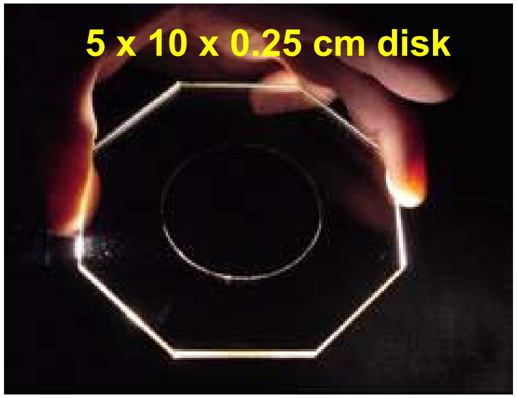
Absorption length = 3 cm
Diode divergence ($\theta_{1/e}$) = 4 deg



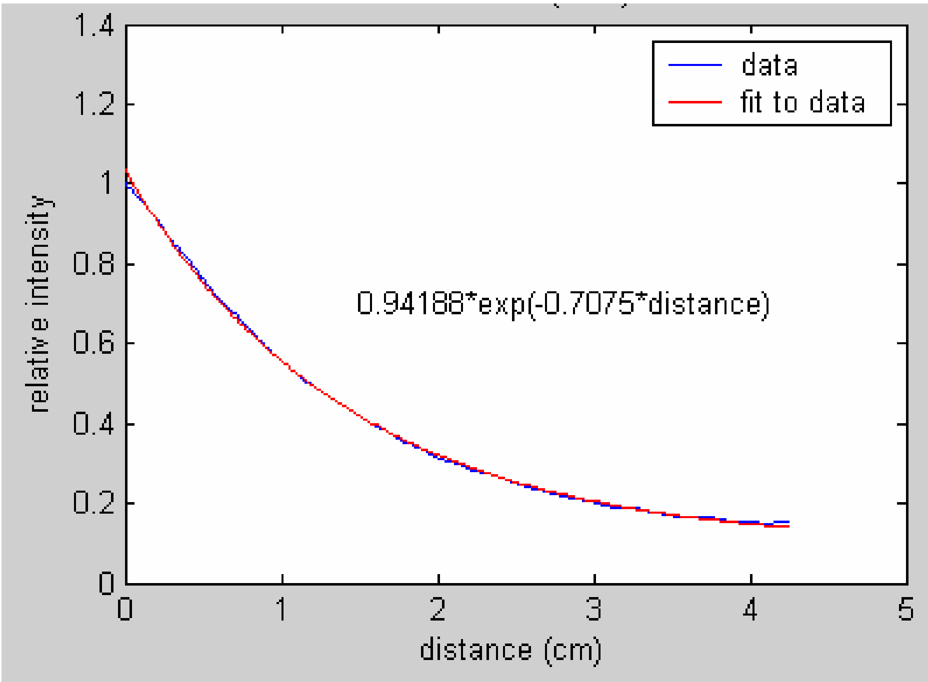
Octagonal Yb:Glass Disk





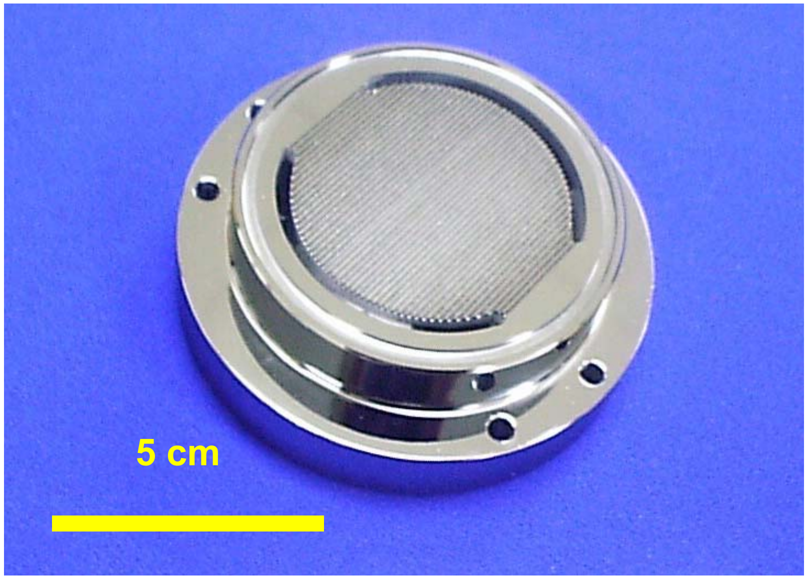


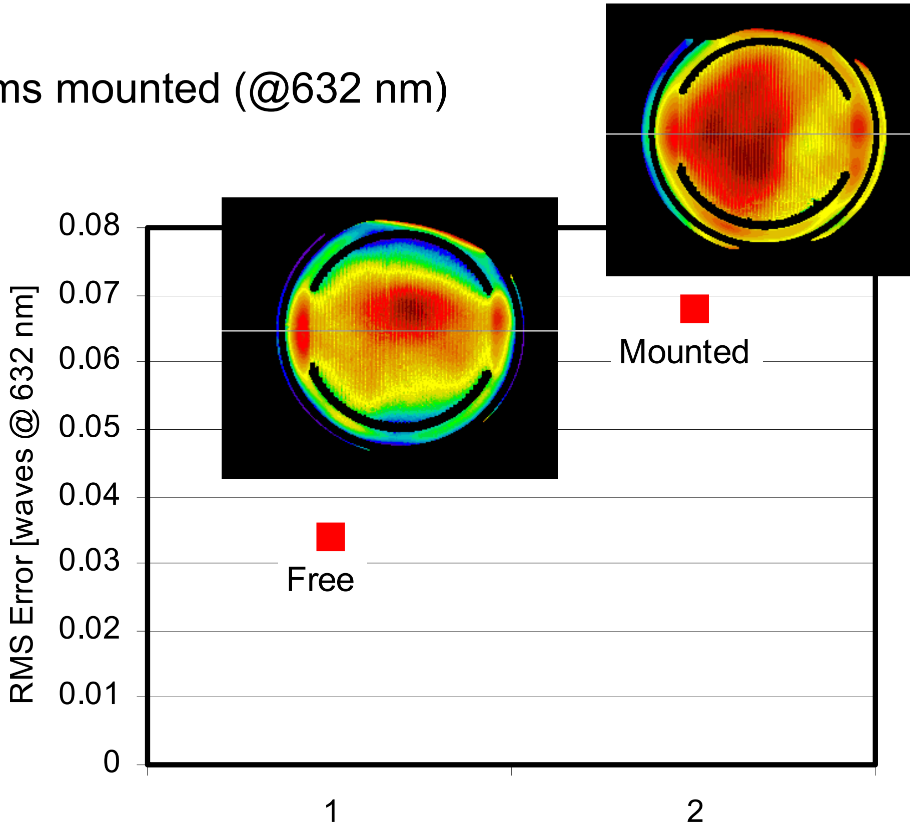
Yb doped Q-98 Kigre's glass at 4% concentration by wt.



µChannel Heat Exchanger for Uniform Cooling

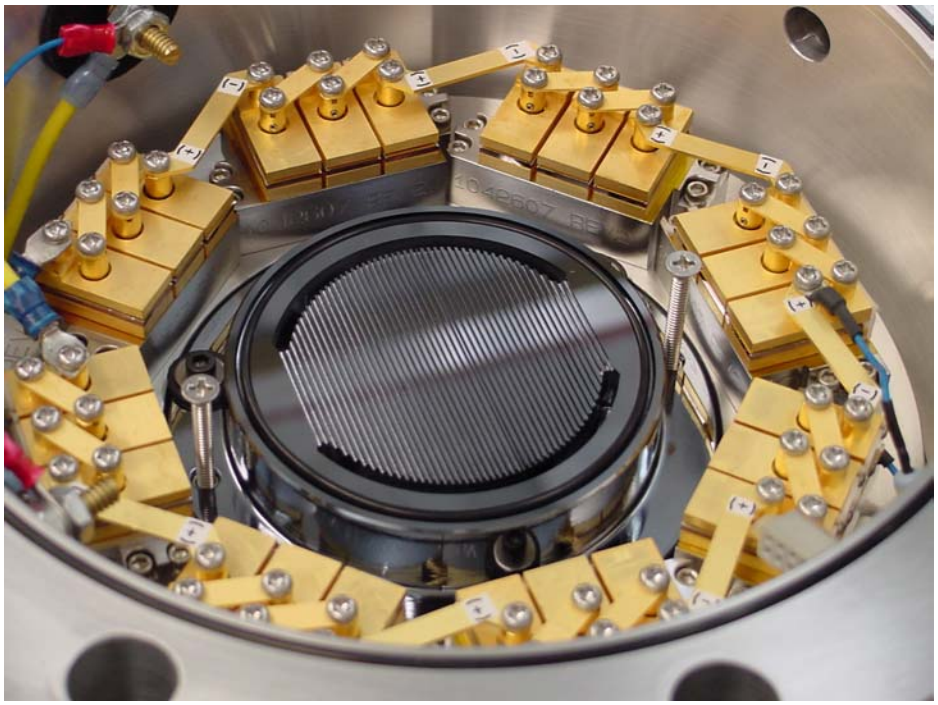
- **µChannel cooling can provide**
  - Very high heat transfer coefficients (~10 W/cm^2-deg is achievable)
  - Uniform heat extraction over a large surface
  - Very low temperature variation over the surface (isothermal)
- **Silicon substrate (single crystal)**
  - High thermal conductivity, stiff & lightweight
  - Front surface flat to <λ/20 rms free, <λ/10 rms mounted (@632 nm)



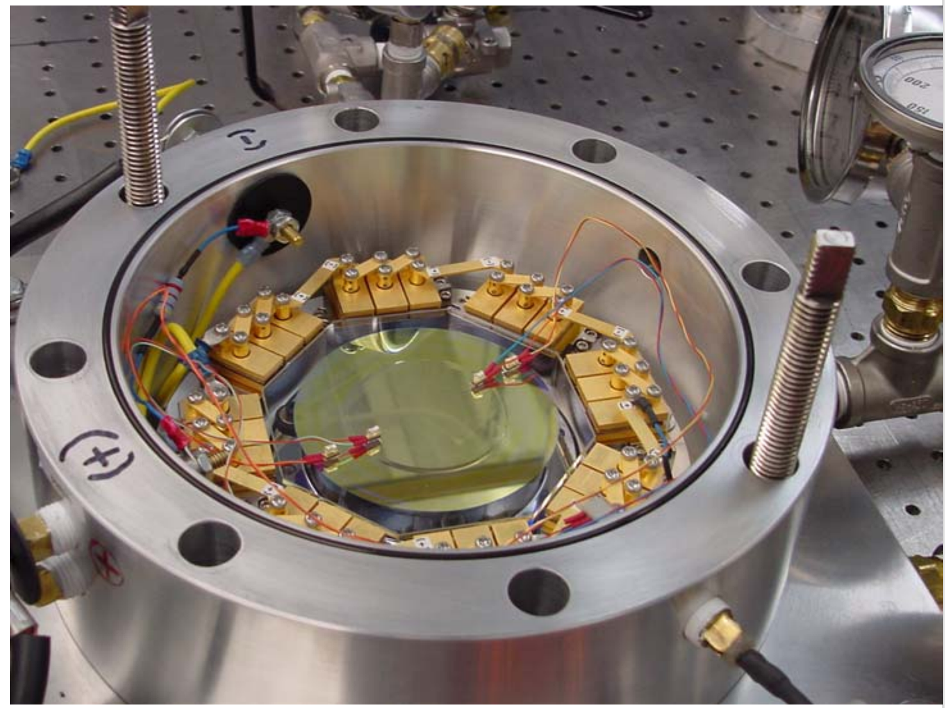


Test Hardware

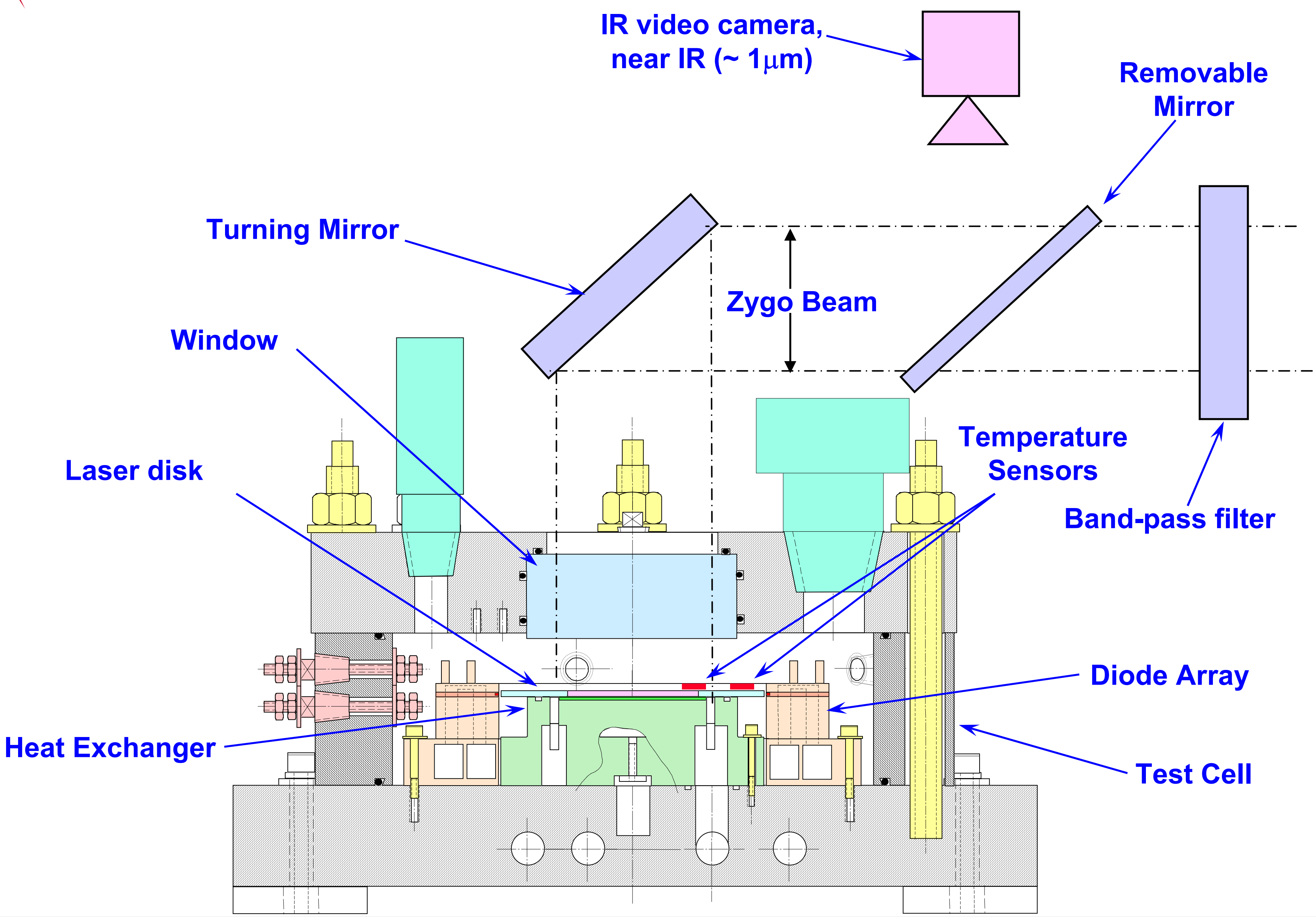
Diodes and heat exchanger installed



Disk installed

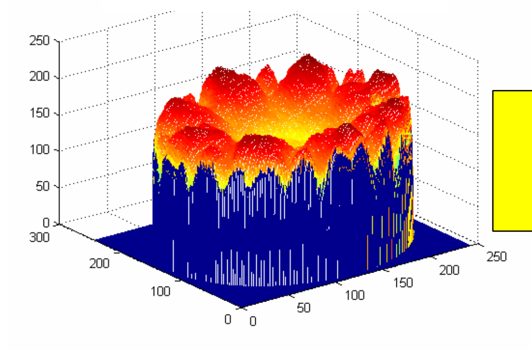


Setup for Interferometric Measurement of Disk Distortions

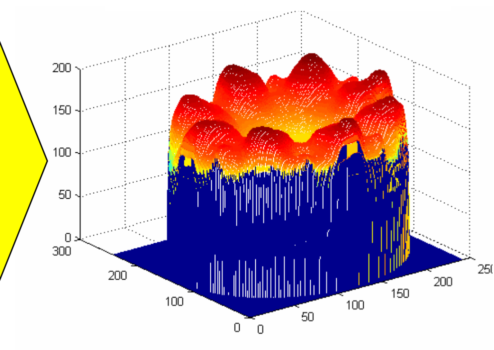


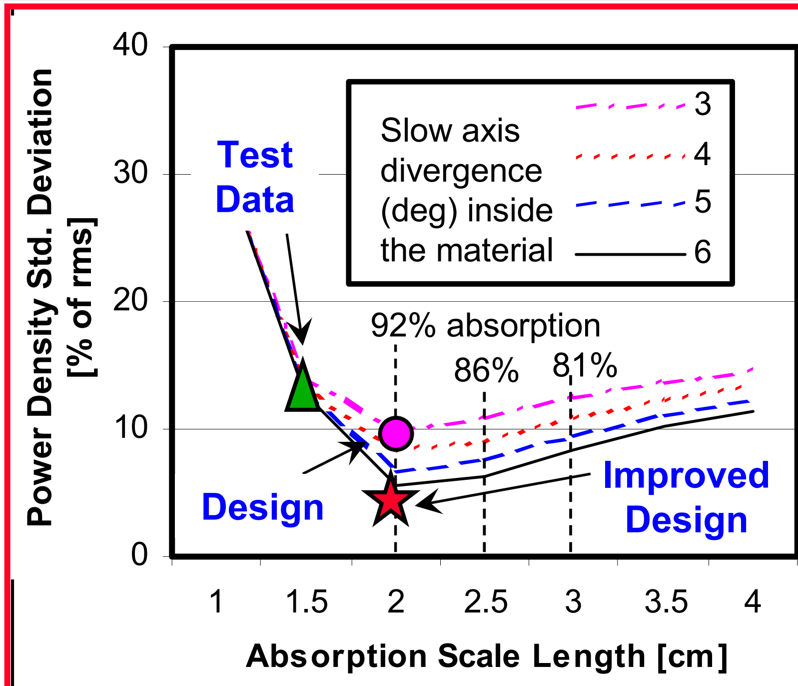
Pump Uniformity 87.5% Achieved

Image data
Variation = 12.5%

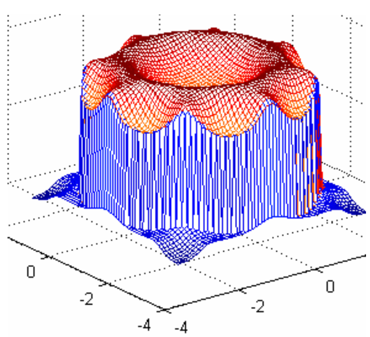


Filtered image data
Variation = 11.8%



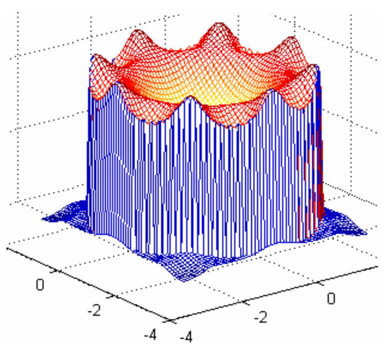


Variation = 10%



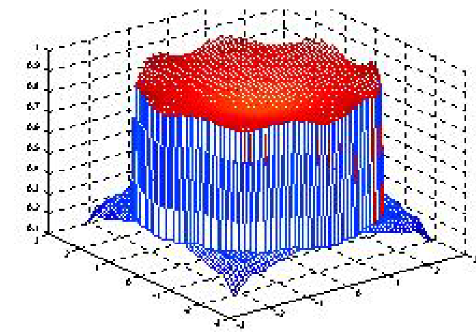
Model prediction for x_L = 2 (orig. design)

Variation = 13%



Model prediction for x_L = 1.4 (test data)

Variation = 4%



Model prediction for x_L = 2 (improved design)

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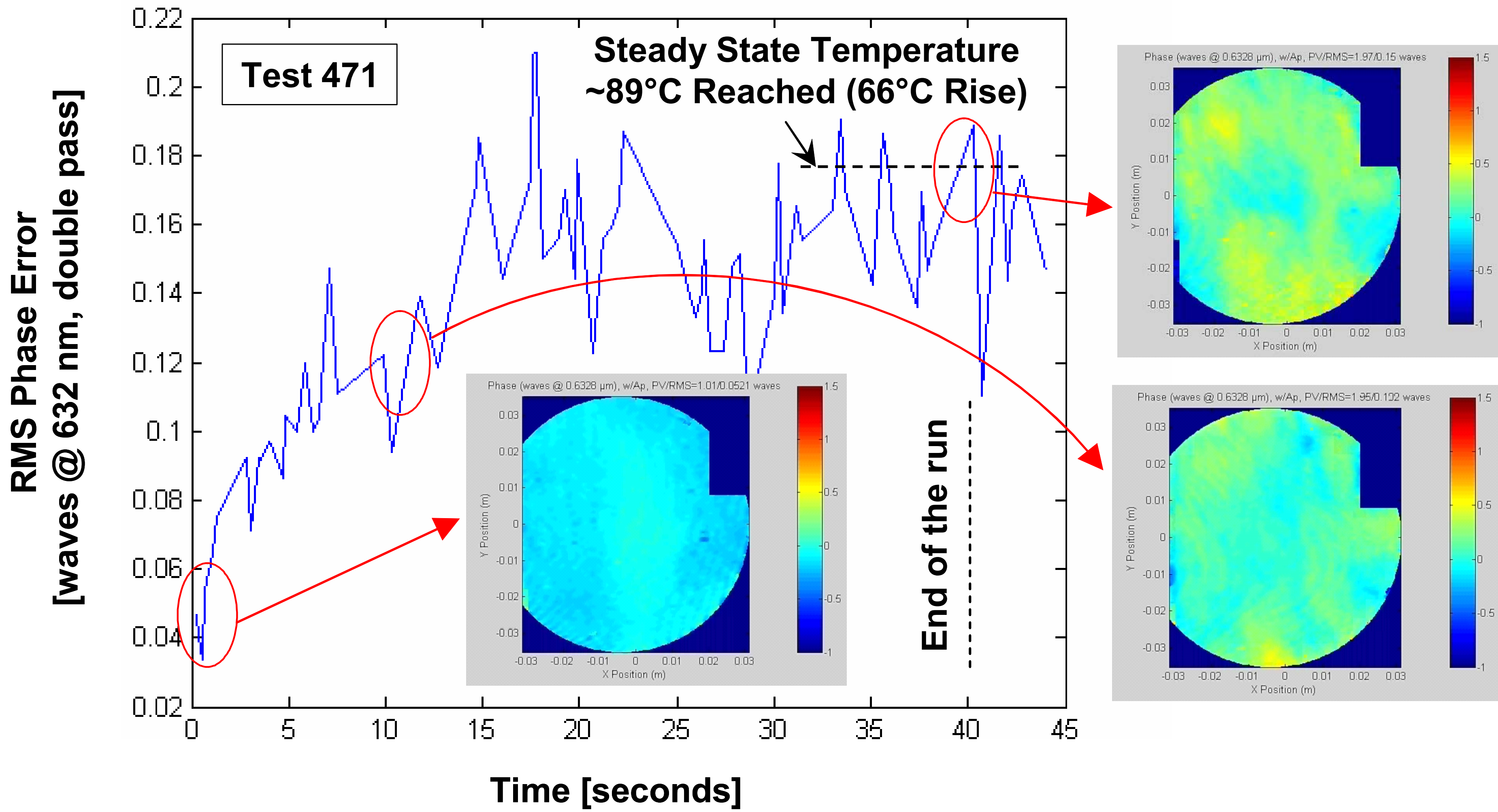
January 29, 2004
BOEING L&EOS

Excellent Optical Quality in Thermally-Loaded Disk

Phase error < λ_{Laser}/10 rms (2 pass configuration)

(Heat load ~18 W/cm^3)



CAMIL MCDL

#2040129-SSDL-16

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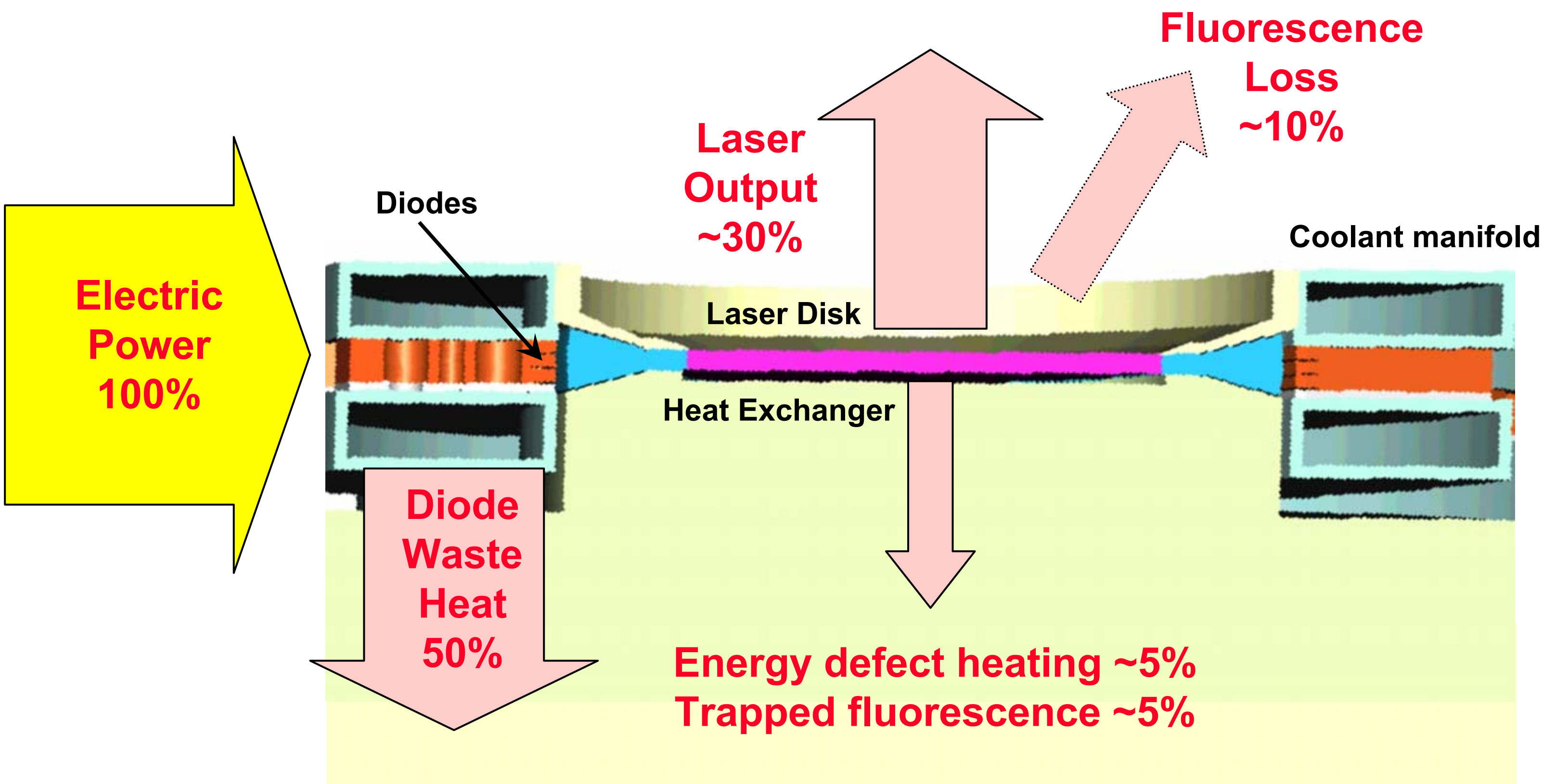
BOEING L&EOS

~30% EO Efficiency in Yb-Doped Disk

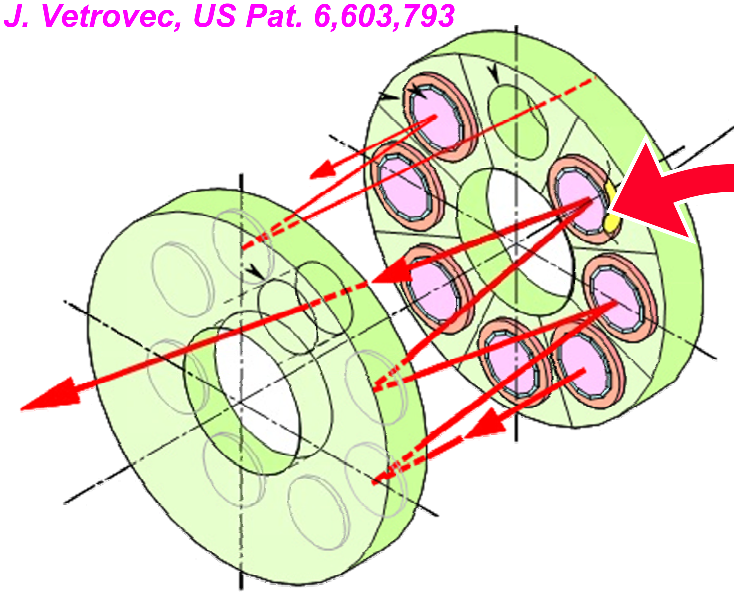
Predicted energy balance for Yb-doped disk pumped by 975 nm diodes

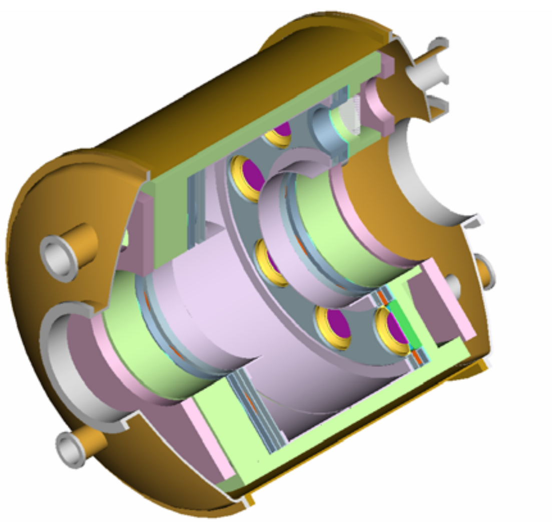


CAMIL Devices
Can Be Simple and Robust

J. Vetrovec, SPIE vol. 4968 (2003)

J. Vetrovec, US Pat. 6,603,793

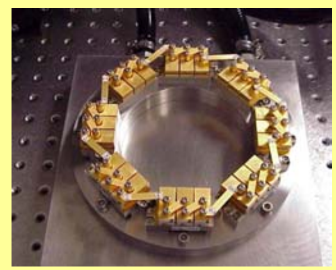




Tested Configuration (1 module)

Composite Laser Disk

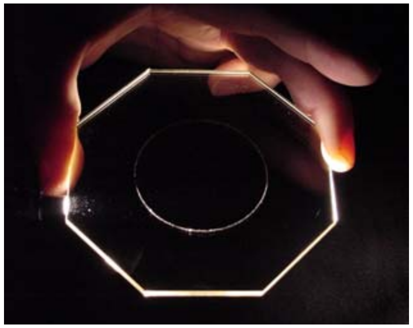
Microchannel Heat Exchanger



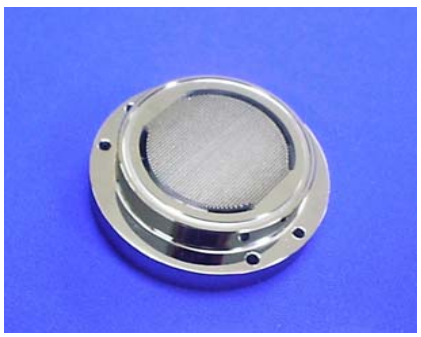
Diode Array for Edge Pumping

- **CAMIL can be used in oscillator and MOPA**
- **Axisymmetric layout for high compactness**
- **Multiple disks placed onto common substrate**
  - Simple design with low component count
  - Stable alignment

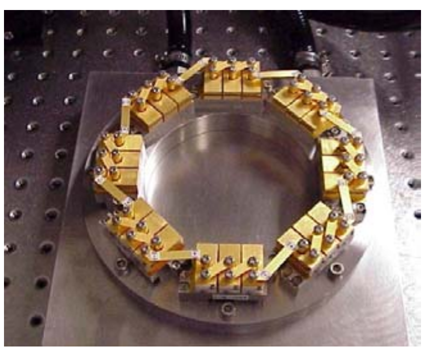
Summary



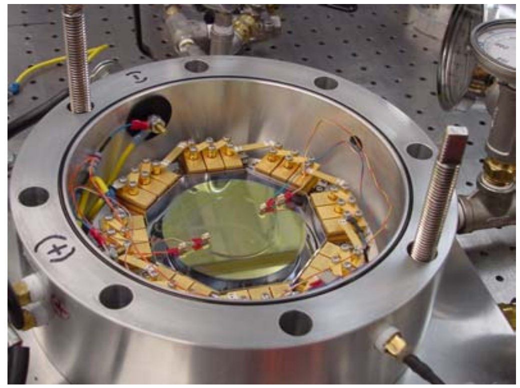
Composite laser disk



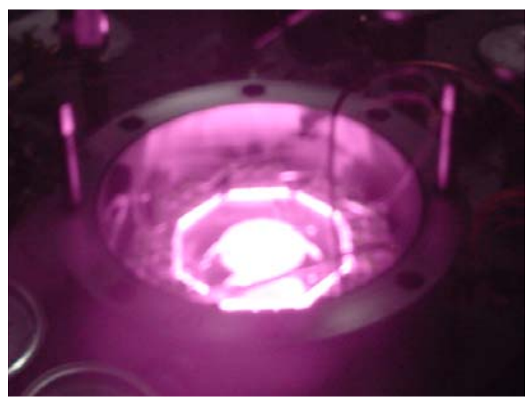
Microchannel heat exchanger



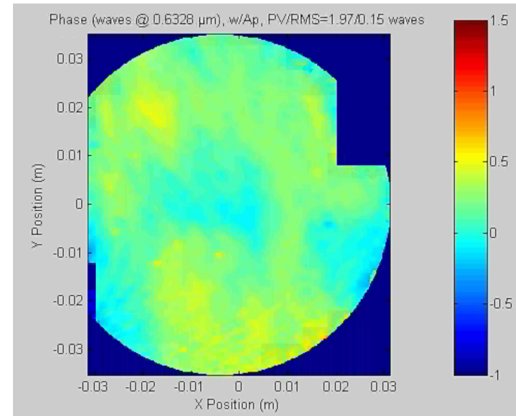
Diode array for edge pumping



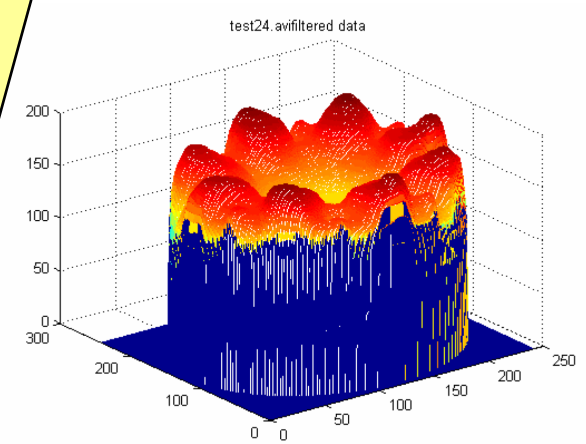
Test module configuration traceable to full scale hardware



Testing at up to 1 kW of diode power



Phase error < $\lambda_{Laser}/10$ in steady state and ~90°C



Pump uniformity 87.5%

John Vetrovec
January 29, 2004

Conclusion

- **CAMIL is a very promising SSL concept for ultra-high average power lasers**
  - Compact and lightweight systems
  - Multiple industrial applications
    - > Material processing in manufacturing
    - > Nuclear D&D
    - > Rock drilling
    - > Laser propulsion
    - > Orbital transfer and debris removal
- **Development testing project demonstrated**
  - Composite disk fabrication
  - Edge pumping
  - Microchannel heat exchanger
  - Pressure clamping of disk to heat exchanger
- **Future publications**