Adaptive Mode matching for advanced LIGO

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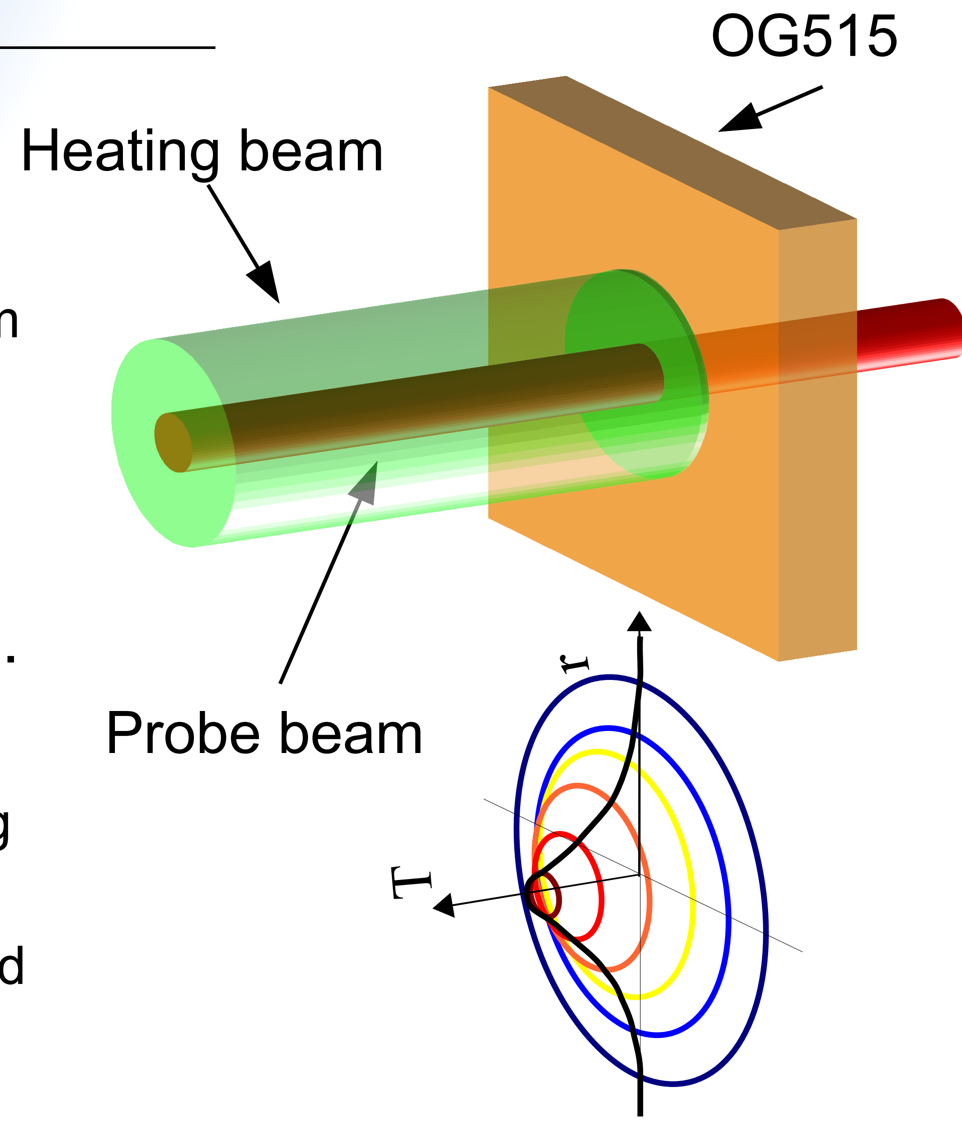
Motivation

Interferometric gravitational wave detectors are basically interferometers with suspended components that are operated in vacuum.

- Objective:
  - Actuator to change the modal parameters of a Gaussian beam without moving parts.
- Requirements:
  - Touch free
  - Vacuum compatible (UHV)
  - Stationary (no movable parts)
- Solution:
  - Telescope with lenses with variable focal lengths

Adjustable lenses

- Use thermal lensing effect
- Use dichroic material
  - high absorption for heating beam
  - low absorption for probe beam
- Schott OG515 is highly transmissive for 1064nm and strongly absorbing for 514 nm.
- Two laser setup
  - Argon-Ion laser provides heating beam to actuate the lens
  - Nd:YAG laser probes the created effect



Calculate temperature profile in substrate

- Solve thermal diffusion equation assuming $\frac{\partial T}{\partial z}=0$ on the faces and $T(r,z)=T_0$ on the rim (Substrate in heat sink).

$$\nabla^2 T(r,z) = -\frac{2\alpha P}{\pi K w^2}\exp\left(-2\frac{r^2}{w^2}\right)\exp(-\alpha z)$$

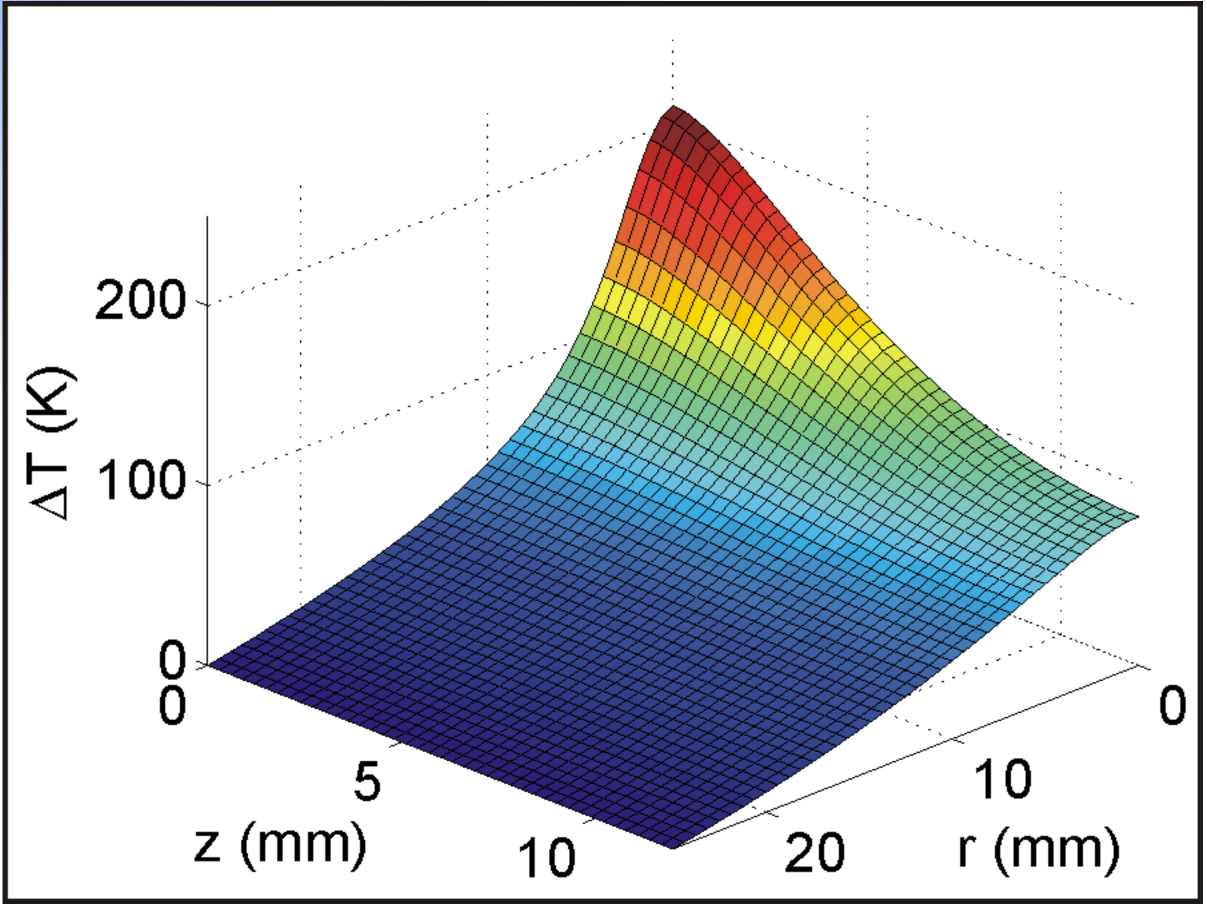
Analytical solution exists:

$$T(r,z) = -\sum_{n=1}^{\infty}\frac{4\alpha P}{\pi K R^2 w^2}\frac{\int_0^R \exp\left(-\frac{2r'^2}{w^2}\right)J_0\left(\frac{k_n r'}{R}\right)r'\,dr'}{(J_0(k_n))^2}J_0\left(k_n\frac{r}{R}\right)f_n(z)+T_0$$

$$f_n(z)=\frac{1}{\alpha^2-\left(\frac{k_n}{R}\right)^2}\left\{\frac{\alpha R}{k_n}\left(\frac{e^{\left(\left(\frac{k_n}{R}-\alpha\right)L\right)}-1}{e^{\left(\frac{2k_n L}{R}\right)}-1}e^{\left(\frac{k_n z}{R}\right)}-\frac{e^{\left(-\left(\frac{k_n}{R}+\alpha\right)L\right)}-1}{e^{-\left(\frac{2k_n L}{R}\right)}-1}e^{\left(\frac{k_n z}{R}\right)}\right)\right\}$$

3D - Temperature profile

- For 4 W heating beam with 3.6 mm radius



Calculated on grid with 460 radial and 1000 axial steps

Evaluating the effects of the temperature profile

- Change of optical path length

$$OPL(r)=\left(\frac{\mathrm{d}n}{\mathrm{d}T}+\alpha_T(n-1)\right)\int_0^L \Delta T(r,z)\,\mathrm{dz} \qquad \text{GRIN lens}$$

- Propagate a Gaussian beam with this OPL

$$u(r,z)=u_{probe}(r,z)\exp\left(-i\,k\,OPL(r)\right)$$
$$=u_{probe}(r,z)\exp\left(-i\,k\left(OPL(0)+OPL''(0)\frac{r^2}{2}+O(r^4)\right)\right)$$

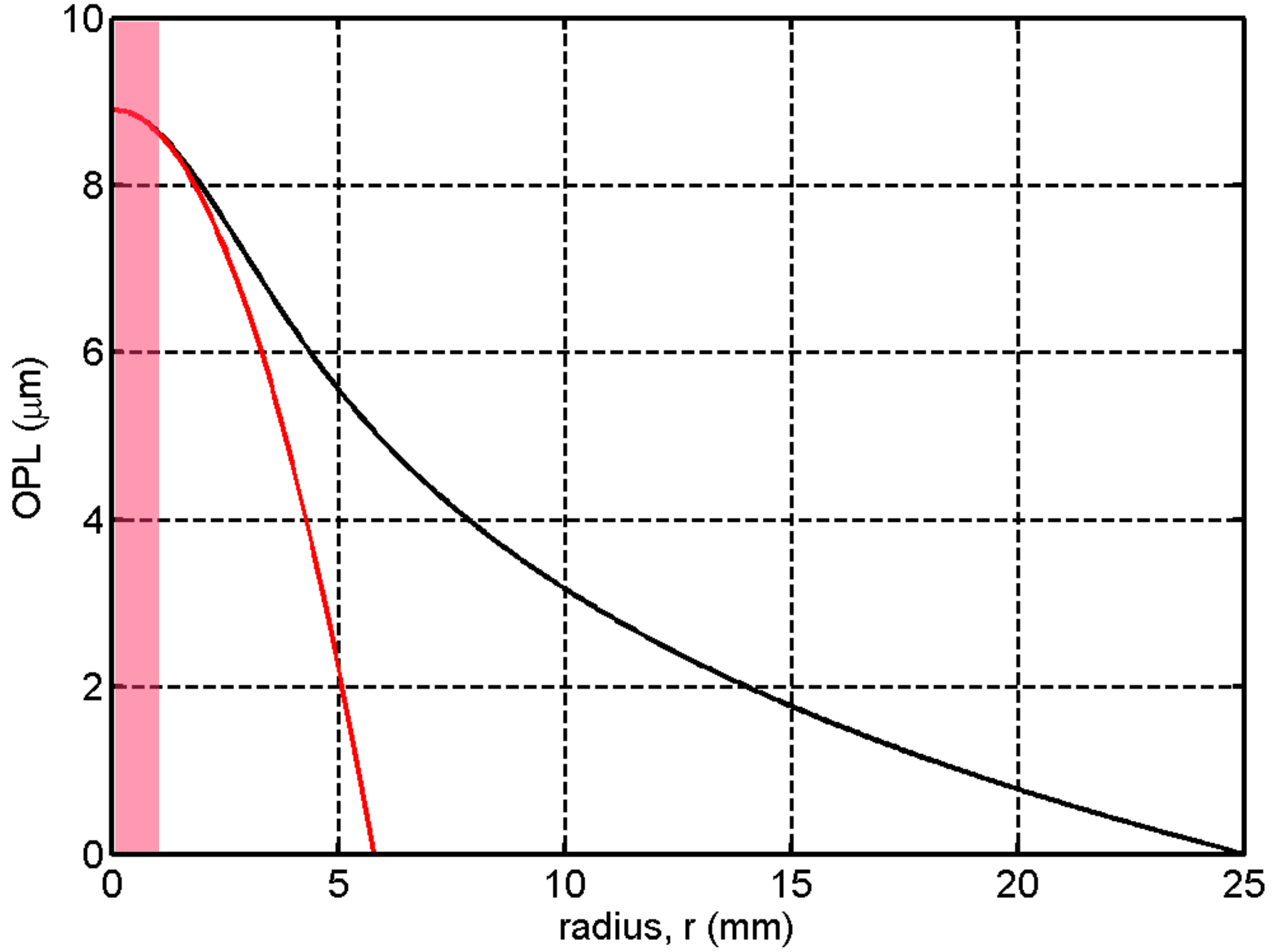
- Compare with propagation through a thin lens

$$u(r,z)=u_{probe}(r,z)\exp\left(i\,k\frac{r^2}{2}\frac{1}{f}\right)$$

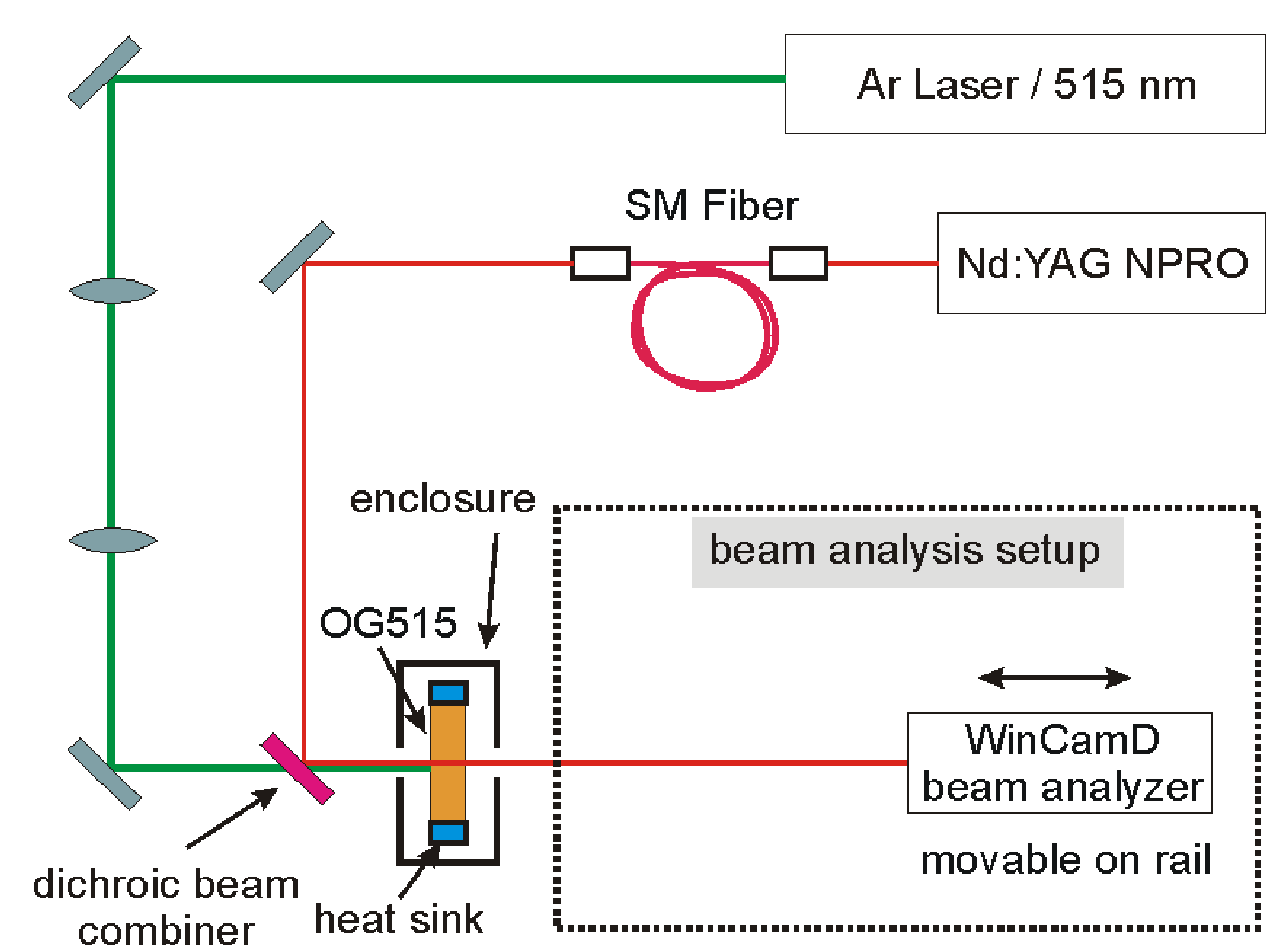
$$\rightarrow \qquad f=\frac{-1}{OPL''} \qquad \text{focal length}$$

Calculated optical path length

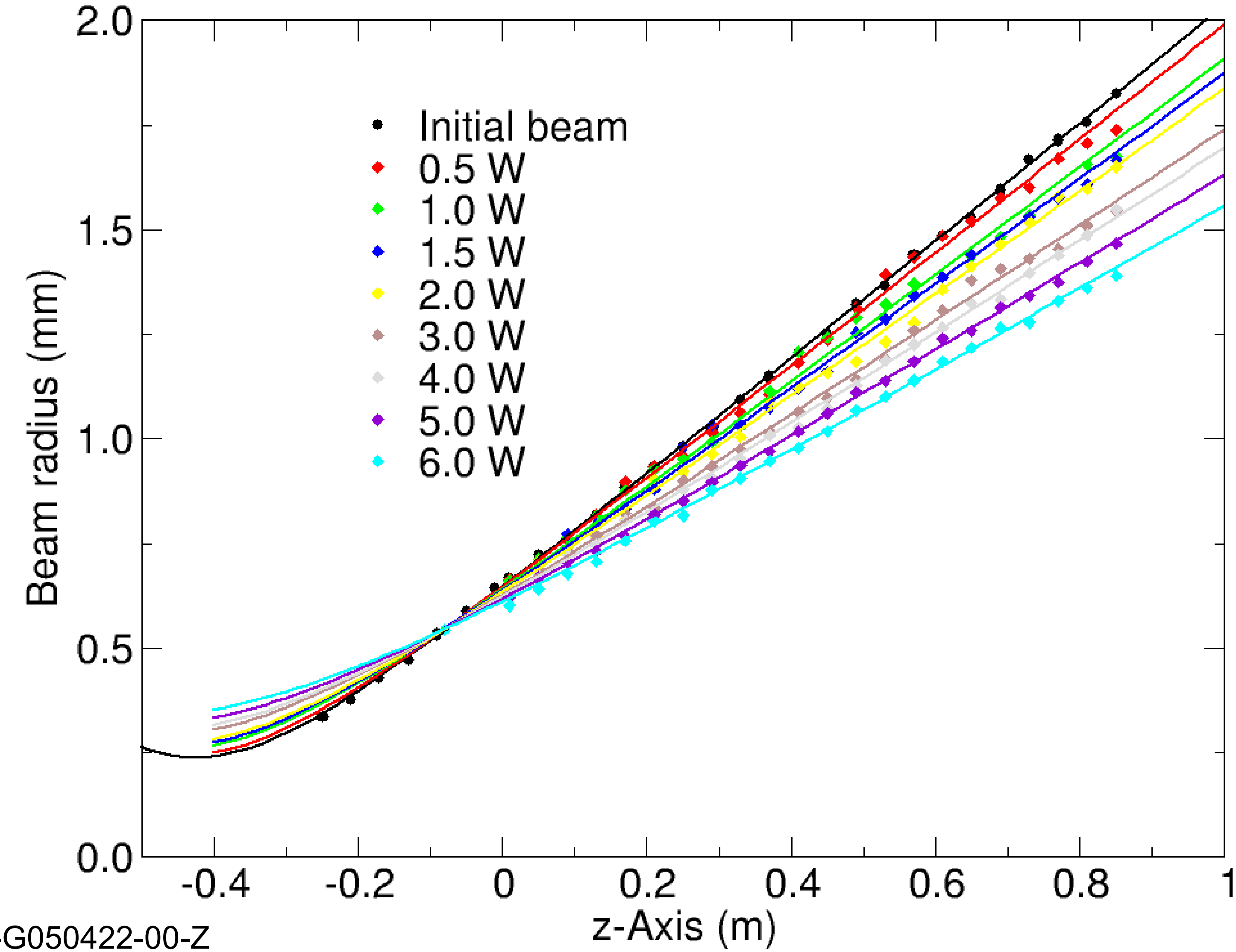
- Comparison with “ideal” thin lens (f = 1.88 m)



Measurement setup - beam analysis

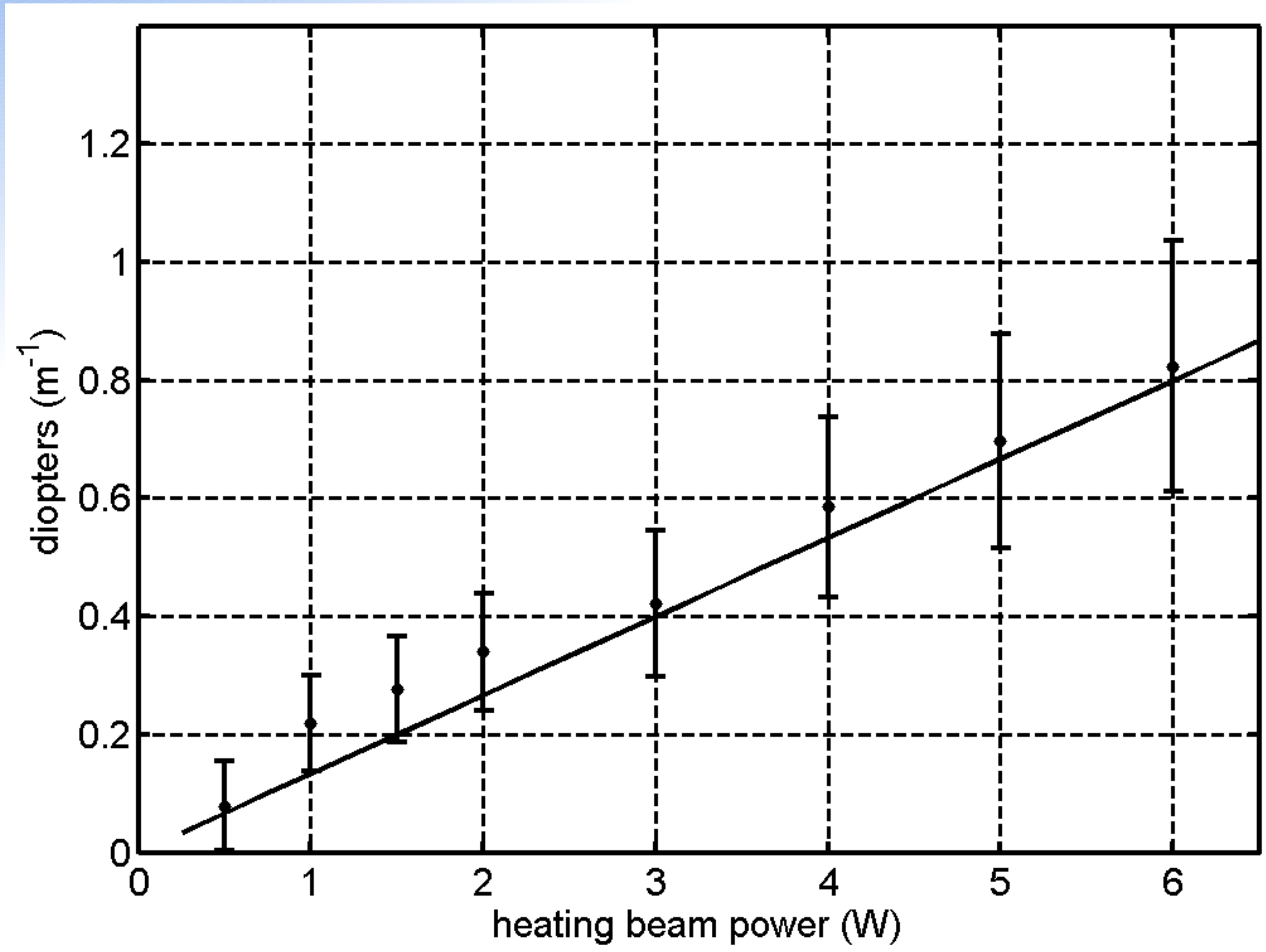


Changes in Gaussian Mode



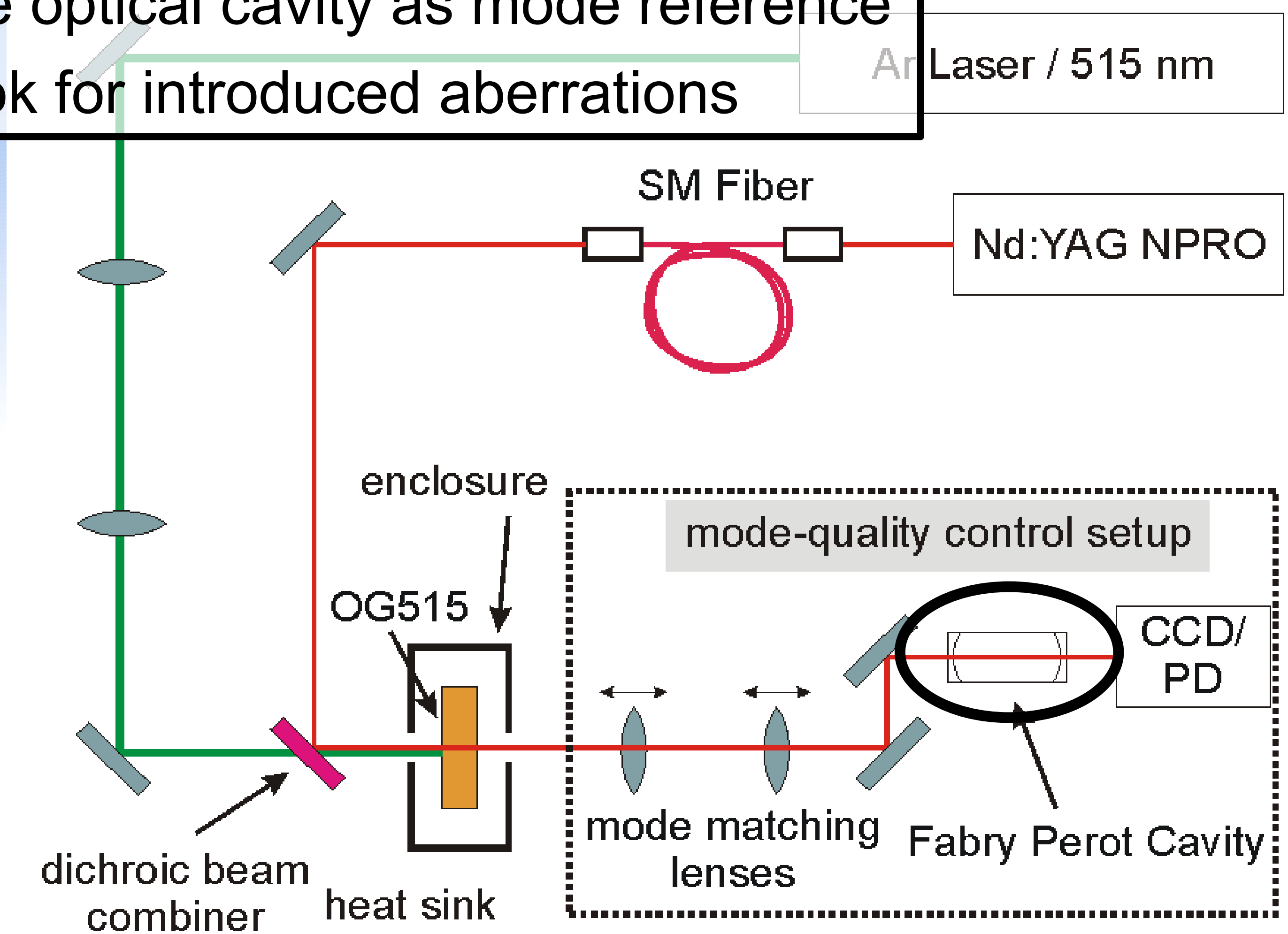
Corresponding focal power changes

- Focal power - diopters

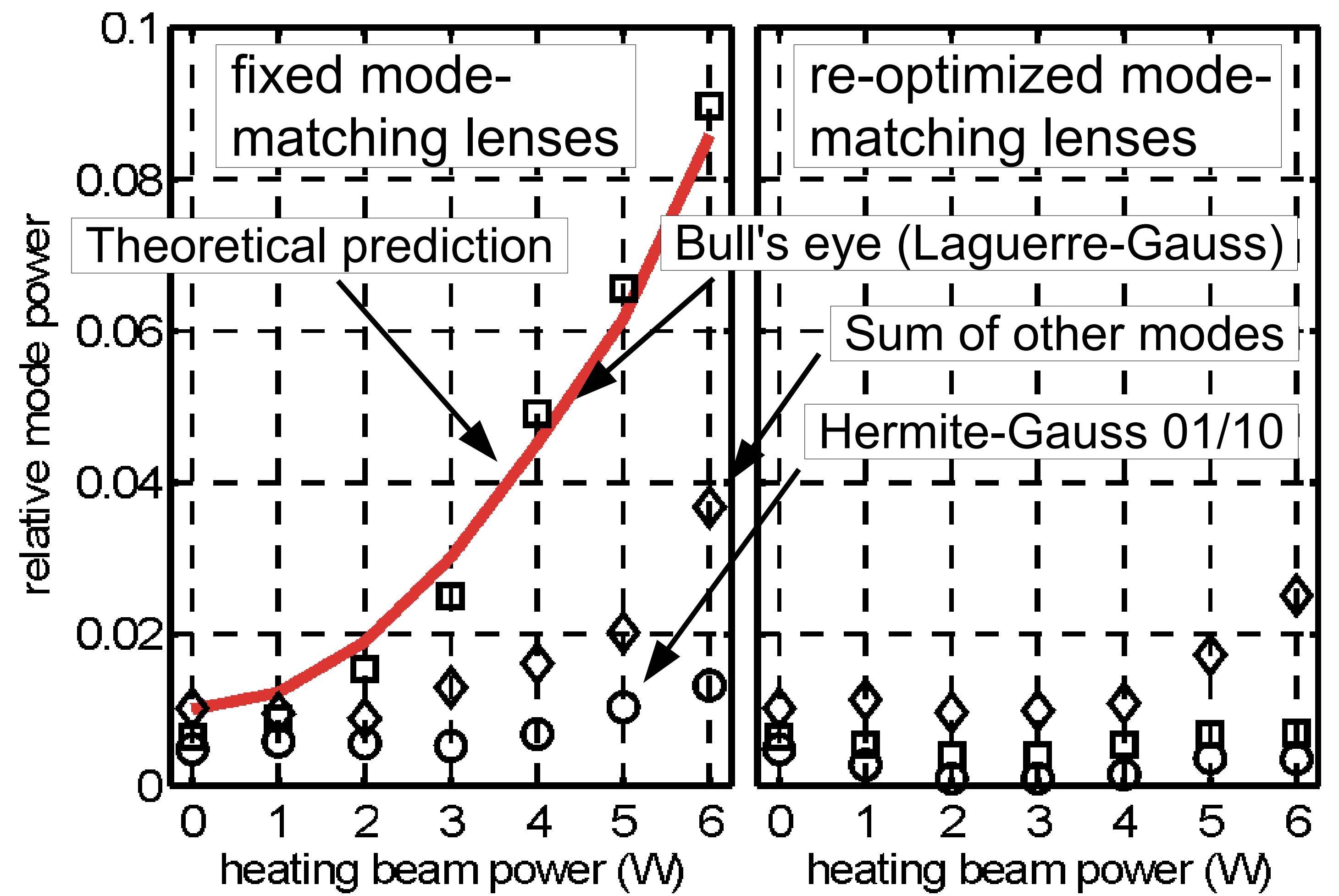


Measurement setup - mode quality

- Use optical cavity as mode reference
- Look for introduced aberrations



Higher order mode content (normalized to TEM_{00})



Conclusion

- Excellent agreement with theoretical model
- Technique is “touch free” and vacuum compatible
- An aberration free lens can be created if:
  – The amount of heat is kept below the structural limit
  – The ratio of heating beam to probe beam radii is sufficiently large

Future work

- Use different absorbing material
  - CO2 laser and fused silica
- Start beam shaping experiments