LIGO I simulation using FFT

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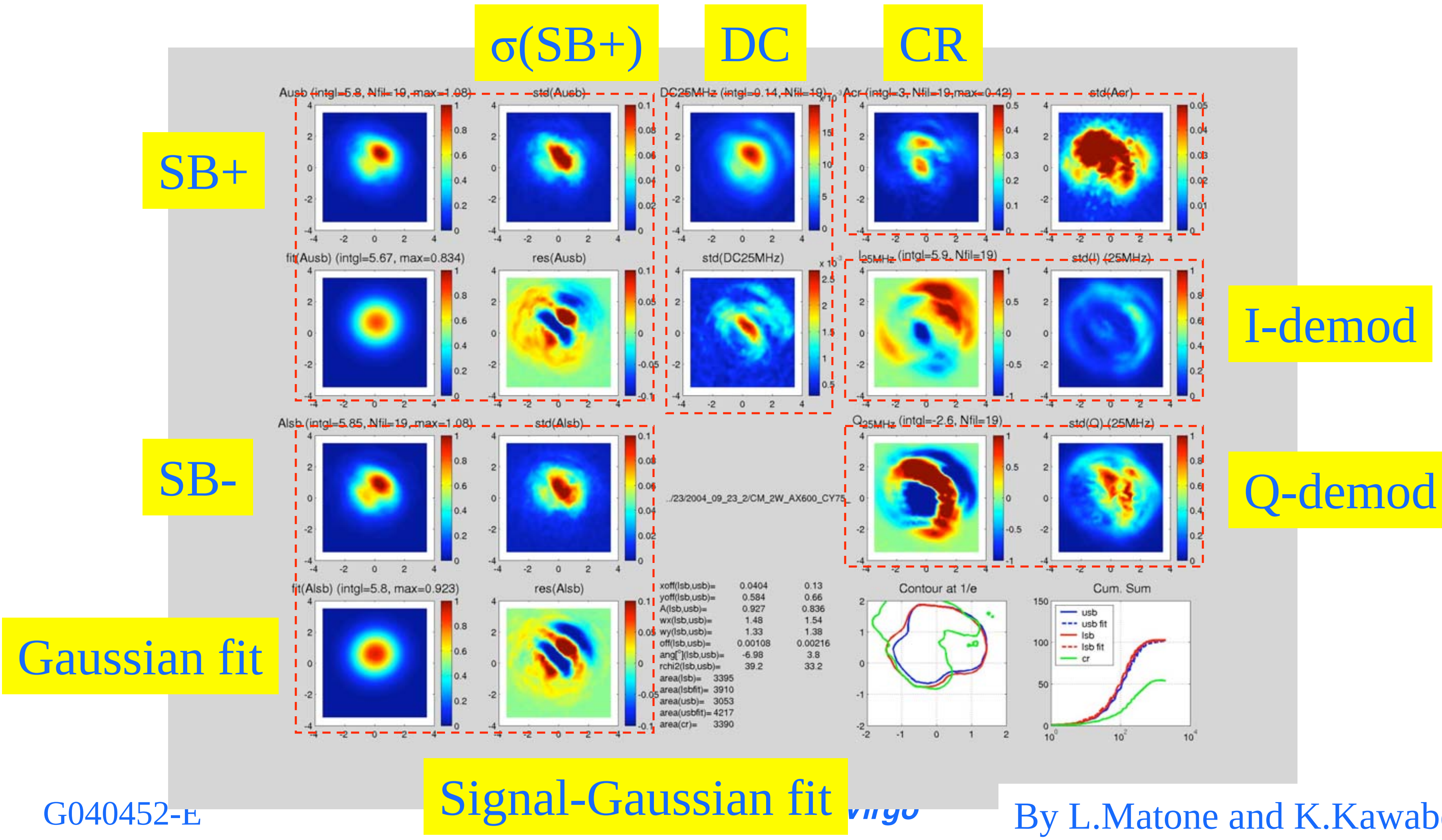
- A few news from LIGO I commissioning
  - thermal compensation system
  - phase camera
- LIGO I mirror phase map
- FFT tools
- Thermal lensing
- Beam splitter curvature
- Interpretation of results using modal model

G040452-E

Phase camera and thermal compensation system

- Phase camera
  - » E_{IFO} : Field from interferometer
    - – SB-, CR, SB+ with modulation frequency of 25MHz
  - » E_{laser} : Field from laser frequency shifted by 75MHz
  - » Demodulate $E_{IFO} + E_{laser}$ by 50, 75 and 100Mhz to measure SB+, CR and SB- separately
- Thermal compensation system (TCS)
  - » CO2 laser to heat ITMs
    - – Central heating : enhance NdYAG heating effect
    - – Annular heating : suppress NdYAG heating effect
  - » Somehow, differential heating, inline ITM cooler than offline ITM, preferred
  - » It seems SB imbalance is related

Phase camera image at dark port 2W Input, TCS : AX600-CY75



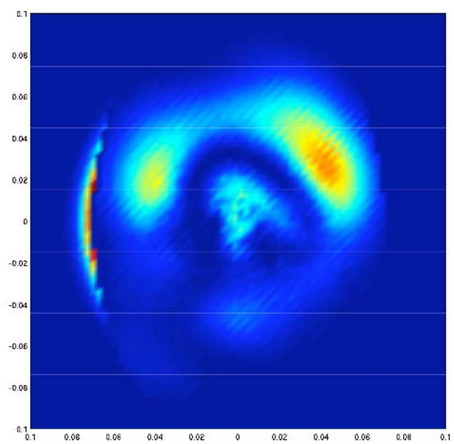
By L.Matone and K.Kawabe

FFT tools

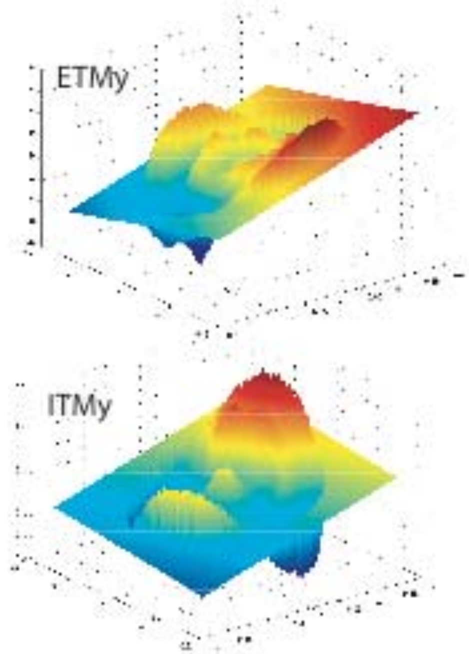
- Calculation of static fields in Core Optics system
  - » Orsay -> MIT
  - » Core optics phase map
  - » Thermal lensing effect
  - » Beam splitter curvature
- Propagation with magnification
  - » Virgo Physics Book, Volume 2 “OPTICS and related TOPICS”, 3.1.7
  - » FFT pixel size can be scaled - 25 cm mirrors to mm detector
  - » Fields can be propagated through telescopes to actual detectors
- FFT lock vs LSC lock
  - » FFT lock uses only CR, LSC lock uses CR and SBs
  - » Lock FFT by itself -> Lock using ASQ,REFL,POB
  - » Arm lengths change by 10^-12m, Michelson lengths by 10^-9m
  - » Quantitative results affected, most of qualitative results OK

Effect of mirror aberration

Dark port CR

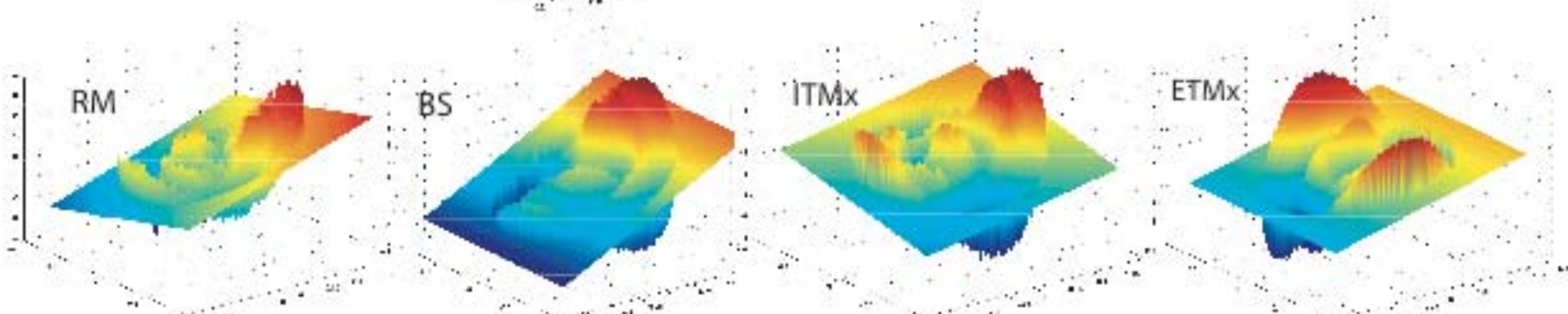


P(CR)=3.2kW -> 2.5kW



Contrast defect

Mode matched, identical arms	5.5e-7
+ as-built arms	6.8e-5
+ BS curvature	1.2e-4
+ Mirror phase maps	2.3e-4
+ Differential heating	2.5e-4



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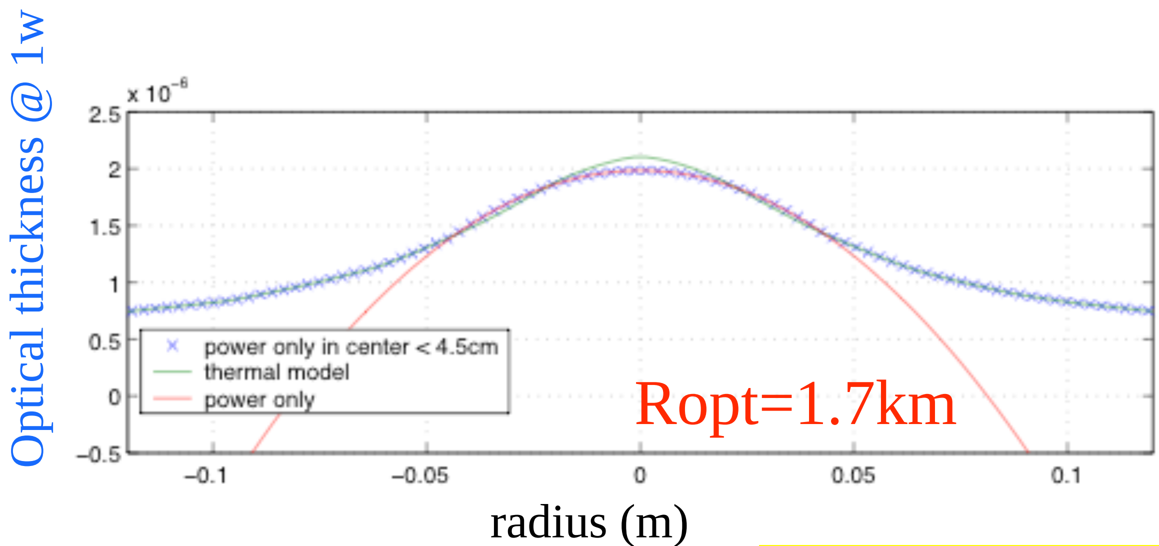
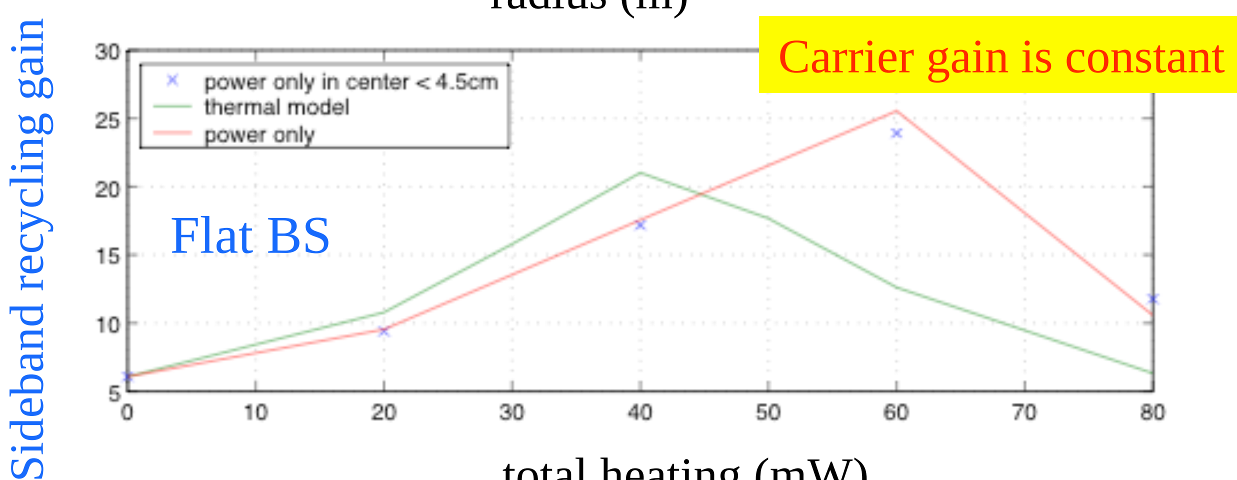
P(CR)=46W ->36 W

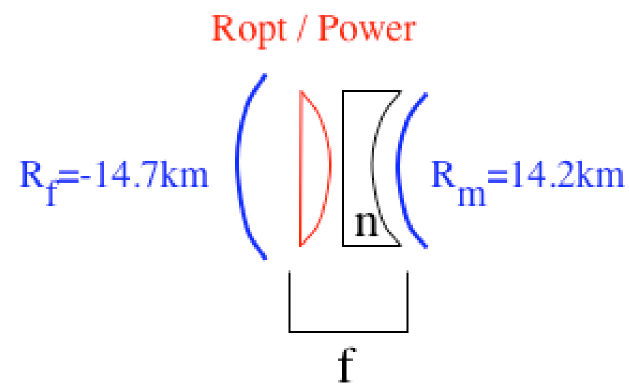
P(CR)=3.3kW -> 2.6kW

Thermal lensing in FFT

- P. Willems calculated based on MIT model -





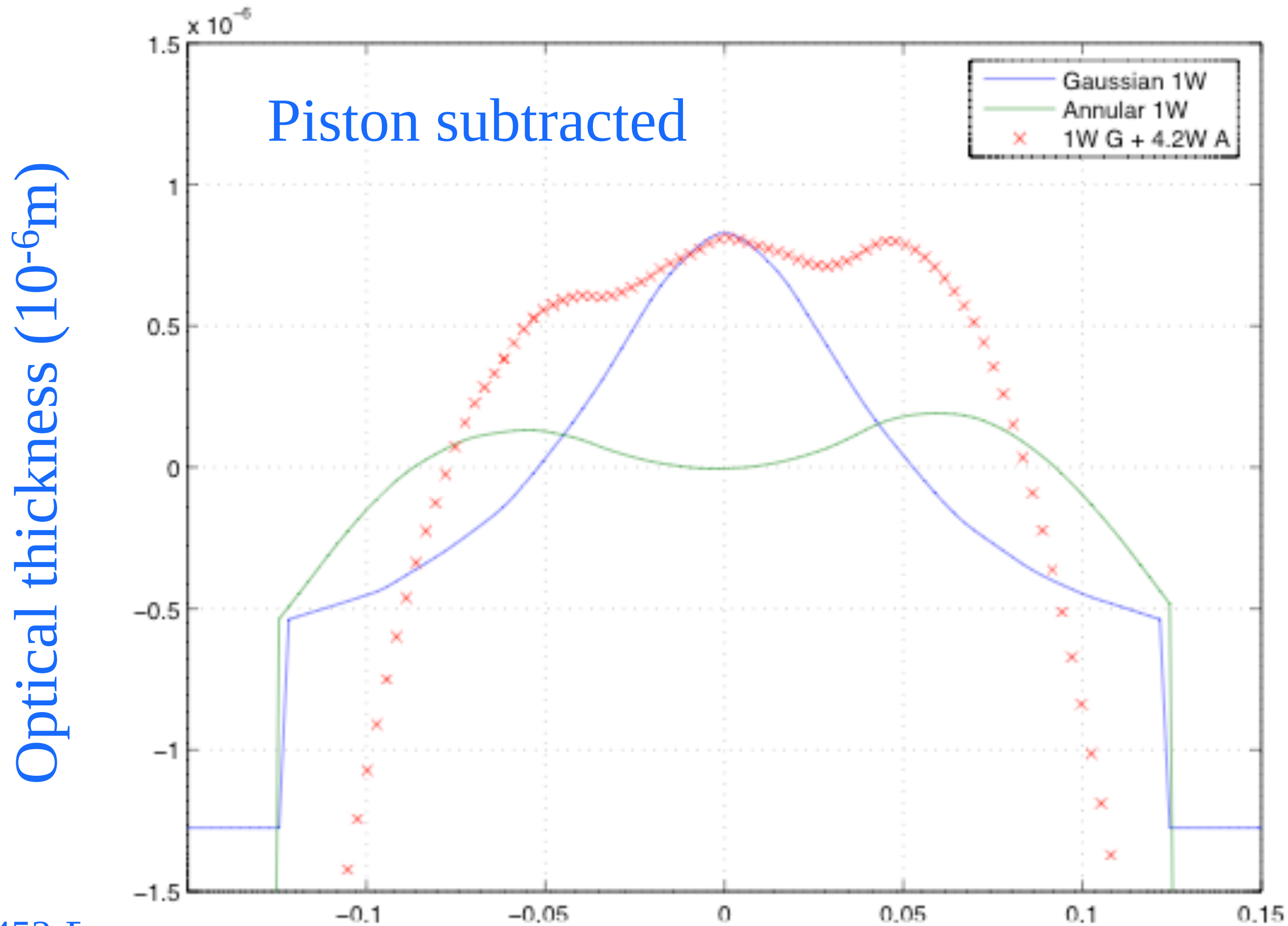


$$\frac{1}{f} = -\frac{n-1}{Rm} + \frac{1}{Ropt} Power$$

$$\frac{1}{R_f(HR)} = \frac{1}{R_f(AR)} - \frac{1}{f}$$

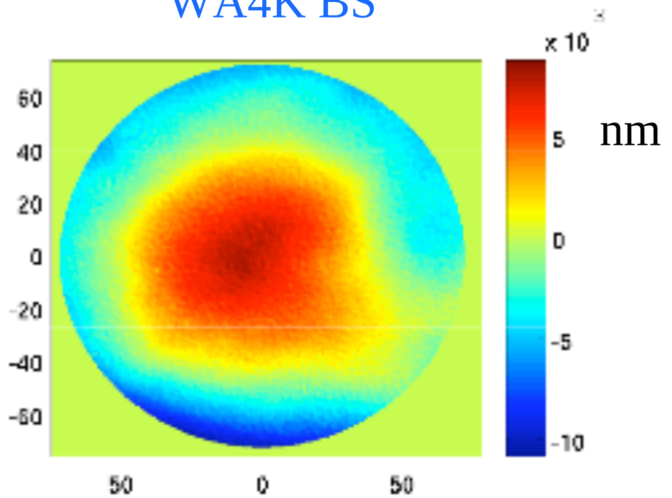
Power = 58mW

Gaussian and Annular

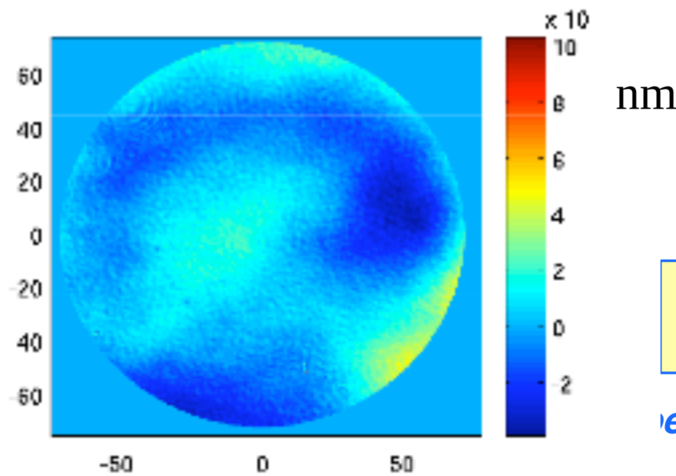


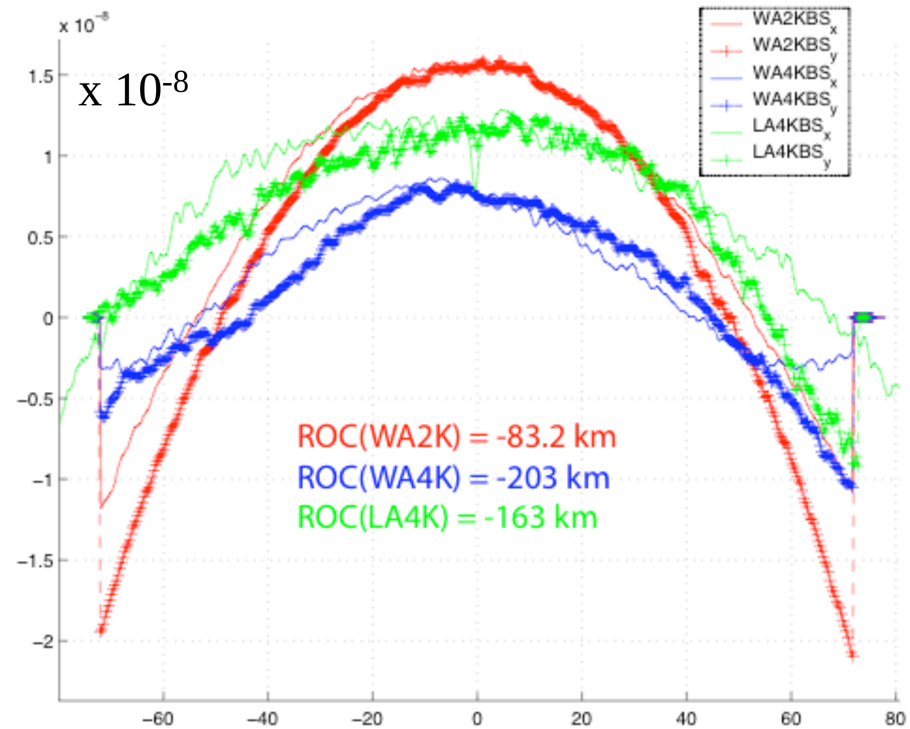
Beam splitter phase map

WA4K BS



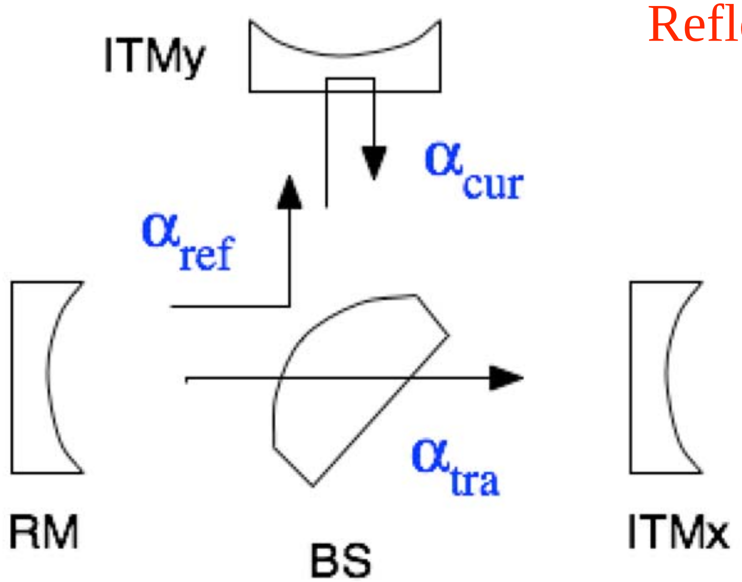
WA4K BS - curvature subtracted





concave ROC > 200km, convex ROC > 720km

Mode disturbance in PRM
- BS and ITM curvature and BS lens -



Reflection and transmission change field curvature

$$\alpha_{cur} = \frac{z}{z_0}\left(1 - \frac{R_f(z)}{R_{ITM}}\right) \quad : 0.23(cold) \sim 0(hot)$$

$$\alpha_{ref}(x/y) = -\frac{z^2 + z_0^2}{z_0 \cdot R_{BS}\sqrt{2}^{\pm 1}} \quad : 0.027$$

$$\alpha_{tra} = -\frac{n-1}{2}\alpha_{ref} \quad : -0.005$$

R_{BS} = -200km

R_{ITM} = -14km

z_0(Rayleigh range) = 3.6km

z(distance to waist) = -1km

$$TEM00(out) = \frac{1}{\sqrt{(1+i\alpha_x)(1+i\alpha_y)}} TEM00(in)$$

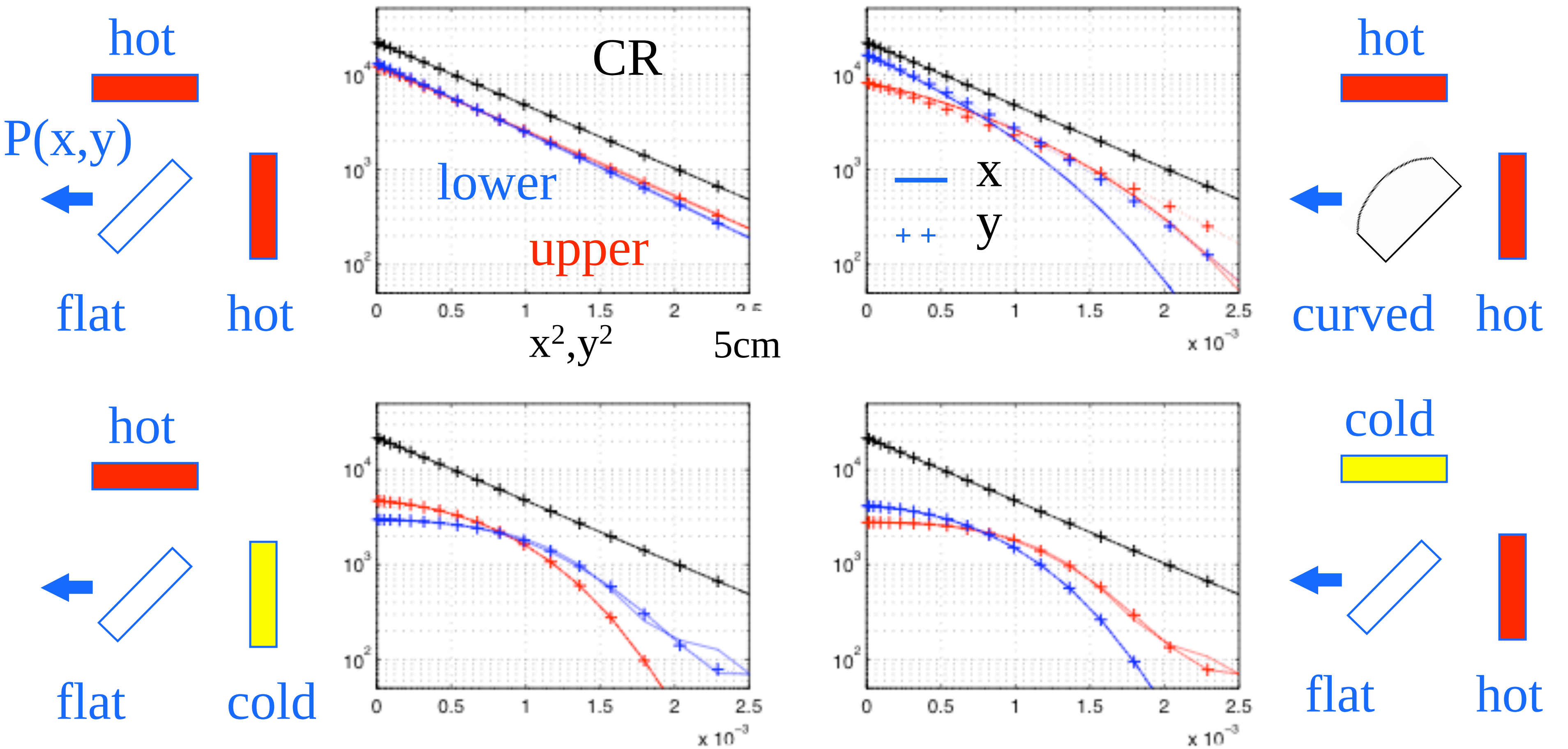
ITM differential heating and beam splitter curvature

Power only thermal

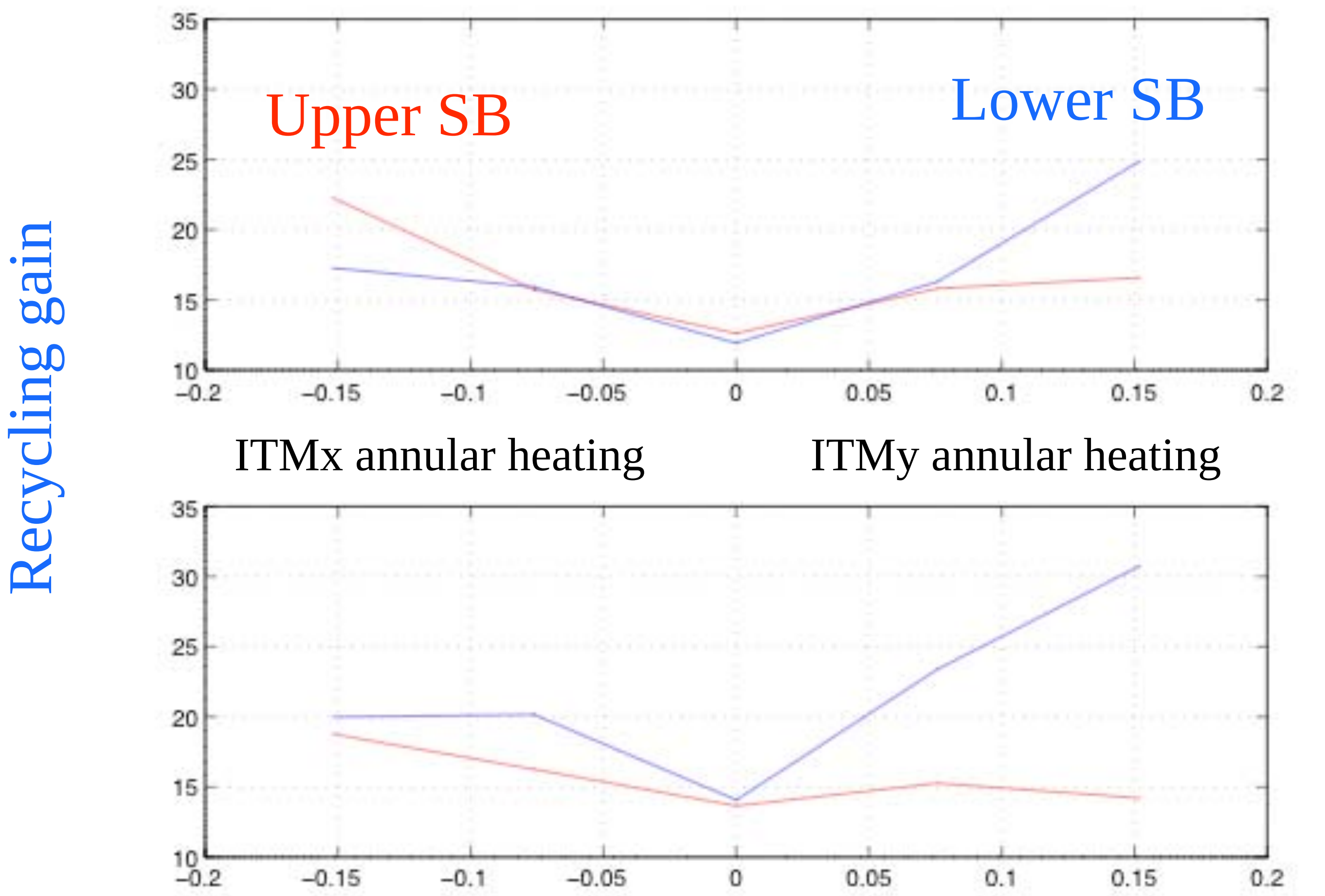
- Linear line : gaussian
- Blue vs red : sideband imbalance
- --- vs + + + : astigmatism

Power on Symmetric port

$P(x,0)$ vs x^2, $P(0,y)$ vs y^2



SB gain vs differential heating



-200 mW

200 mW

Flat BS

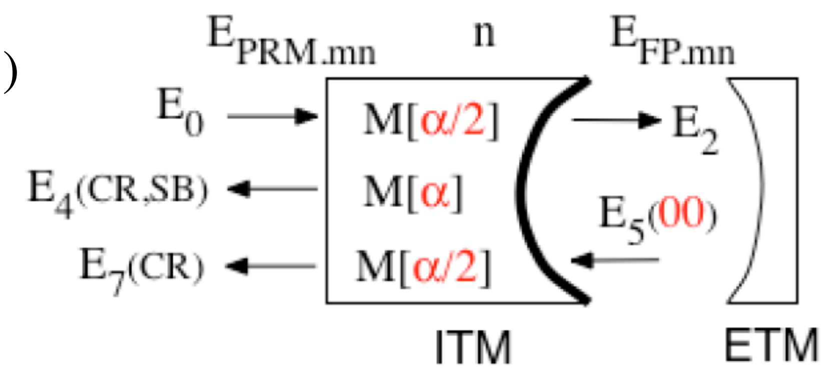
60mW
Gaussian
On both

200km BS

Reflection by a locked arm

- CR~00, SB~00+02/20 -

$$\alpha = \frac{z}{z_0}\left(1 - \frac{R_{Field}}{R_{ITM}}\right) \approx \frac{z}{z_0}\left(n_{substrate} - \frac{R_{ITM}}{R_{RM}} - \frac{R_{ITM}}{R_{thermal}}\right)$$



$$E_{SB} = \frac{1}{1+i\alpha}E_{00} - \frac{i\alpha/\sqrt{2}}{(1+i\alpha)^3}(E_{02}+E_{20}) + O(\alpha^2)$$

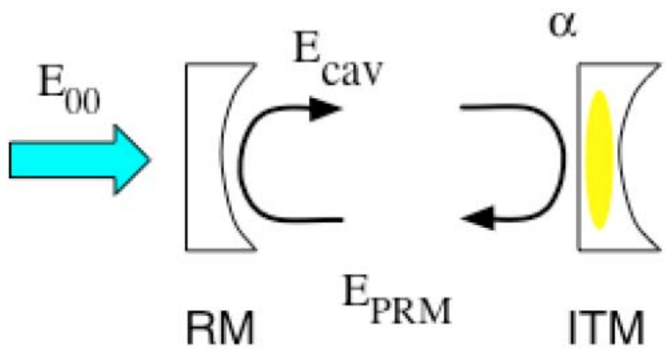
$$E_{CR} = \frac{1}{1+i\alpha}E_{00} - \frac{i\alpha/\sqrt{2}}{(1+i\alpha)^3}(E_{02}+E_{20}) + O(\alpha^2) \quad \Leftarrow E_4$$

$$-2\frac{1}{1+i\alpha/2}\left(\frac{1}{1+i\alpha/2}E_{00} - \frac{i\alpha/2/\sqrt{2}}{(1+i\alpha/2)^3}(E_{02}+E_{20}) + O(\alpha^2)\right) \quad \Leftarrow E_7$$

$$= -\frac{1}{1+i\alpha}E_{00} + O(\alpha^2)$$

Fields in mode mismatched FP

$$E_{cav} = \frac{t_{RM} \cdot E_{in}}{(1-R)(1+C_0 \cdot \alpha^2)}(E_{PRM,00} - i \cdot \alpha \cdot C_2 \cdot (E_{PRM,02} + E_{PRM,20})) + O(\alpha^3)$$



$$R = R_0 \cdot Exp[i\phi_{CR,00} + i\phi],\ R_0 = r_{RM} \cdot r_{ITM}$$

$$\phi_{CR,00} = -2k_{CR}L + 2\eta - \arctan(\alpha)$$

$$\phi_{mix} = -\frac{1}{2}\cot(2\eta) \cdot \alpha^2$$

$$\phi = -2k_{SB}L + \phi_{mix}$$

$$C_0 = \frac{(1 - i \cdot \cot(2\eta)) \cdot R}{2(1 - Exp(i4\eta)R)}$$

$$C_2 = \frac{Exp(i \cdot 2\eta)}{\sqrt{2}(1 - Exp(i \cdot 4\eta)R)}$$

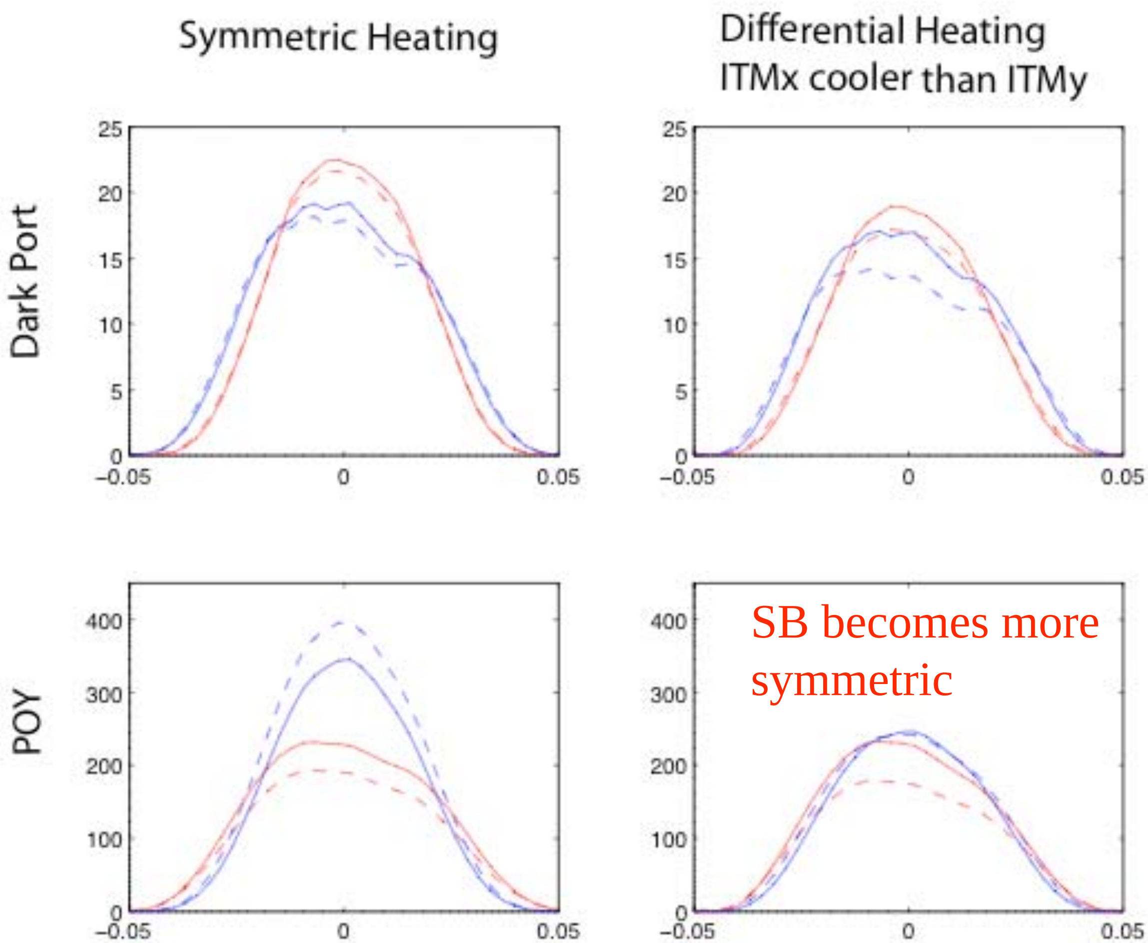
$$SBPower(k_{SB}) = F(k_{SB}L + f_1(\eta) + f_2(\alpha))$$

$$SBPower(k_{SB}) \neq SBPower(-k_{SB})$$

FFT vs LSC lock

n(ITMx)-n(ITMy)

0.96-0.96 1.10-0.96



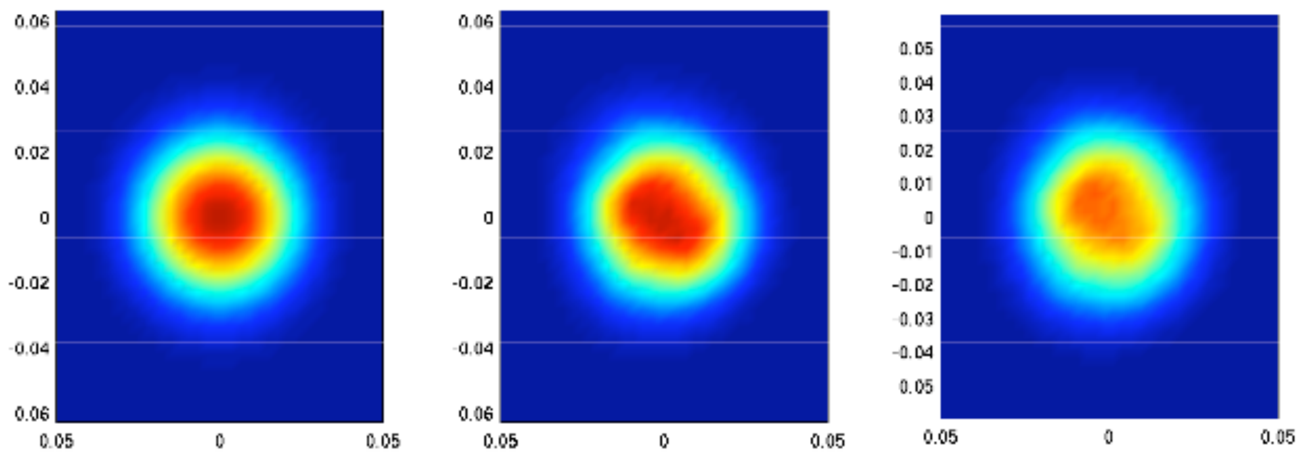
lower SB upper SB

FFT lock LSC lock

		FFT	LSC
symmetric	θCR	0.3	-1.9
	θSB+	-0.6	-2.3
	θSB-	7.2	5.1
	Spob	-0.57i	-0.57i
differential	θCR	0.2	-8
	θSB+	4.9	-1.2
	θSB-	11.8	5.1
	Spob	-0.48i	-0.50i

Dark Port sideband profile by FFT
- after LSC lock -

upper SB



200k BS curvature

No phase map
Symmetric heating

With phase map
Symmetric heating

With phase map
Differential heating

lower SB