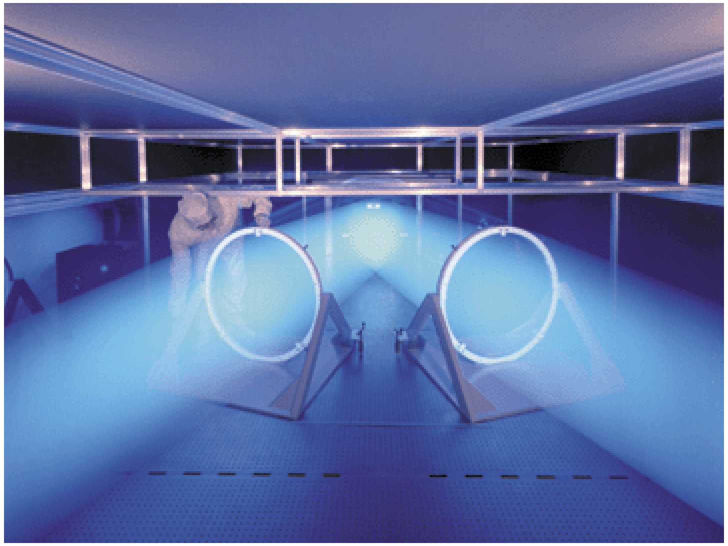
Large Aperture Dielectric Gratings for High Power LIGO Interferometry



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Motivation

- **LIGO needs reflective grating beamsplitters for high-power interferometry.**
  - **Transmissive optics suffer from thermal lensing.**
    - **CO_2 heating laser already required for ITM's on initial LIGO.**
    - **Advanced LIGO will require 830kW of circulating power in the arms. For a 6cm spot size, that comes out to 30kW/cm^2 of intensity.**

- **Significant investment and progress has been made in the development of multilayer dielectric diffraction gratings for high-energy Petawatt-class laser systems.**
  - **Projects such as LIGO are poised to take advantage of this capability.**

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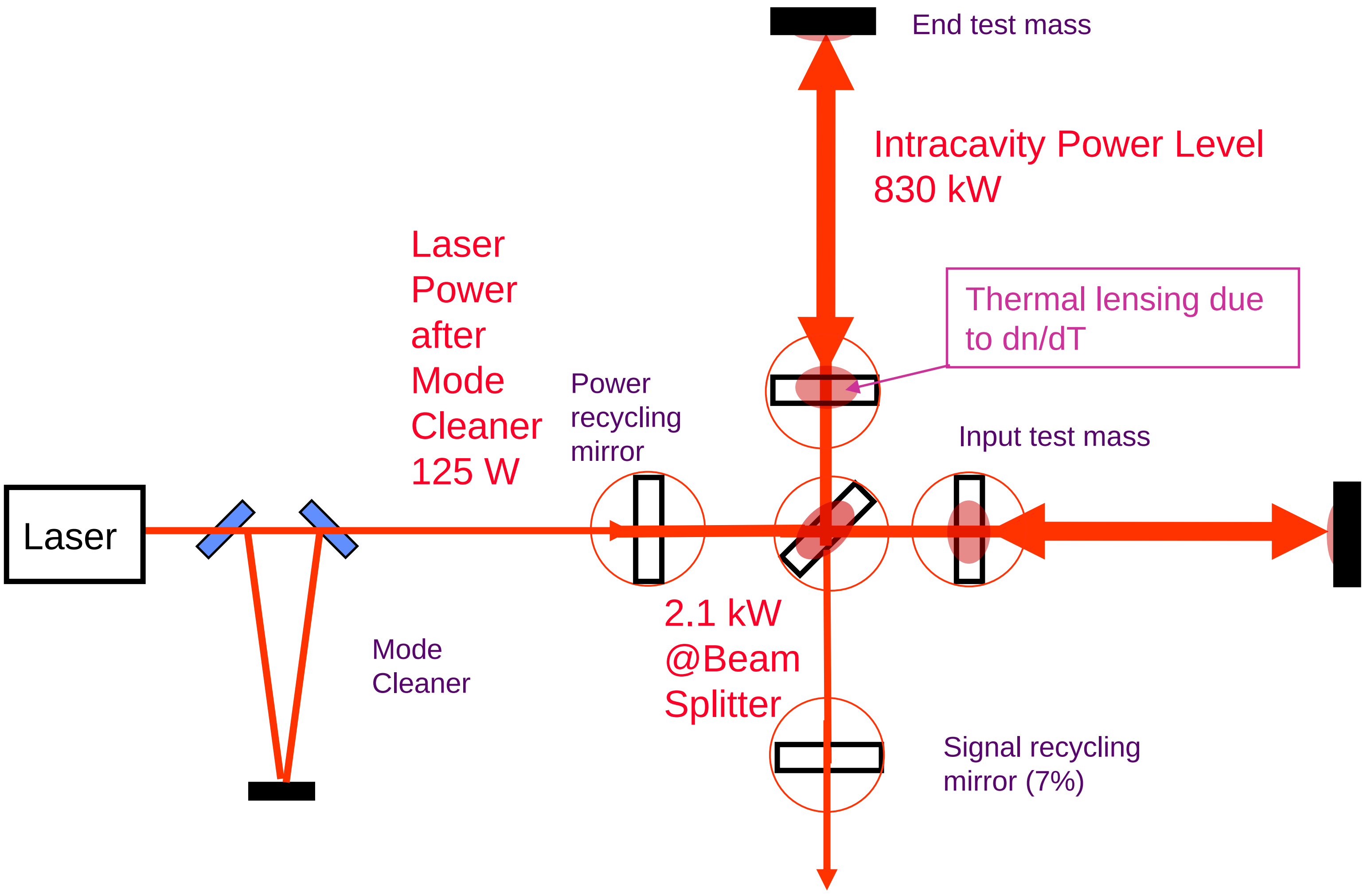
Laser Heating in Advanced LIGO



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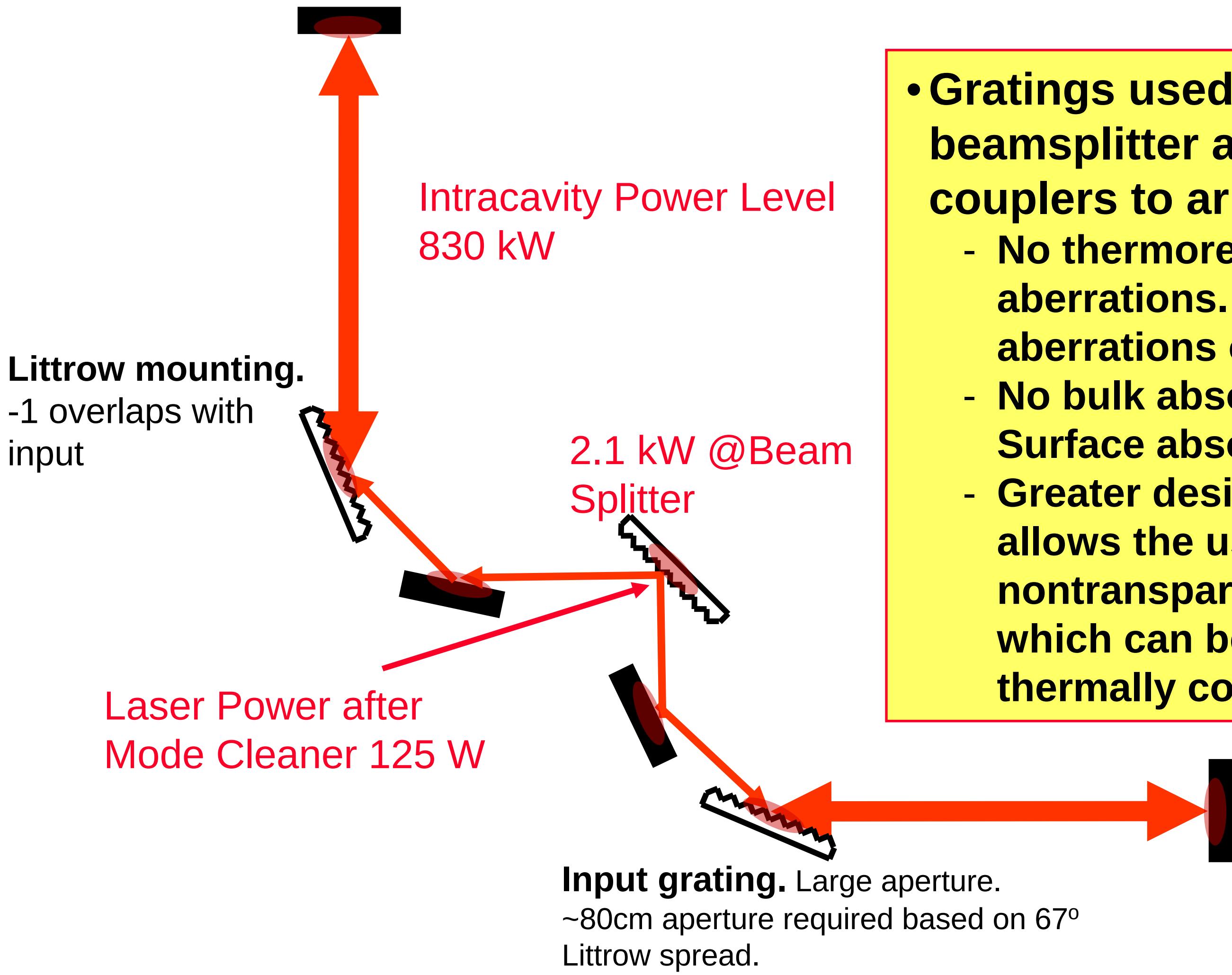
All Reflective Grating Reduces Bulk Heating



- **Gratings used as beamsplitter and input couplers to arm cavities.**
  - **No thermorefractive aberrations. Thermoelastic aberrations only.**
  - **No bulk absorption. Surface absorption only.**
  - **Greater design flexibility: allows the use of nontransparent substrates, which can be more thermally conductive.**

K.X. Sun, et. al, "All-reflective Michelson, Sagnac, and Fabry-Perot interferometers based on grating beam splitters," Optics Letters, **8**(23), p. 567-9 (1998)

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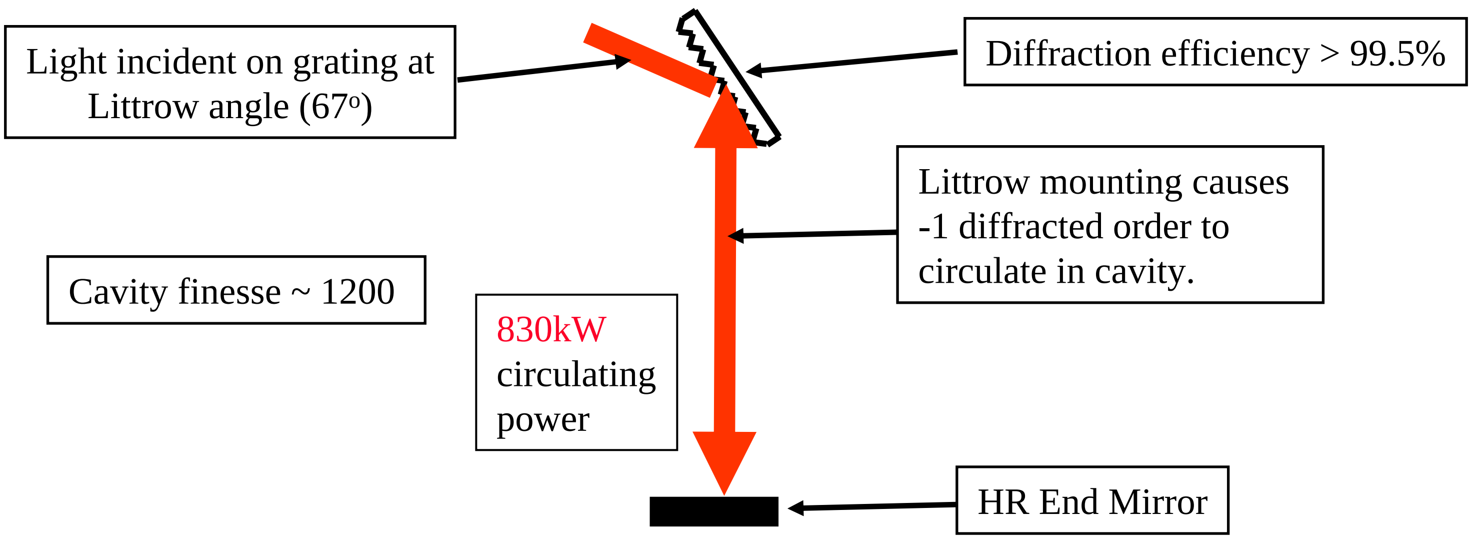
Current Subject of Investigation

Advanced LIGO Arm Cavity



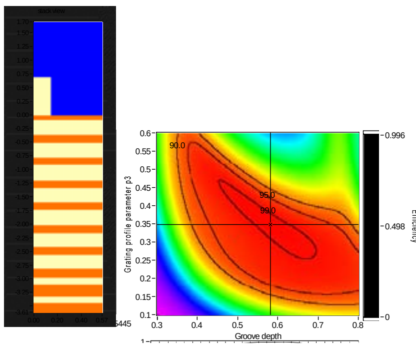
The goal of this study is to build and test a working model of this configuration.

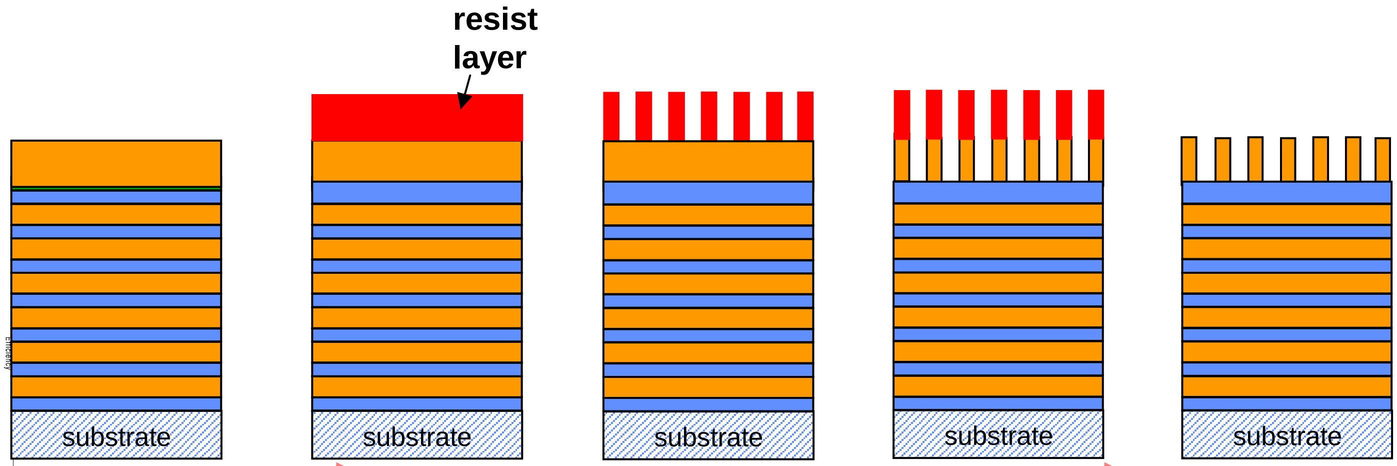
LIGO's Requirements for Gratings

• **Large Aperture** - **31.4 cm mirror diameter[1].** - **Gratings must be 83 cm based on a 67º Littrow angle.**	• **Low thermal aberrations** - **Advanced LIGO: 830 kW circulating in arm cavities[2]** - **6 cm spot size** - **Intensity: 30kW/cm^2**
• **High Efficiency** - **99.5% desired[3]** - **Over large aperture for beam quality**	• **Low Scattering** - **Light scattering noise couples seismic activity into signal**

[1] P. Barriga, et. al, "Numerical calculations of diffraction losses in advanced interferometric gravitational wave detectors," http://www.ligo.org/pdf_public/barriga.pdf
[2] C. Zhao, et. al, "Compensation of Strong Thermal Lensing in High Optical Power Cavities," gr-qc/0602096 v2
[3] Miyakawa, et. al, "Measurement of Optical Response of a Detuned Resonant Sideband Extraction Interferometer," LIGO-P060007-00-R

MLD grating fabrication process flow





Design (efficiency, E-field distribution, …)

Multilayer oxide deposition

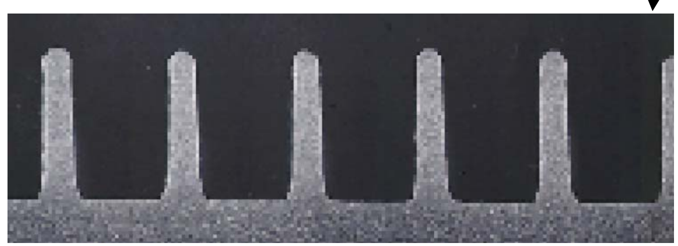
Clean Prime Resist coat

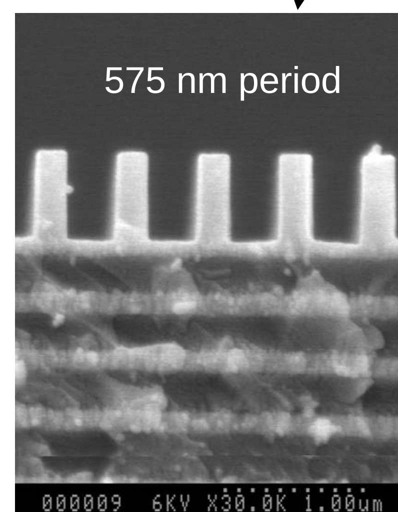
Expose Develop Metrology

Transfer-etch (RIBE)

Cleaning & Metrology

(only part of process not done at LLNL)





During manufacture, optics are exposed to heat, aggressive liquids, and vacuum processing.

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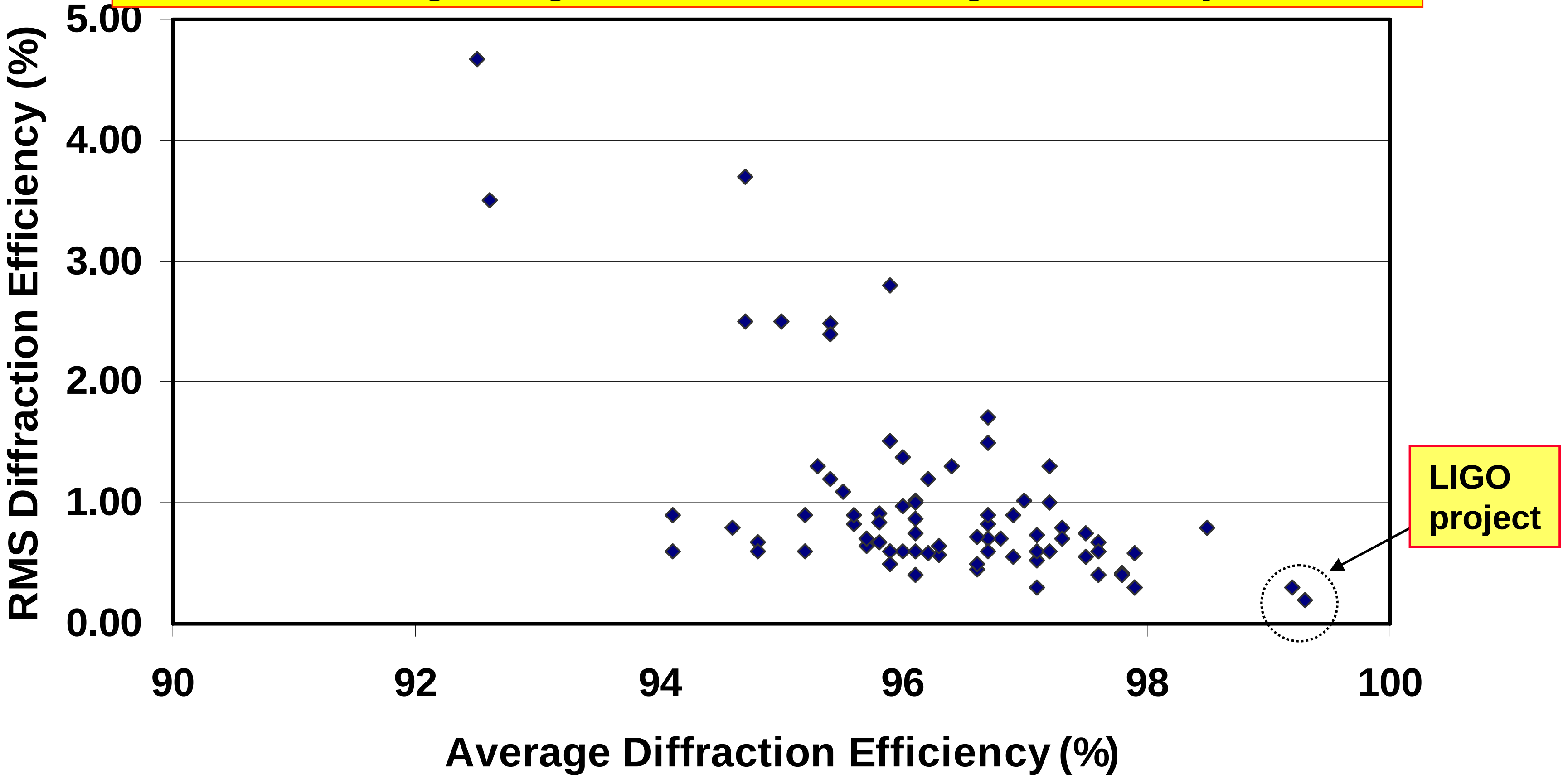
In the past 18 months LLNL has produced 77 production gratings @ 1740 l/mm

Apertures from 140 mm to 800 mm

Over 11 m^2 of grating surface with average efficiency > 96%



For use wavelengths from 1017 nm to 1064 nm

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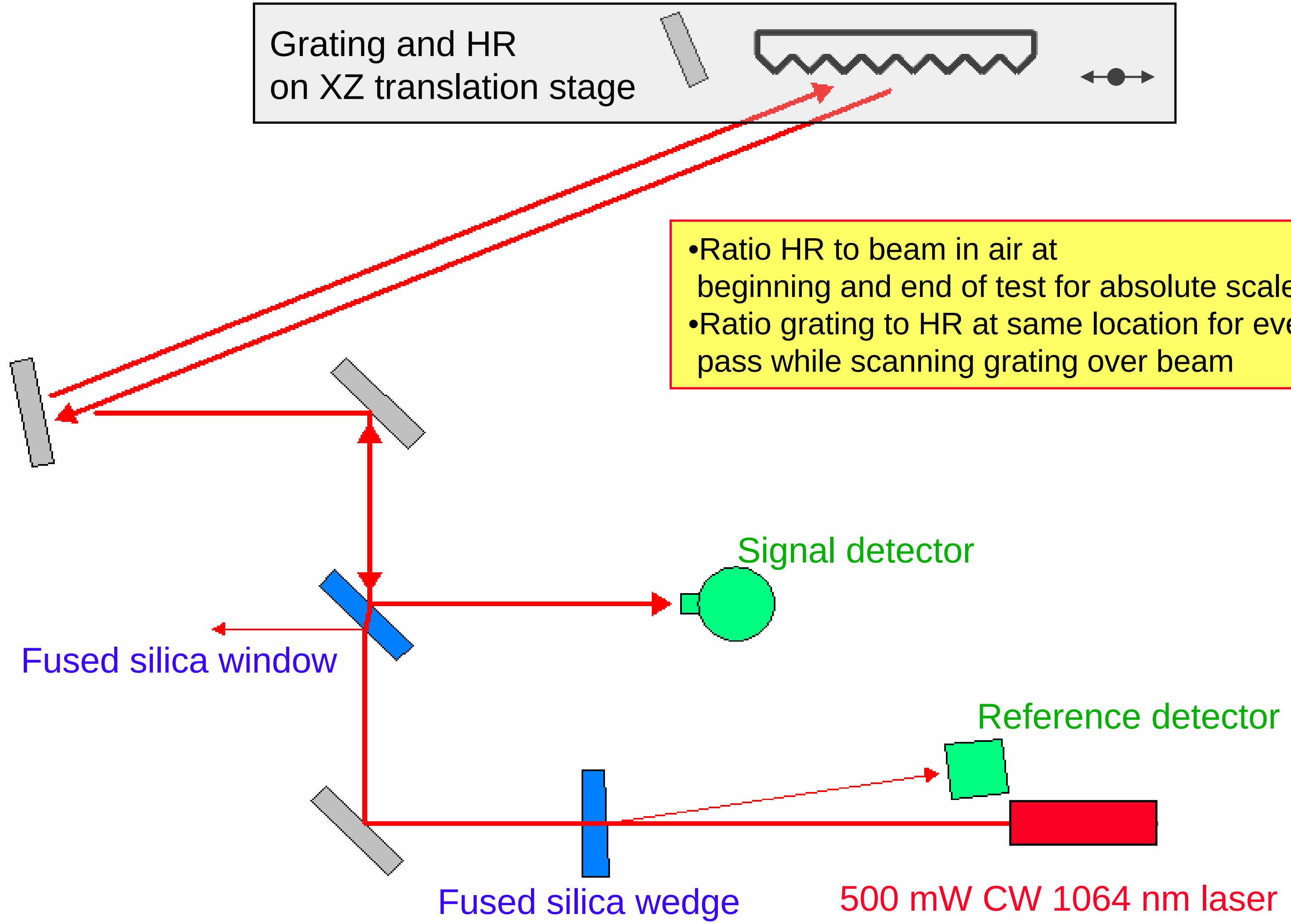
Ratioing scanning photometry setup @ LLNL for efficiency measurements



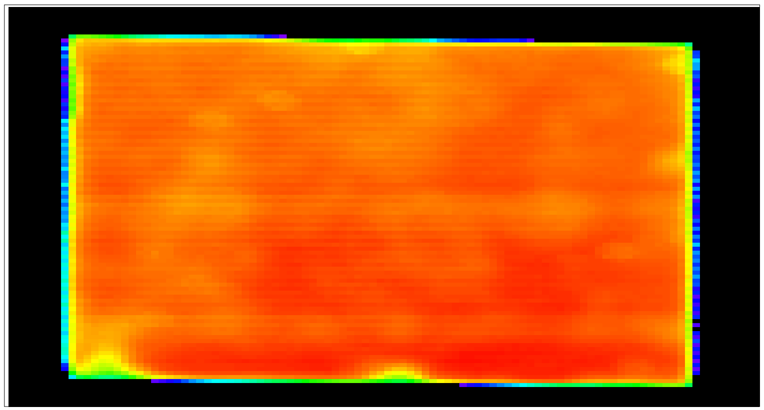
- Ratio HR to beam in air at beginning and end of test for absolute scale
- Ratio grating to HR at same location for every pass while scanning grating over beam

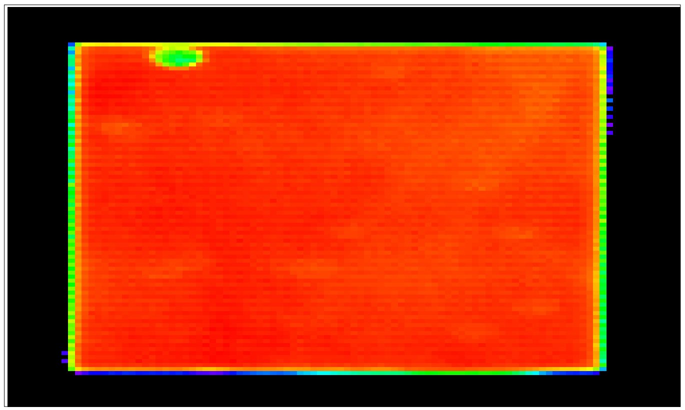
>99% diffraction efficiency gratings have been delivered to Stanford

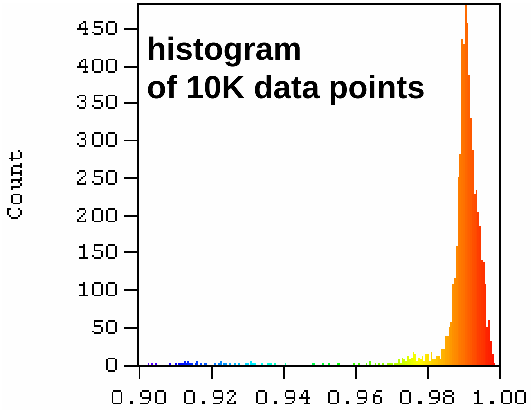
1740 line/mm HfO_2/SiO_2 grating on BK7 substrates

#011 (200x100 mm):
99.2% Ave, 0.3% RMS

#021 (170x100 mm):
99.3% Ave, 0.2% RMS

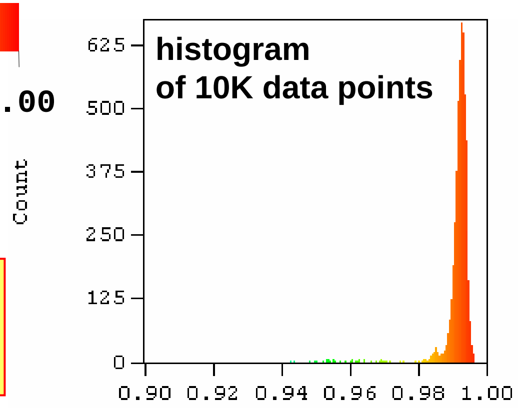






SN11_Littrow_06_10_02_202919_EFF_XLS

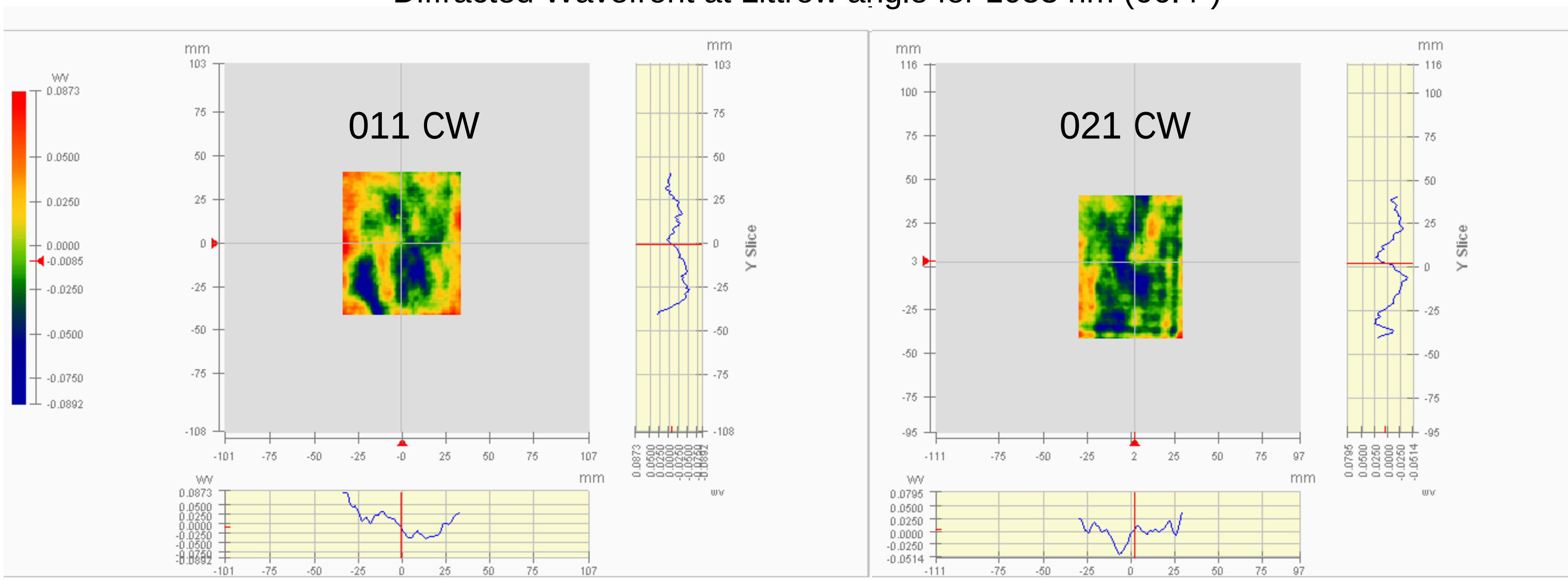
Design spec of >99.5% is achievable



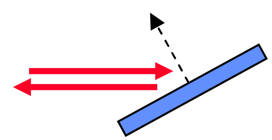
qs021_littrow_06_12_06_111421_EFF_XLS

Gratings exhibit flat diffracted wavefront

Diffracted Wavefront at Littrow angle for 1053 nm (66.4°)



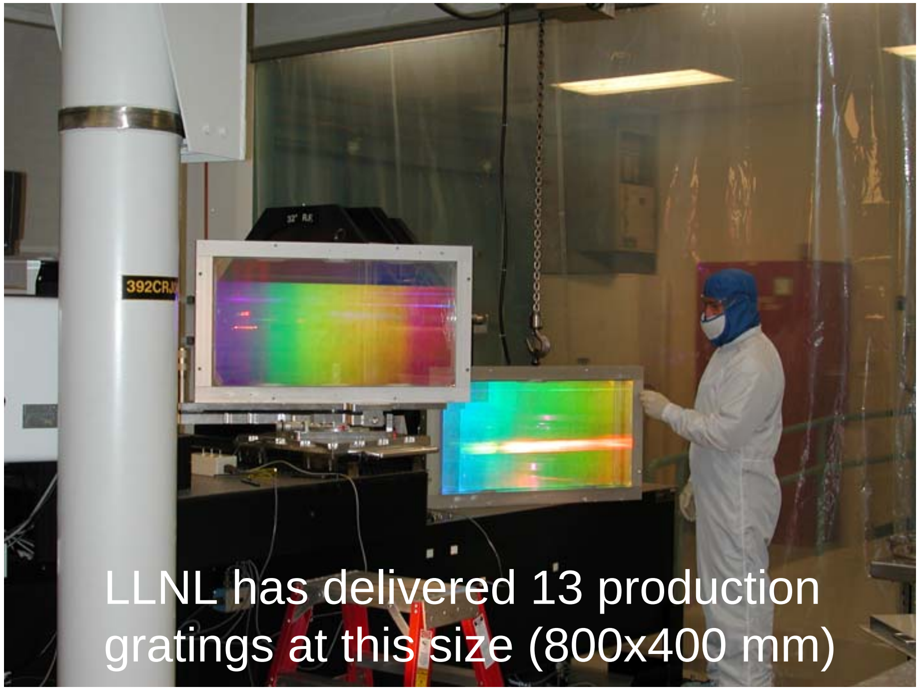
Resolution	**991 x 1005**
Wedge	**1.000**
PV	**0.1765 wv**
PVq(99%)	**0.1509 wv**
RMS	**0.0292 wv**
Strehl	**0.967**



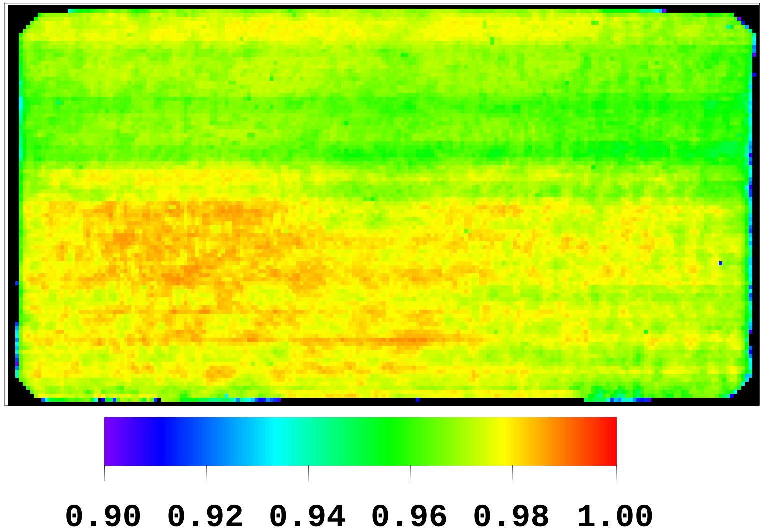
CW orientation
w/ S/N up

Resolution	**991 x 1005**
Wedge	**1.000**
PV	**0.1310 wv**
PVq	**0.0837 wv**
RMS	**0.0175 wv**
Strehl	**0.988**

LIGO aperture required has been demonstrated for other projects

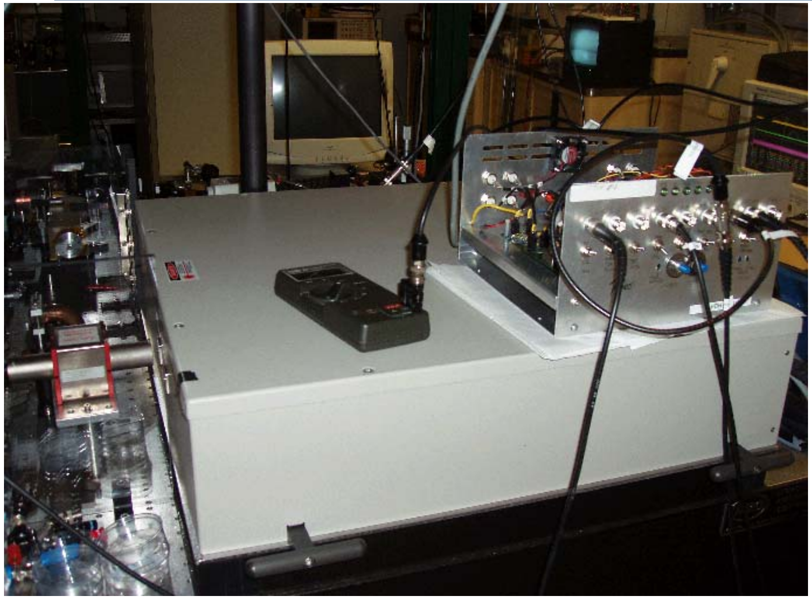


#005 (800x400 mm) @ 1053 nm, 72.5°: **97.3% Ave, 0.7% RMS**



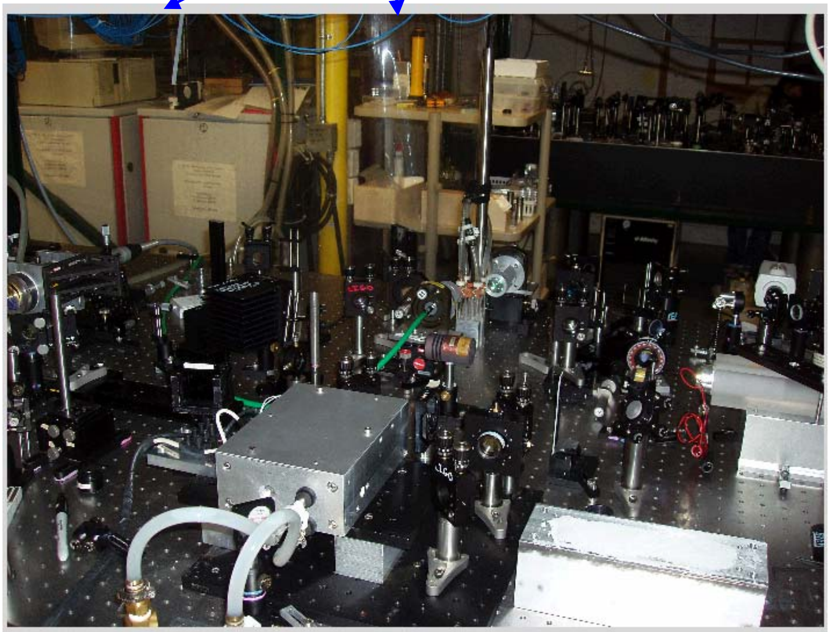
#011: **97.1% Ave** @ 1053 nm, 72.5°,
so this grating could be >99% for LIGO conditions

Byer Group Laser Lab



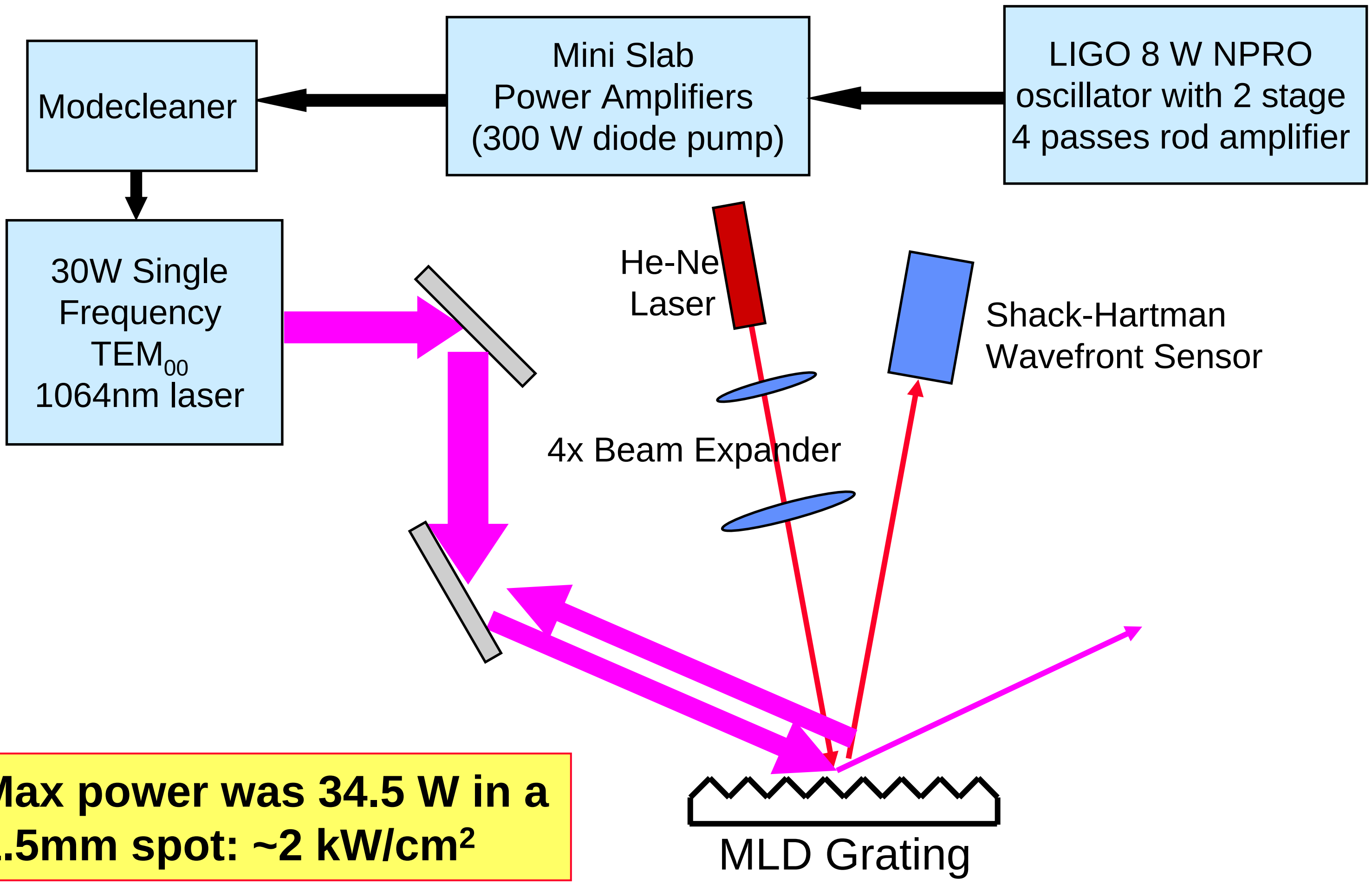
NPRO Oscillator and Rod Amplifiers

100~200 W Amplifiers



Laser lab is being set up for high power cw laser heating characterization of LLNL gratings

Initial thermal testing of 100 mm diameter LLNL MLD witness grating



Max power was 34.5 W in a 1.5mm spot: ~2 kW/cm²

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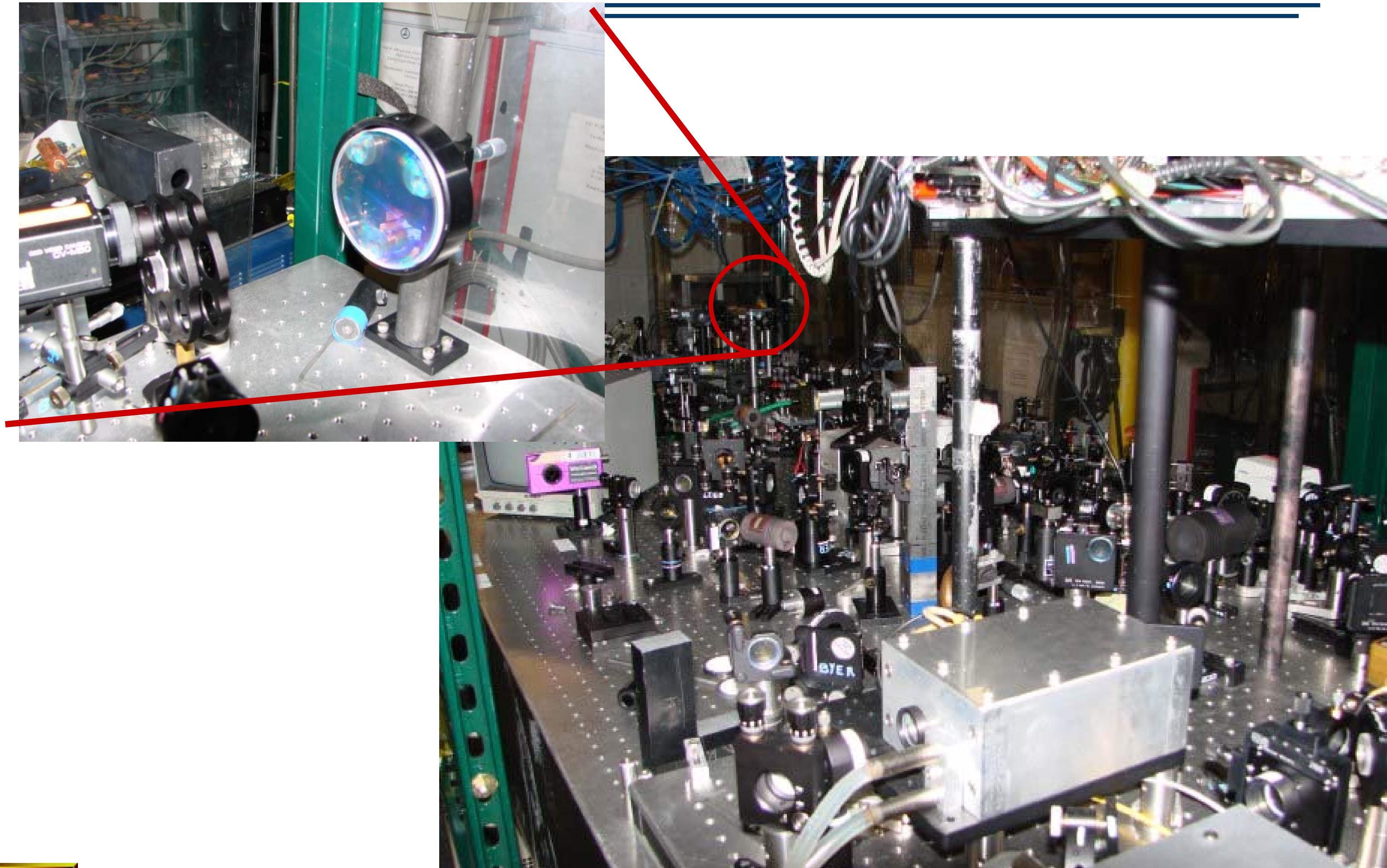
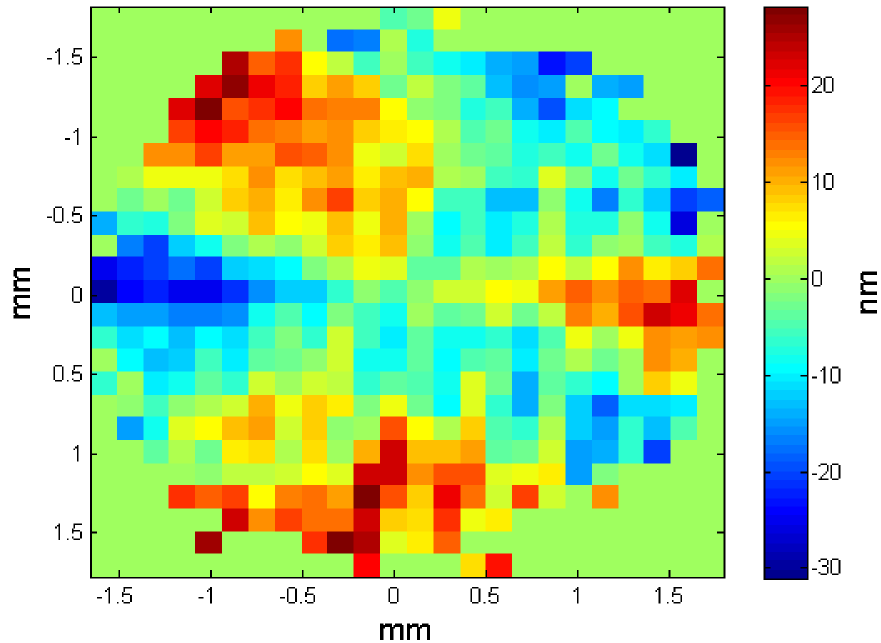
Thermal testing of 100 mm diameter LLNL witness grating



Grating wavefronts measured at two power densities show no difference

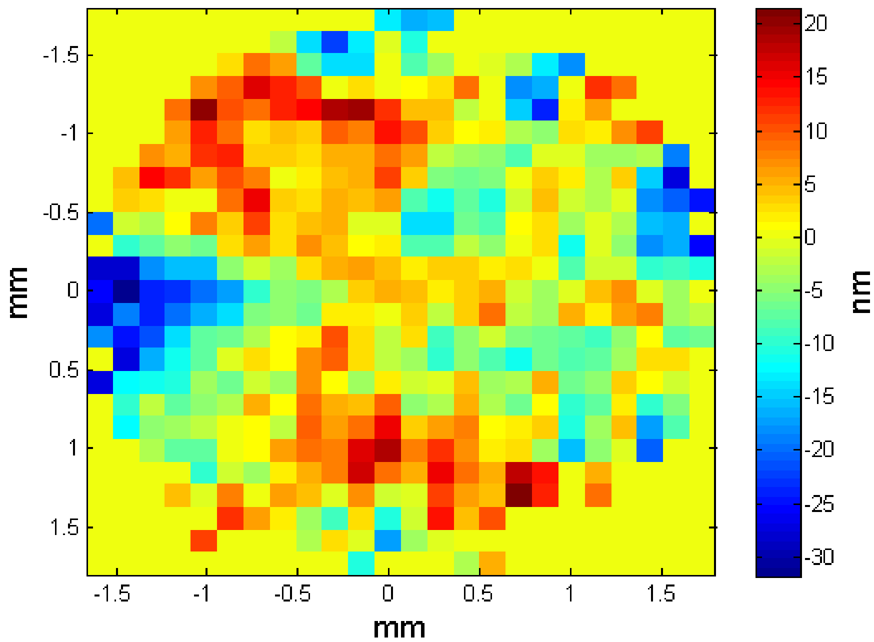
removed Tip, Tilt, and Piston

11 W, 0.6 kW/cm²



PV: 59.3 nm, Rms: 11.2 nm

34.5 W, ~2 kW/cm²



PV: 53.4 nm, Rms: 9.4 nm

3mm HeNe Probe Beam

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Next Steps

- **Fiber laser and amplifiers to enable 100 W of single mode light**
- **Cavity configuration to enable thermal tests to reach ~30 kW/cm^2 for centimeter-scale beams**
- **Large-aperture efficiency measurements will be made at Stanford to corroborate LLNL measurements**
- **Scatterometer measurements, including back leaks**

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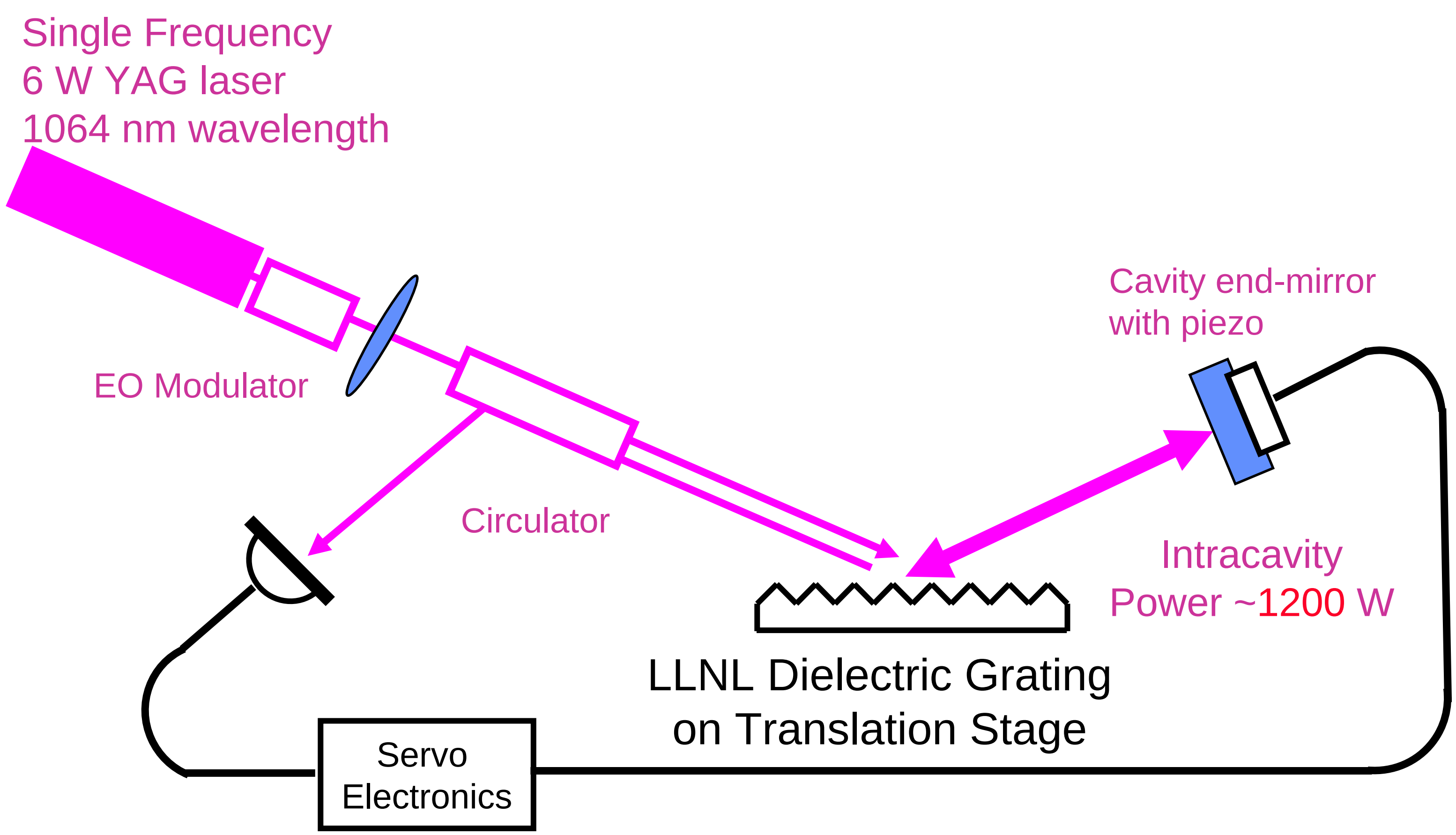
Efficiency/Finesse Measurements planned for near future



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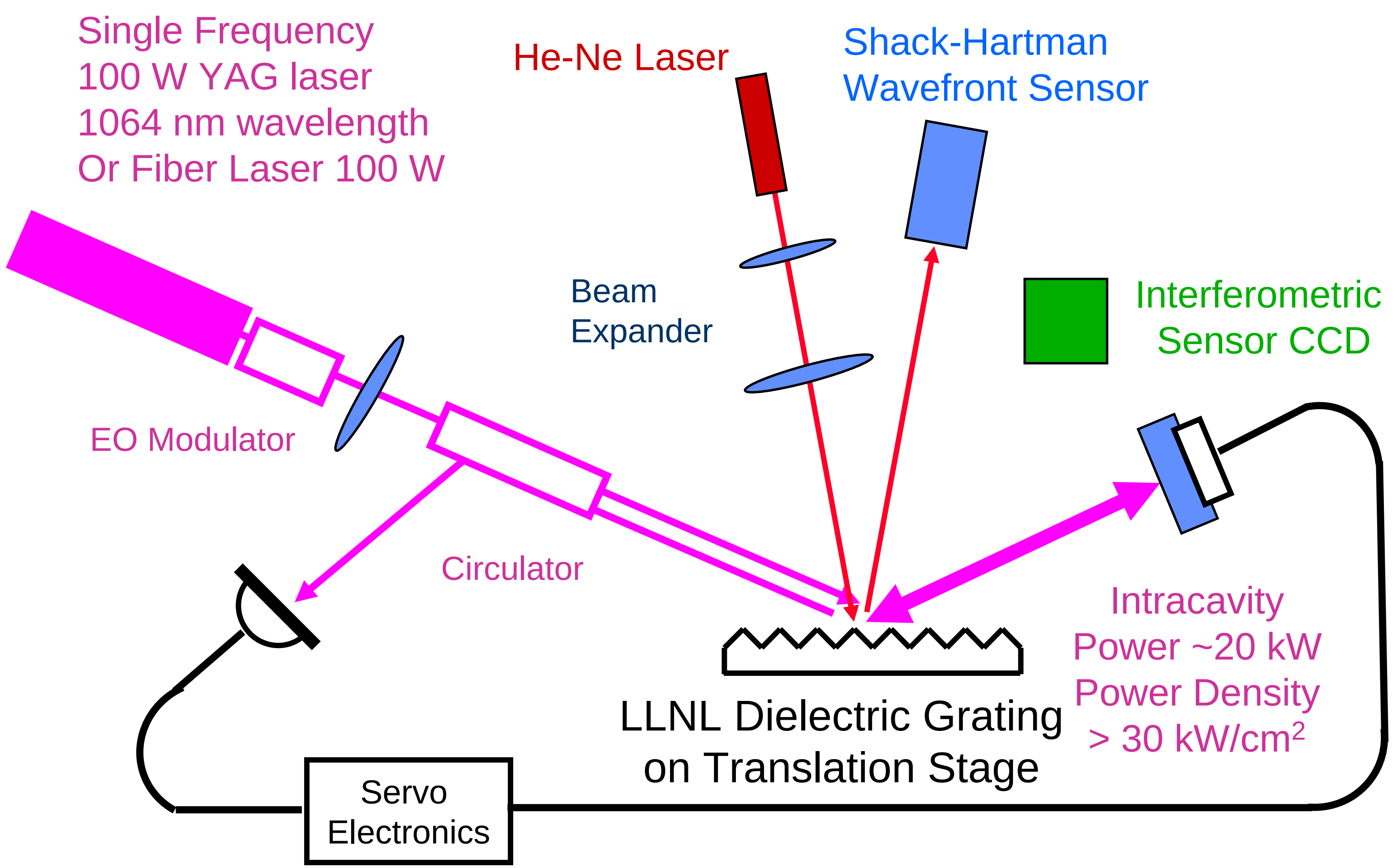
Thermal aberration measurement at higher power planned for near future



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Conclusions

- **Capability exists to manufacture large-aperture multilayer dielectric diffraction gratings for demanding LIGO applications**
  - **>99% diffraction efficiency in Littrow mount**
  - **kW power-handling capability**
  - **80+ cm apertures**

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