Virgo Phase Camera

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Why a phase camera?

Advanced Virgo has a marginally stable Power Recycling Cavity

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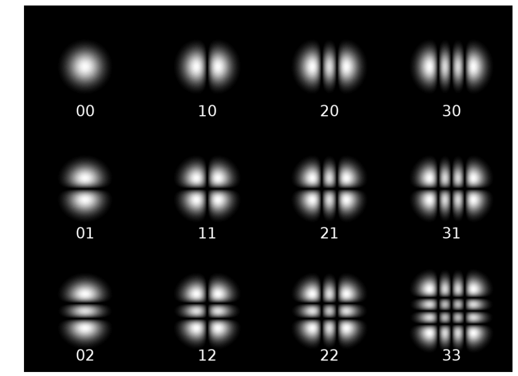
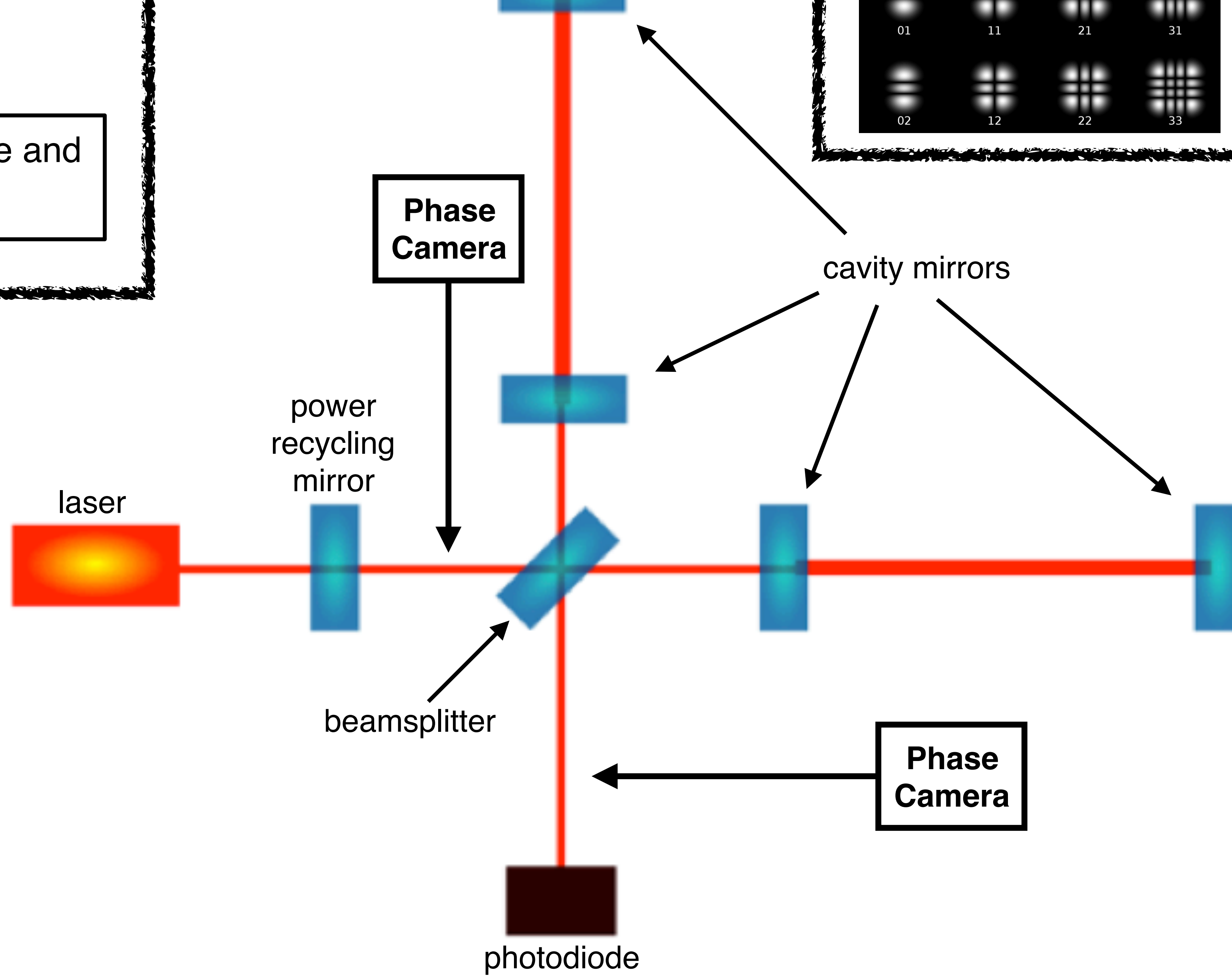
Higher Order Modes (HOM) can resonate and complicate the cavity control

Hermite-Gaussian modes





Phase cameras provide phase and amplitude images

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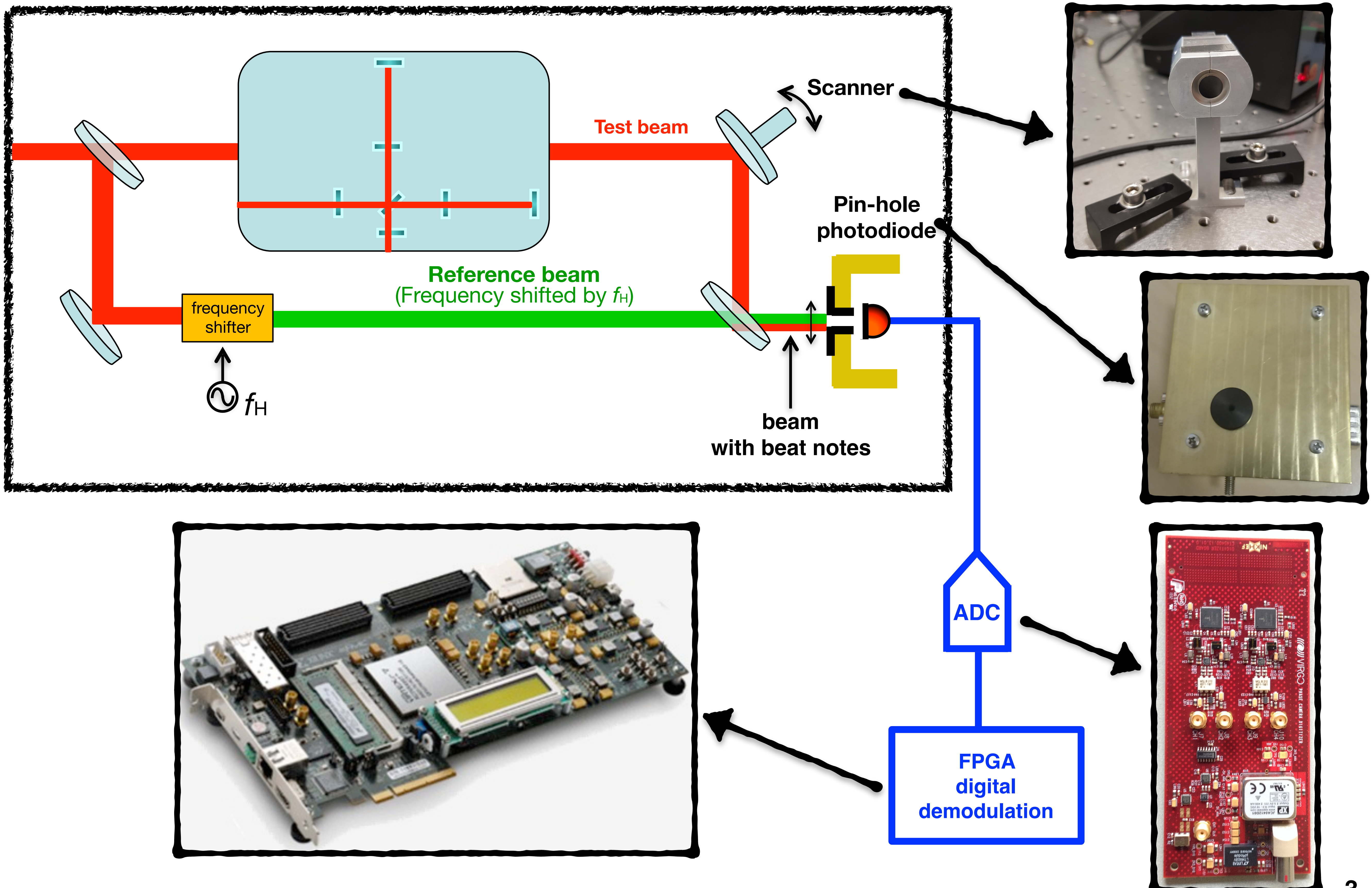
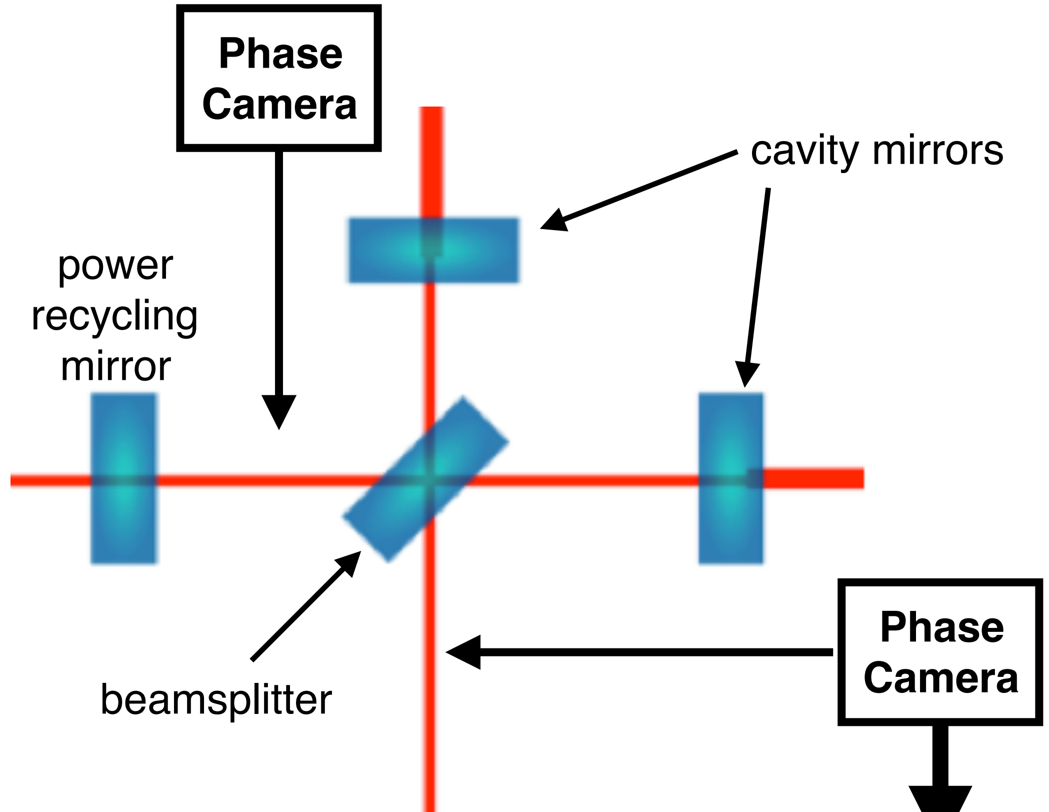
aid commissioning

provide input to correct thermal effect

The principle behind Phase Camera



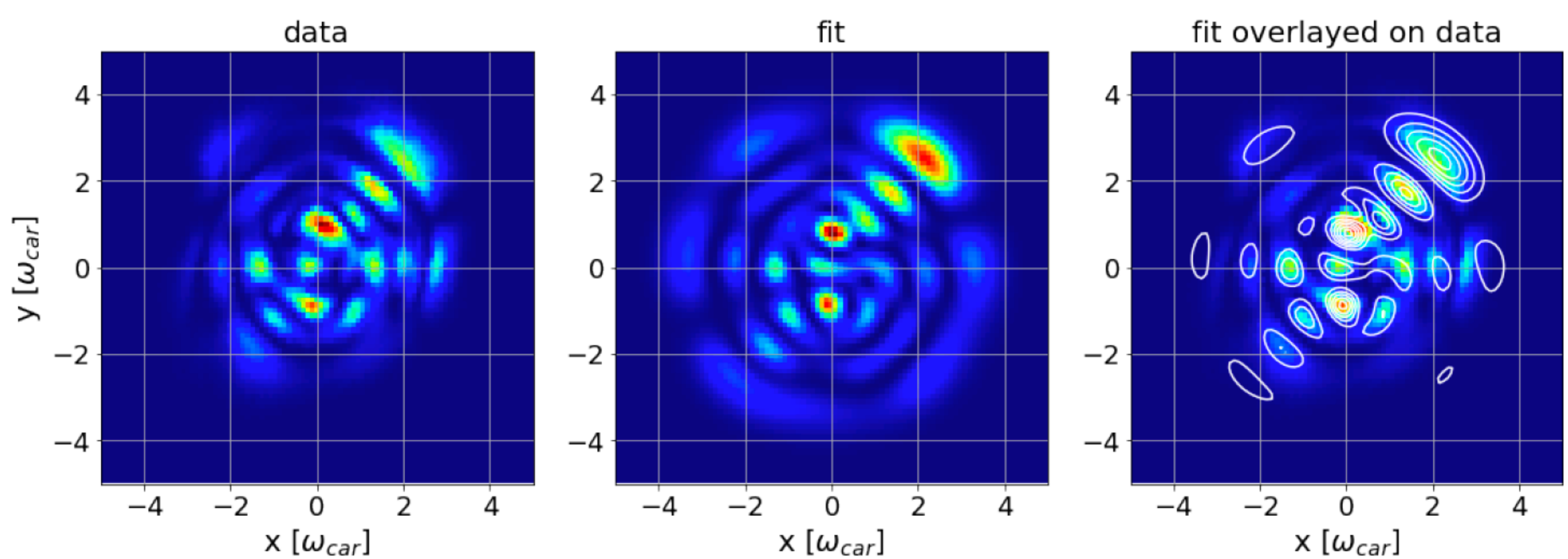
HOMs and thermal effects



The input power to the interferometer is increased from about 18 W to about 26 W (and will be further increased).

This makes mirrors thermally expand and changes the mode matching.

Thermal effects are a source of HOMs.

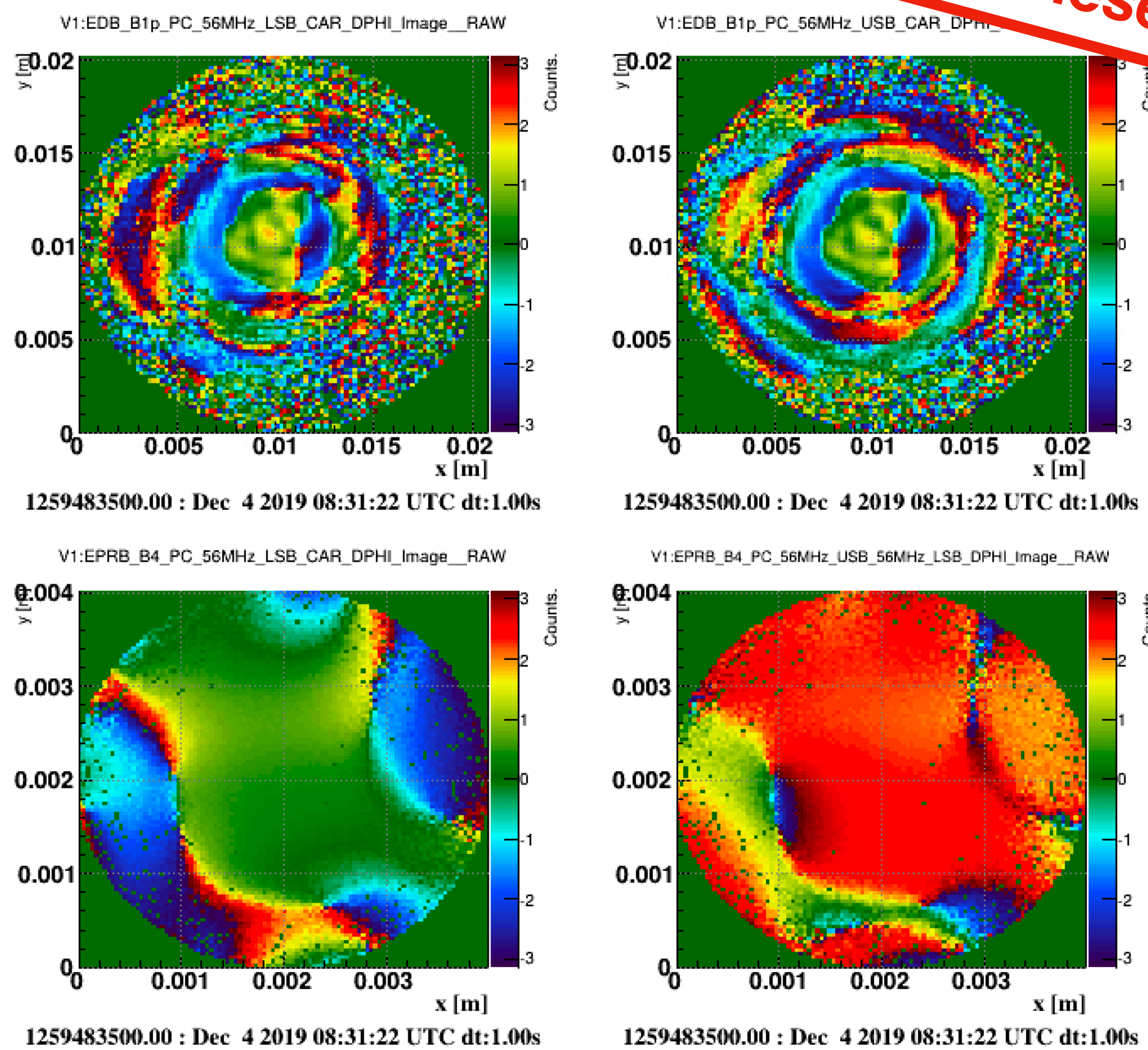


Outlook

- Understand the data:
  - ➡ what do the phase images represent?
- Use the data:
  - ➡ provide feedback to correct the thermal effects
- Producing 3 phase cameras for LIGO

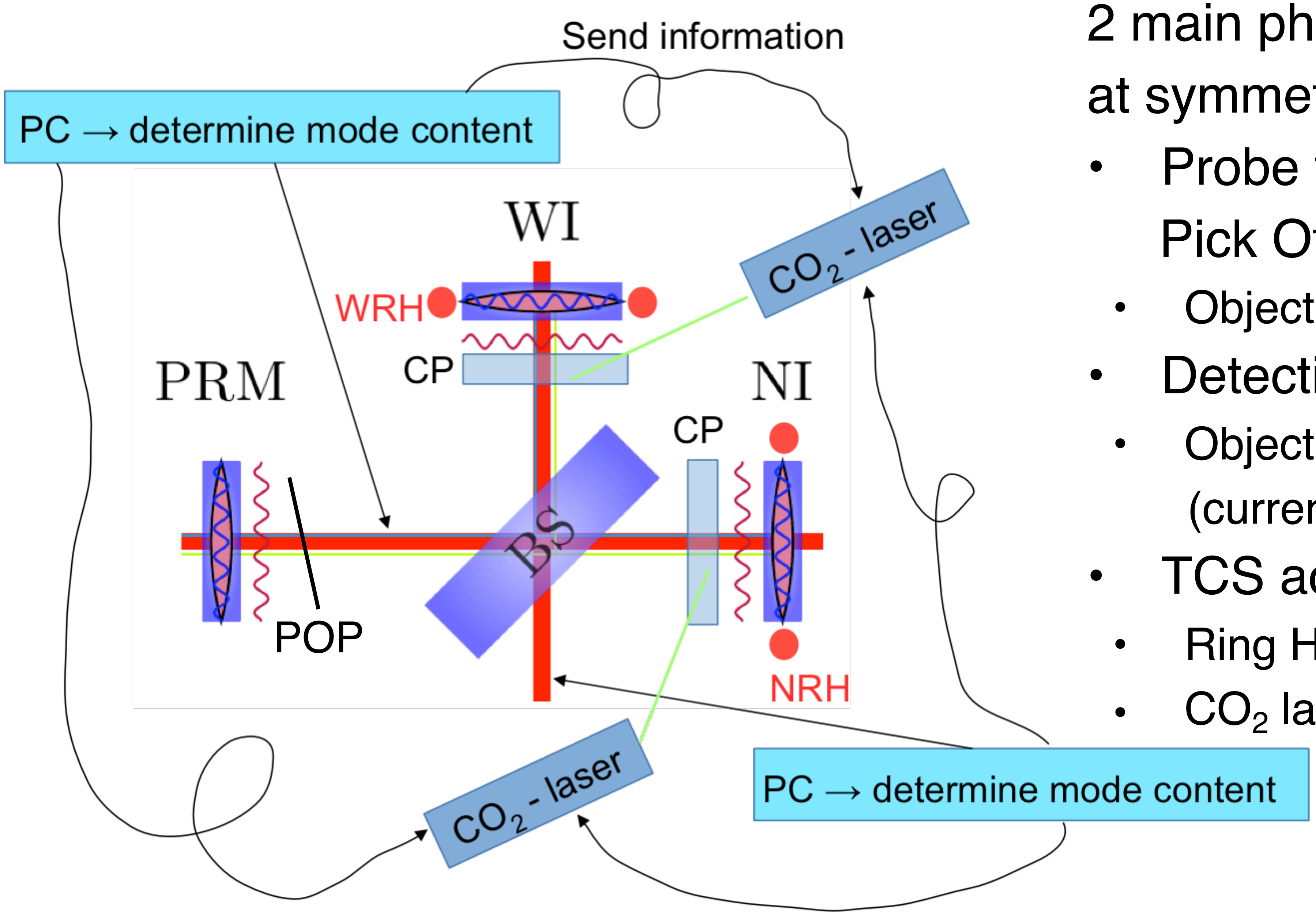
  (in collaboration with the University of Birmingham)

What are these?



Backup slides

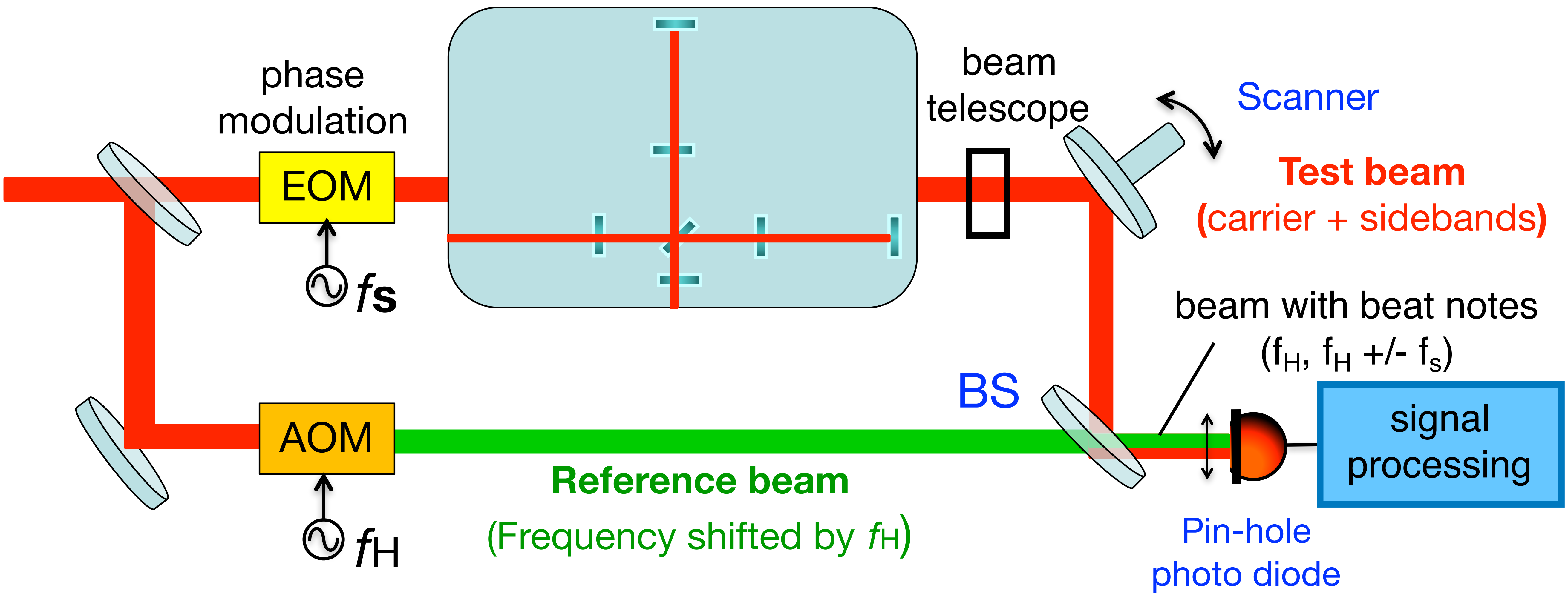
Phase Camera and Thermal Compensation



2 main phase cameras,
at symmetric and asymmetric port

- Probe field in Power Recycling via Pick Off Plate (POP)
  - Object plane is POP
- Detection Beam (B1p) before OMC
  - Object plane is Signal Recycling Mirror (currently only a lens)
- TCS actuators:
  - Ring Heaters (RH)
  - CO_2 laser on Compensation Plate

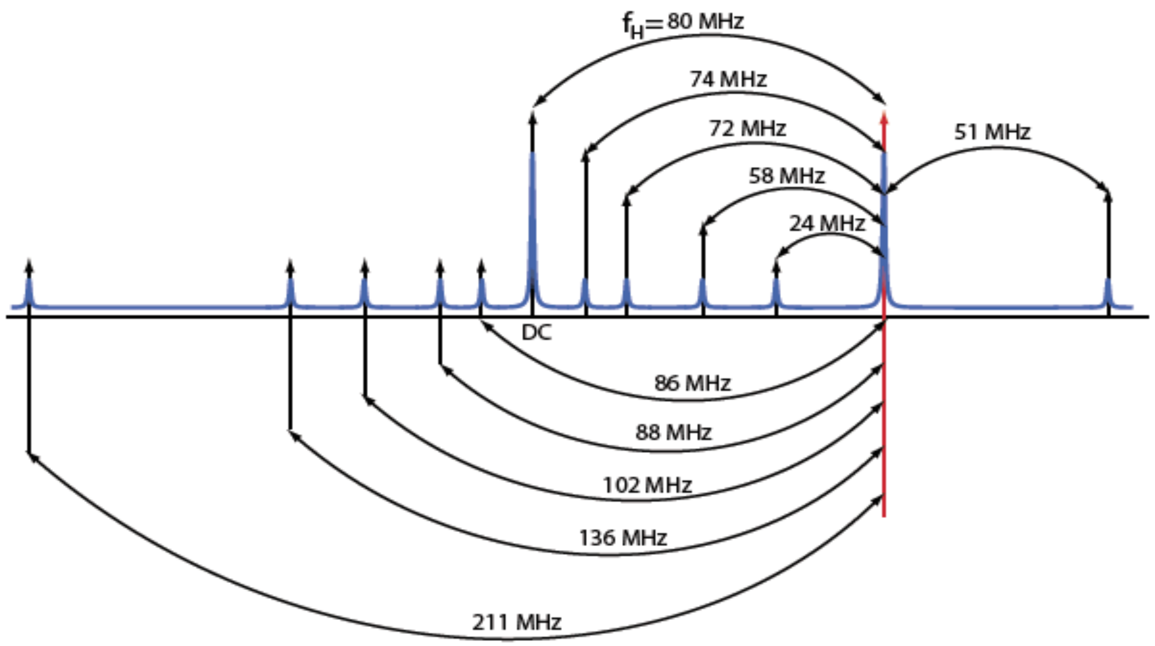
Basic principle scanning Phase



- Upper and lower sidebands (USB/LSB) are at (slightly) different optical frequencies
- Access each sideband separately by mixing it with a 80 MHz frequency shifted beam
- Beat signal with f_H, and f_H +/- f_s

Phase Camera initial requirements

- Images with > 100 x 100 points, covering 5 x beam size
  - we use 128 x 128 measurement points
- Image LSB and USB separately, i,e. use heterodyne
  - 11 demodulation frequencies (including 80 MHz heterodyne)
  - highest demodulation freq. is 131 + 80 = 211 MHz
  - simultaneous acquisition to allow common 'noise' subtraction
- Sensitivity for deformations better than 2 nm: phase resolution ~ λ / 500
  - within 1 beam diameter
- Image frequency at least 1 Hz (higher image rate if possible)

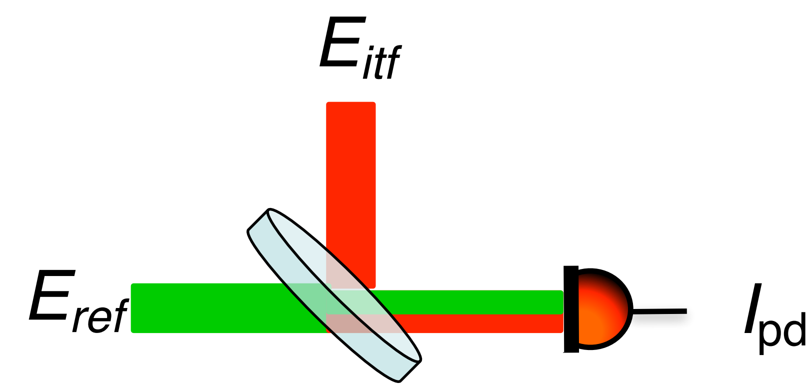


- (Least possible electronics near the optical bench)
- (Beam powers not well defined at design time)

Heterodyne detection

$$E_{itf}(x) = A(x)e^{i(\omega_c+\omega_s)+i\phi_s(x)}$$

$$E_{ref} = Be^{i(\omega_c+\omega_h)+i\phi_h}$$

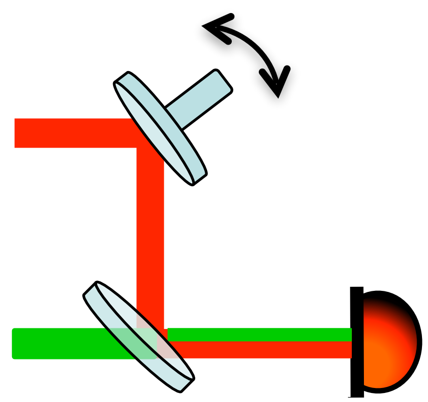


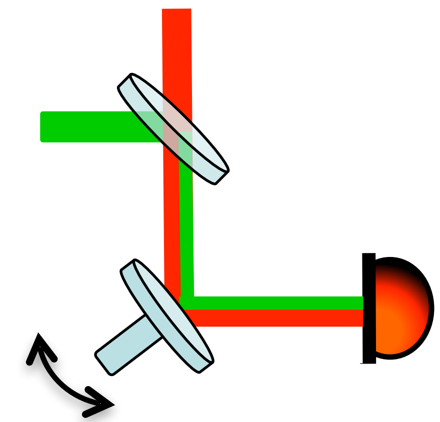
At beam splitter: $E_{sum}(x) = \frac{E_{itf}(x)}{\sqrt{2}} + \frac{iE_{ref}}{\sqrt{2}}$

$$I_{pd}(x) = E_{sum}(x)E_{sum}^{*}(x) = \underbrace{\left|A^2(x)\right| + \left|B^2\right|}_{\text{DC}} + 2\underbrace{\left|A(x)\right|\left|B\right|}_{\text{Amplitude}}\cos((\omega_h +/- \omega_s)t + \underbrace{\phi_h + \phi_s(x)}_{\text{phase}})$$

- Measured E-field of ITF field (A(x)) scales with amplitude of reference beam (B)
- More power in the reference beam helps to overcome electronics noise; ultimately SNR is limited by shot noise

Intermezzo: 1 beam versus 2 beam



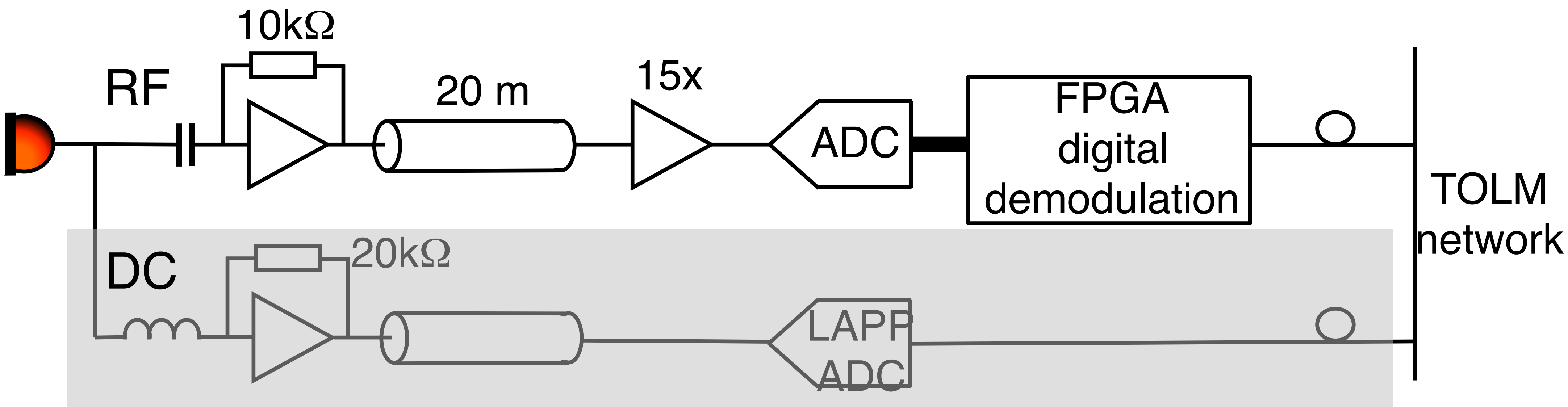


- More ref. beam power, hence higher SNR
- Correction needed for geometrical effects due to different beam angles
- but not for phase differences: sideband-carrier, LSB-USB

Current configuration in AdV

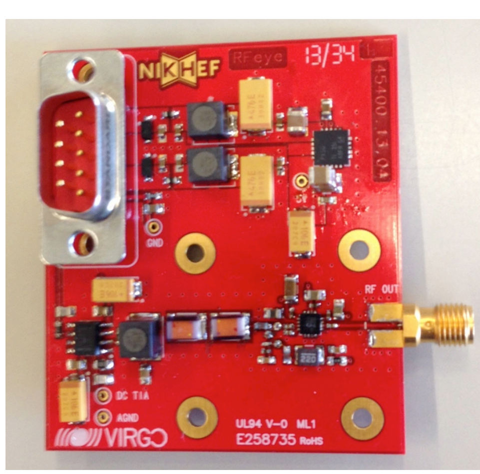
- Lower ref. beam power, lower SNR
- No correction for geometrical effects
- Calibration of ref. beam wavefront

Electronics chain

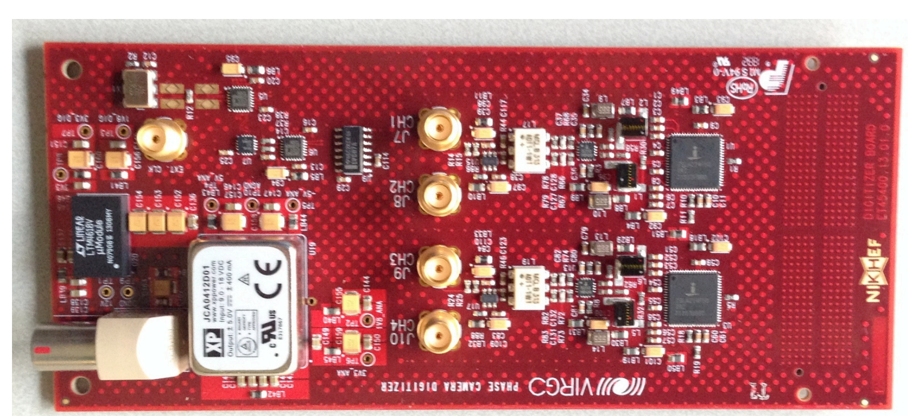


InGaAs diode
50 μm diameter

700 MHz BW
dynamic range 1 Vpp
e_{n_out} = 46 nV/rt(Hz)



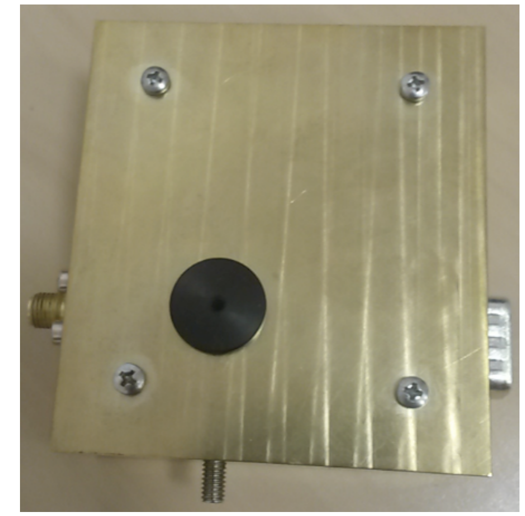
14 bit
500 MS/s
4 channels

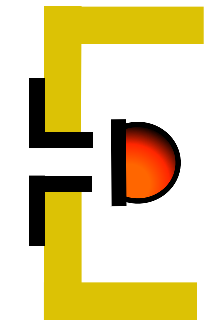


Xilinx VC707 board
Virtex7 FPGA

PhotoReceiver

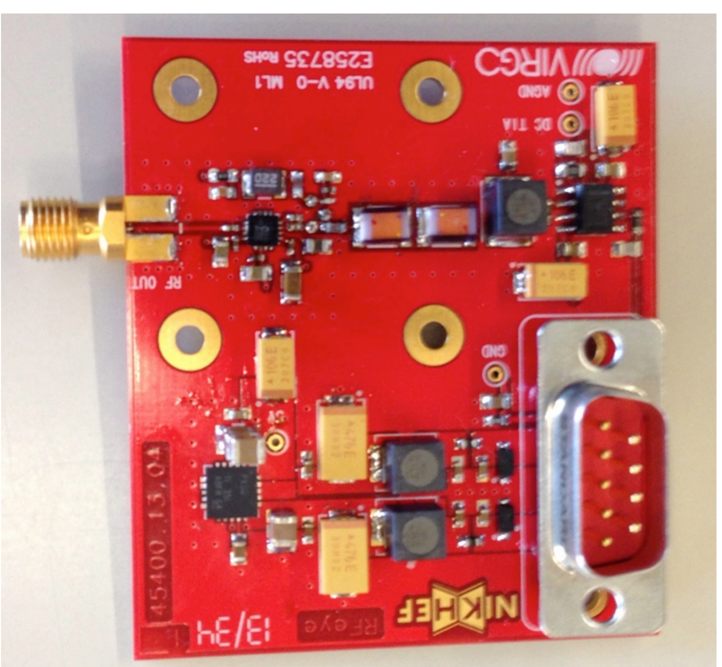
- High transimpedance (10 kΩ)
- Dominant electronics noise source
- Small aperture, hence relatively little light
  - only shot noise limited at beam center

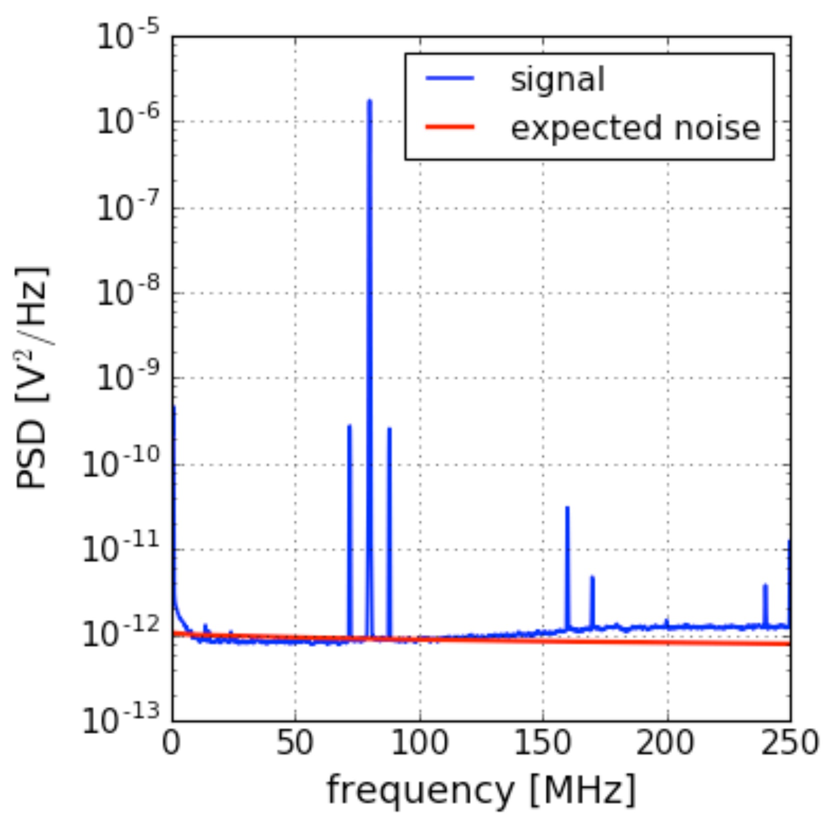




PD Diaphragm:

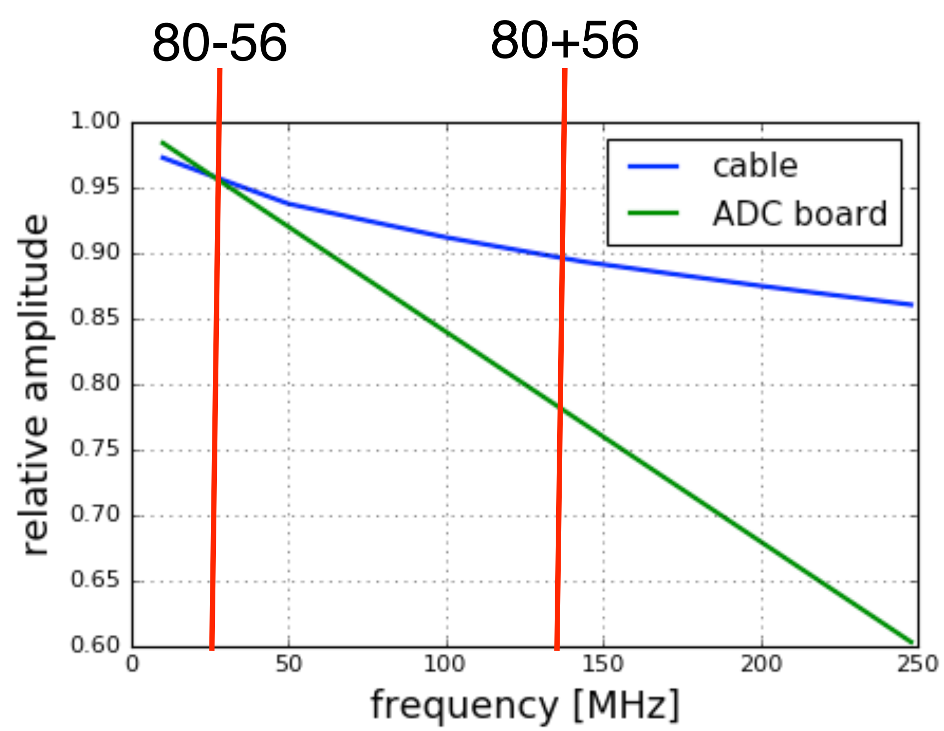
- 1st version plastic
  - OK scattering wise, but cannot handle high power flashes
- 2nd version: black anodised Alu.
  - not OK scattering wise
- 3rd version Vantablack coated
  - results look promising
  - diaphragms hard to handle because coating is very fragile



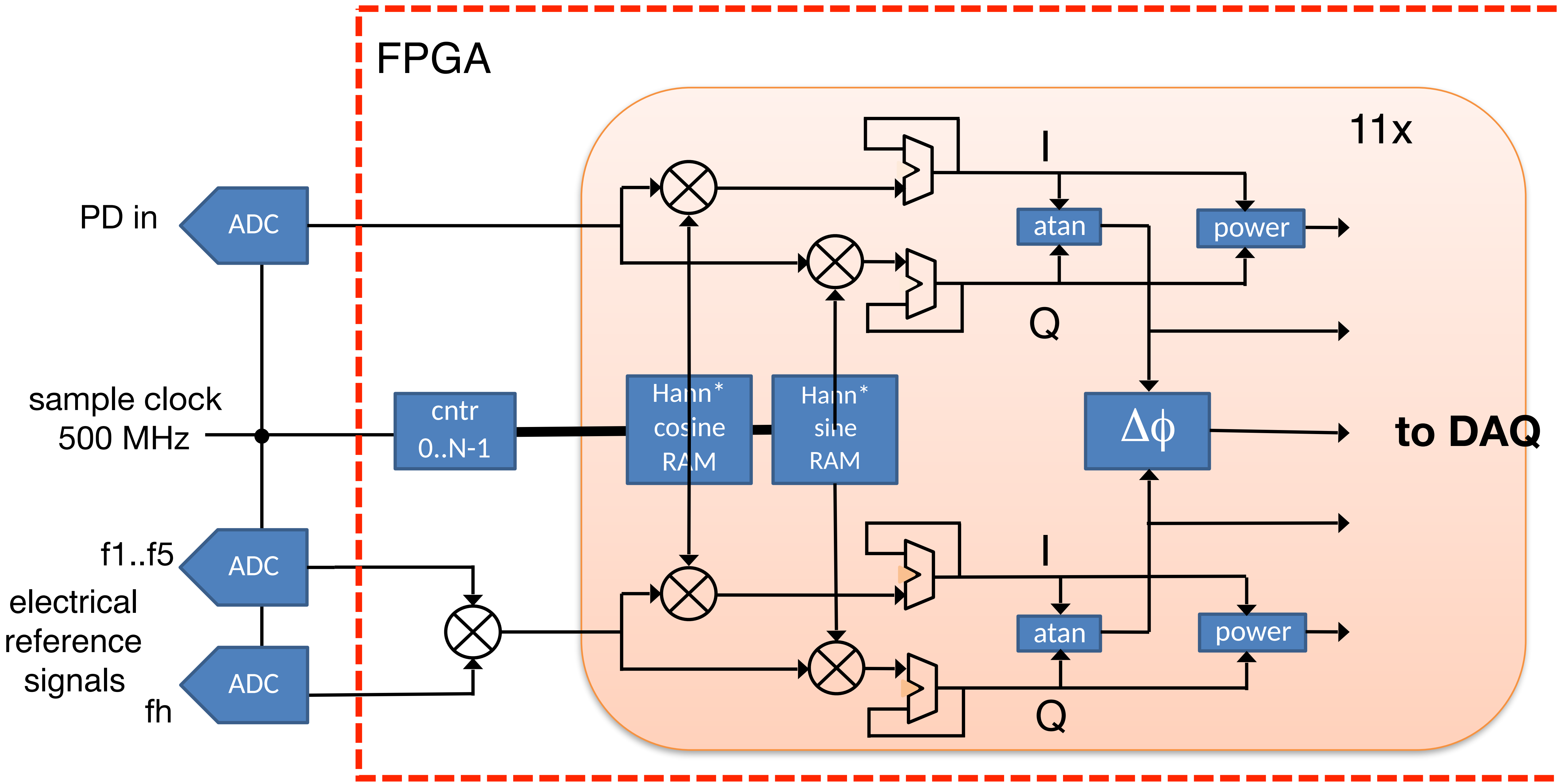


Frequency response correction

- Calibration of frequency response needed for sideband (un)balance measurement
- Upper and lower sidebands are far apart, e.g. 56 MHz SB, distance is 112 MHz
- Frequency response of amplifiers is not flat
- But also attenuation in 20 m long (high quality) cable is not negligible
- Dependence can be calibrated, using dedicated measurements



Digital demodulation



Signal processing

- For each image point we calculate the I and Q:

$$I = \sum_{i=0}^{N} PD(i) * Hann(i) * Cos(2\pi i f_{sb} / f_s)$$

$$Q = \sum_{i=0}^{N} PD(i) * Hann(i) * Sin(2\pi i f_{sb} / f_s)$$

$$\varphi = \tan^{-1}(Q / I)$$

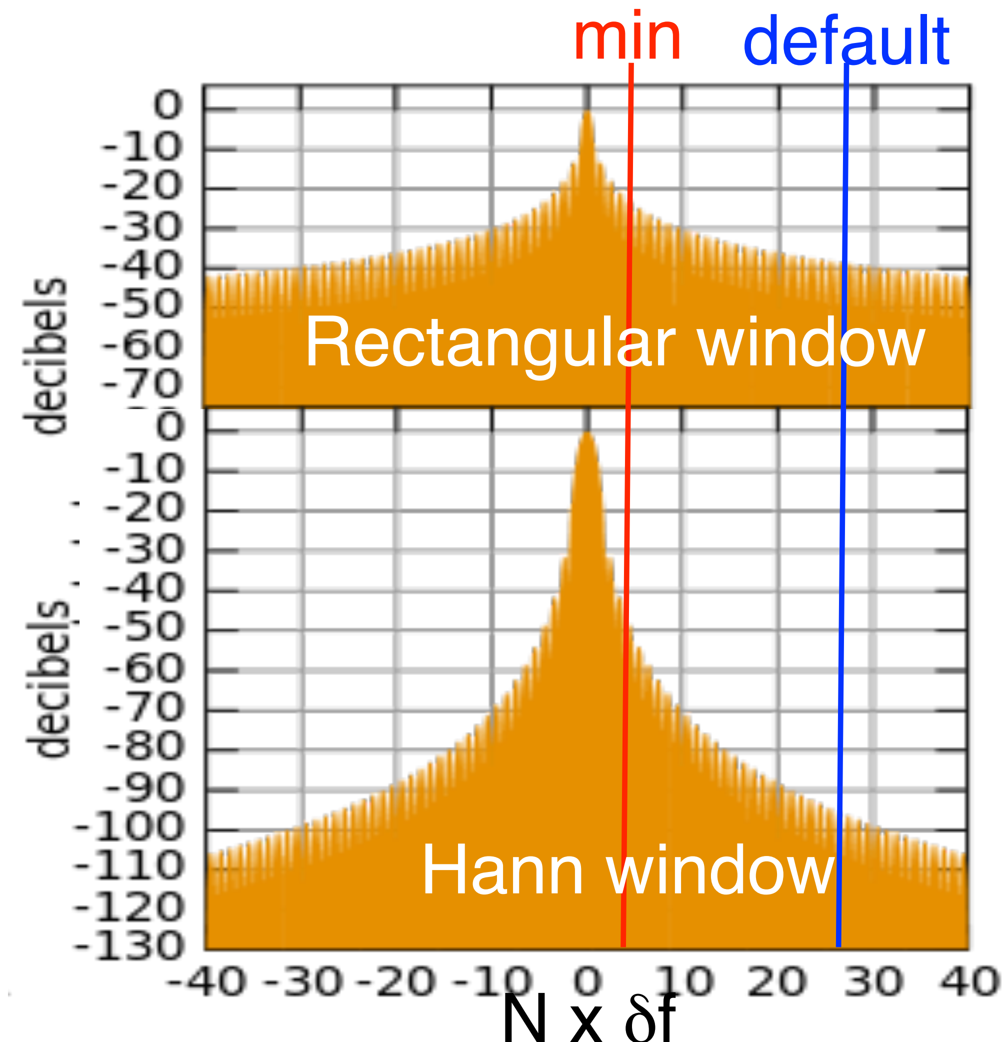
$$A = \sqrt{Q^2 + I^2}$$

- Sum acts as filter (FIR with N equal coefficients)
- Electrical reference frequencies (sideband and heterodyne) sampled with same clock as PD signal
- We measure the phase difference of PD signal w.r.t. the electrical reference
- Demodulation frequencies are stored in tables (RAM)
- Window function, currently Hann, stored in same table, hence easily adaptable

Frequency resolution and acquisition time

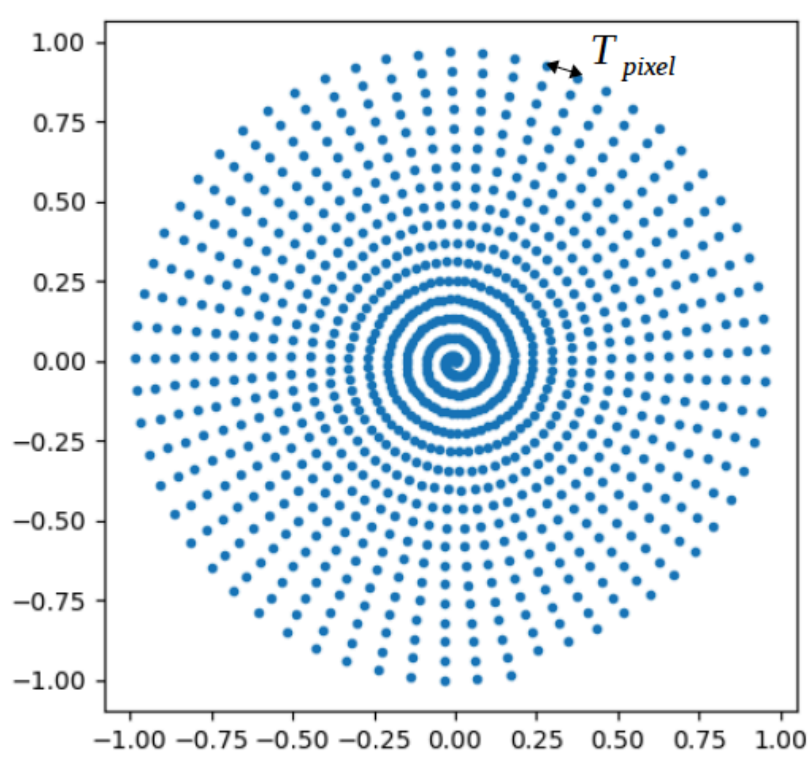
- Scanning camera: image points are measured sequentially
- Measurement time per point determines frequency resolution and SNR
- Max. time is set by 1 Hz image frequency, min. time by frequency resolution

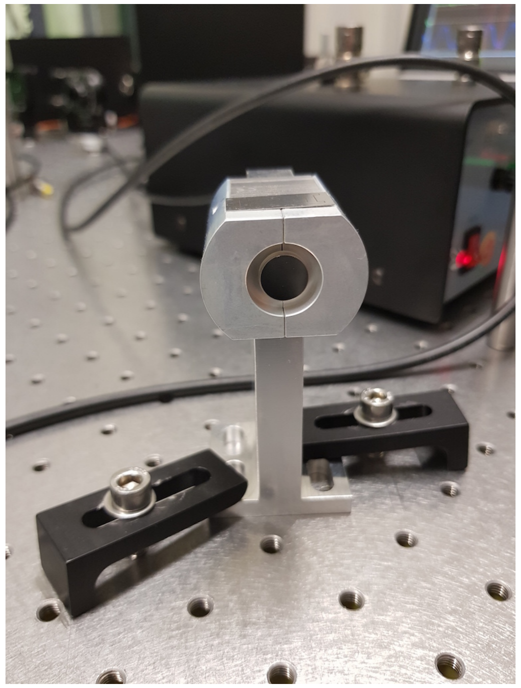
- max. N_s = 30517 samples / image point
  - Sampling frequency f_s = 500 MS/s
  - 128 x 128 image points in 1 sec
- min. N_s = 957 samples / image point
  - FFT frequency spacing: $\delta f = f_s / N_s$
  - sideband distance: ΔF = 2.09 MHz
  - and requirement $\delta f < \Delta F/4$
- PC can do 30 images/s from freq. resolution p.o.v.
- Default: 16k (2^14) samples / image point
  - 0.54 sec for a complete image

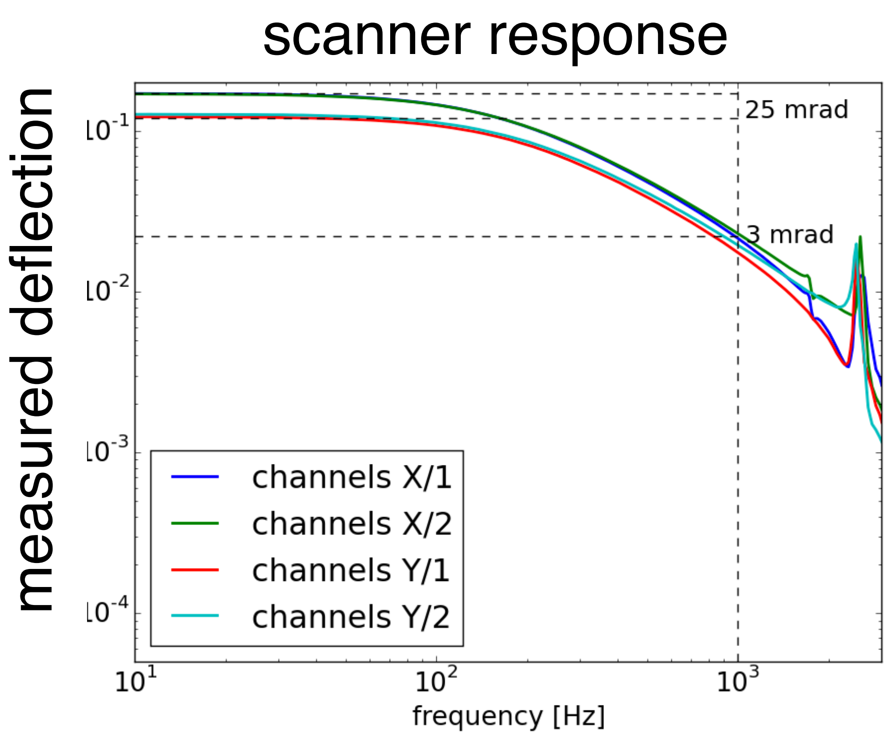


Scanner

- Scanning pattern is an Archimedean spiral: minimize vibrations & better accuracy
- Scanner moves continuously, hence measures a small spatial region, not a pure point
- Actual position measured with strain gauges
- With a max angular frequency of 1 kHz, one could take ~ 16 images / s
  - however angular range drops drastically -> need a longer distance to PD to compensate

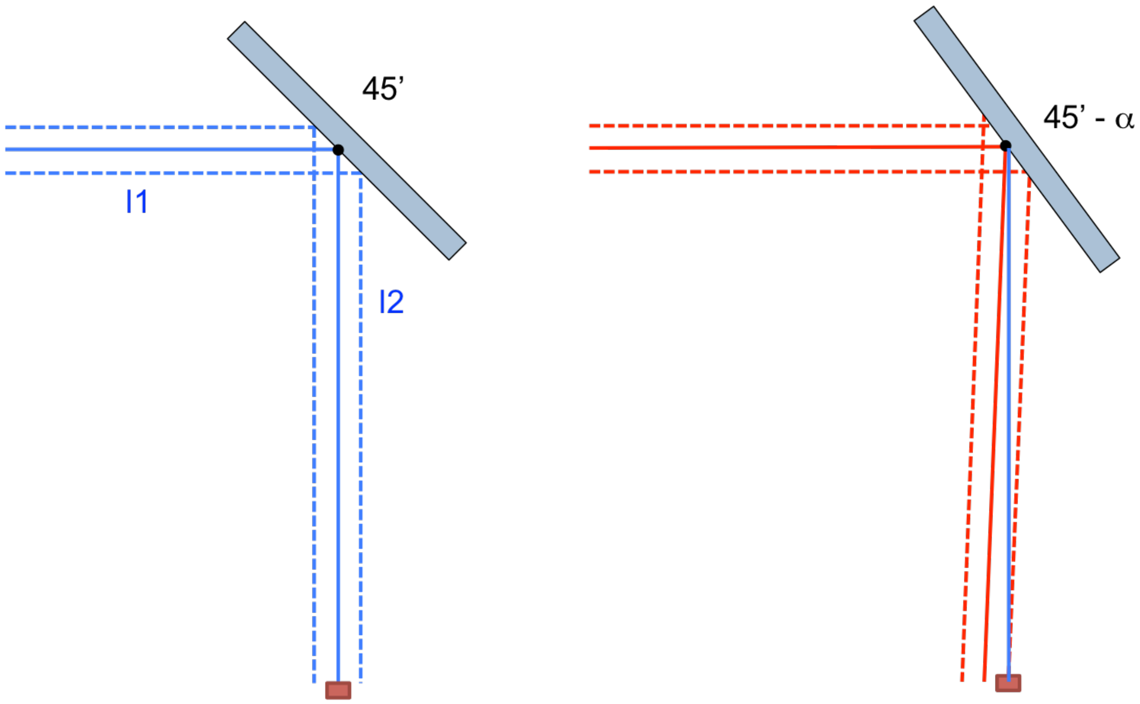






Relative phase measurement

- We take the relative phase of sideband and heterodyne, or between sidebands
- Main reason: remove common phase noise due to e.g. optical fiber in AOM path
- Additional benefit: no correction needed for wave front curvature due to scanning angle
  - Correction would be needed for absolute phase measurement as scanning angle introduces path length difference in one of the two beams
  - Could in principle be corrected for, but correction is huge (tens of radians) and can easily lead to inaccuracies

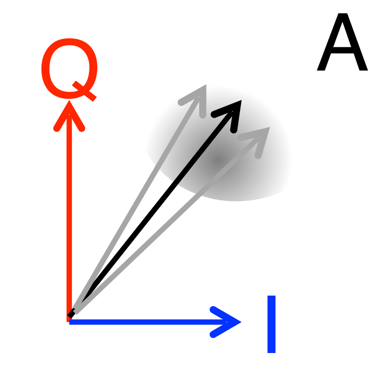


Phase measurement error

- phase error obtained via error propagation of I/Q signals

$$\phi = \arctan\left(\frac{Q}{I}\right) \qquad A = \sqrt{Q^2 + I^2}$$

$$\sigma_\phi = \sqrt{\left(\frac{\partial\phi}{\partial Q}\right)^2 \sigma_Q^2 + \left(\frac{\partial\phi}{\partial I}\right)^2 \sigma_I^2} \qquad \text{with} \qquad \frac{\partial\phi}{\partial Q} = \frac{I}{A^2} \quad \frac{\partial\phi}{\partial I} = \frac{-Q}{A^2}$$

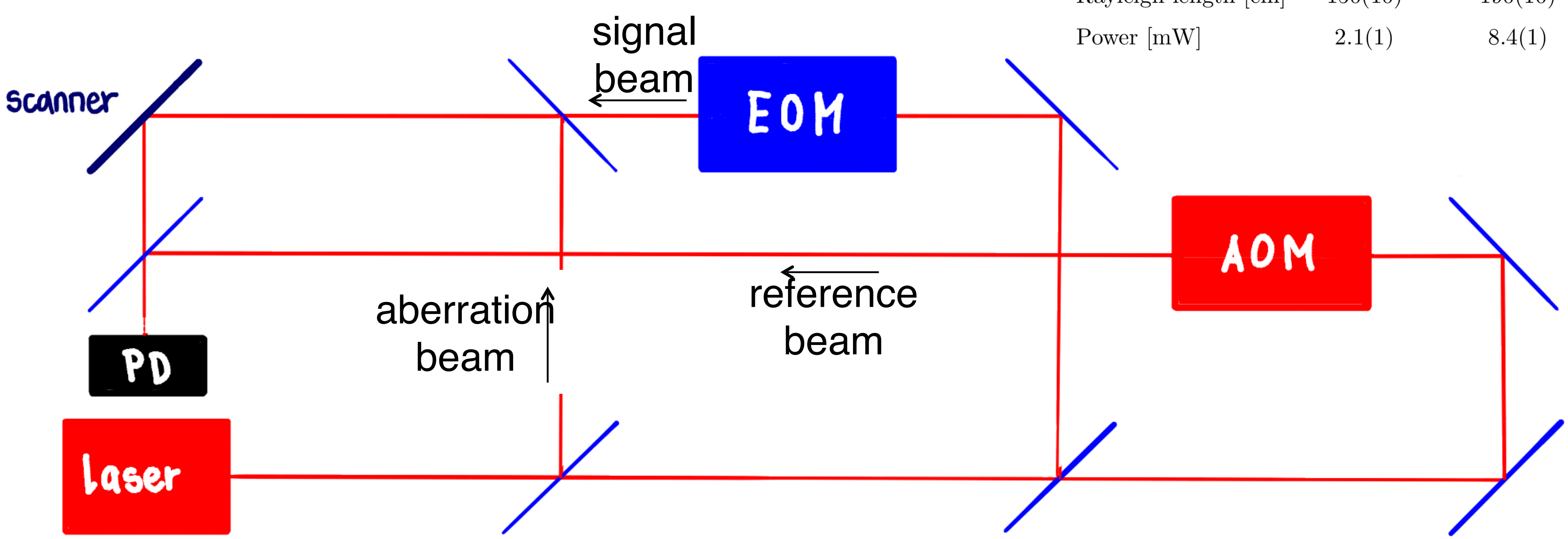


- If $\sigma_I = \sigma_Q = \sigma$ then $\sigma_\phi = \frac{\sigma}{A} = \frac{\sigma_A}{A}$

- Once shot noise limited (center of image) σ_A depends on A

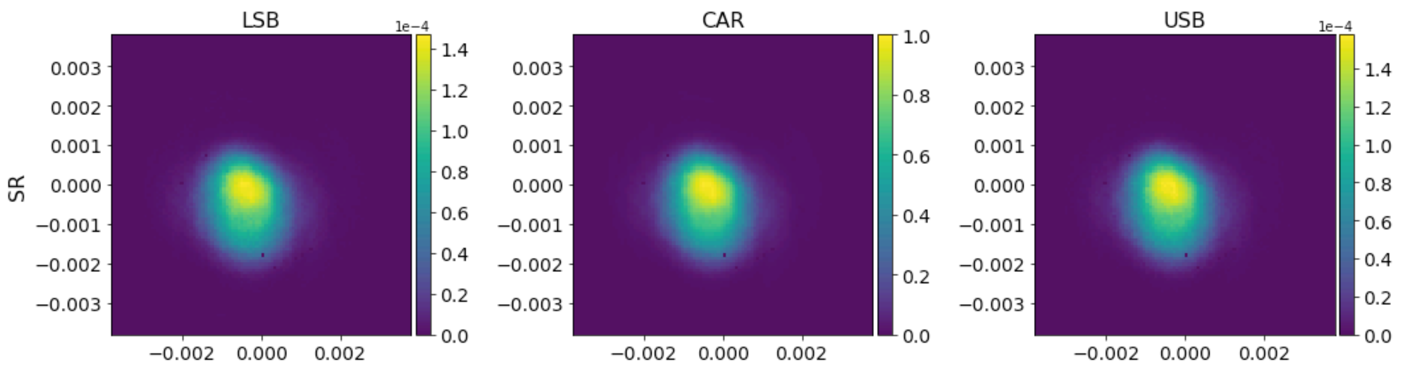
Schematic diagram of prototype set-up

Beam parameter	Signal (S)	Referrence (R)	Aberration (A)
waist size [μm]	705(10)	800(10)	120(10)
waist location [cm]	40(10)	-160(10)	30(10)
Rayleigh length [cm]	150(10)	190(10)	4(1)
Power [mW]	2.1(1)	8.4(1)	2.5(1)

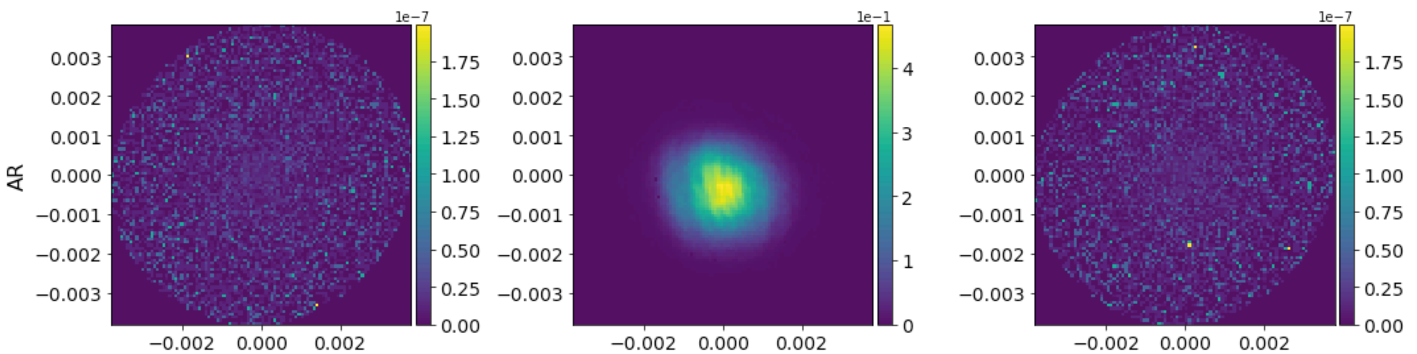


- With lenses (not shown) we shape the beams
  - Signal and reference beam have a flat wavefront at the PD position
  - Aberration beam is curved at the PD position

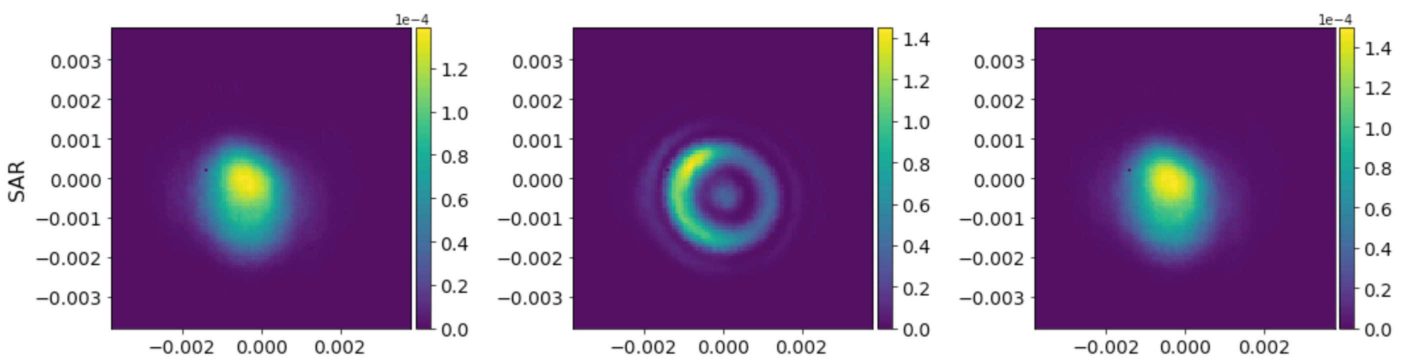
Intensity images



aberration beam blocked
(only beams with flat wavefront)

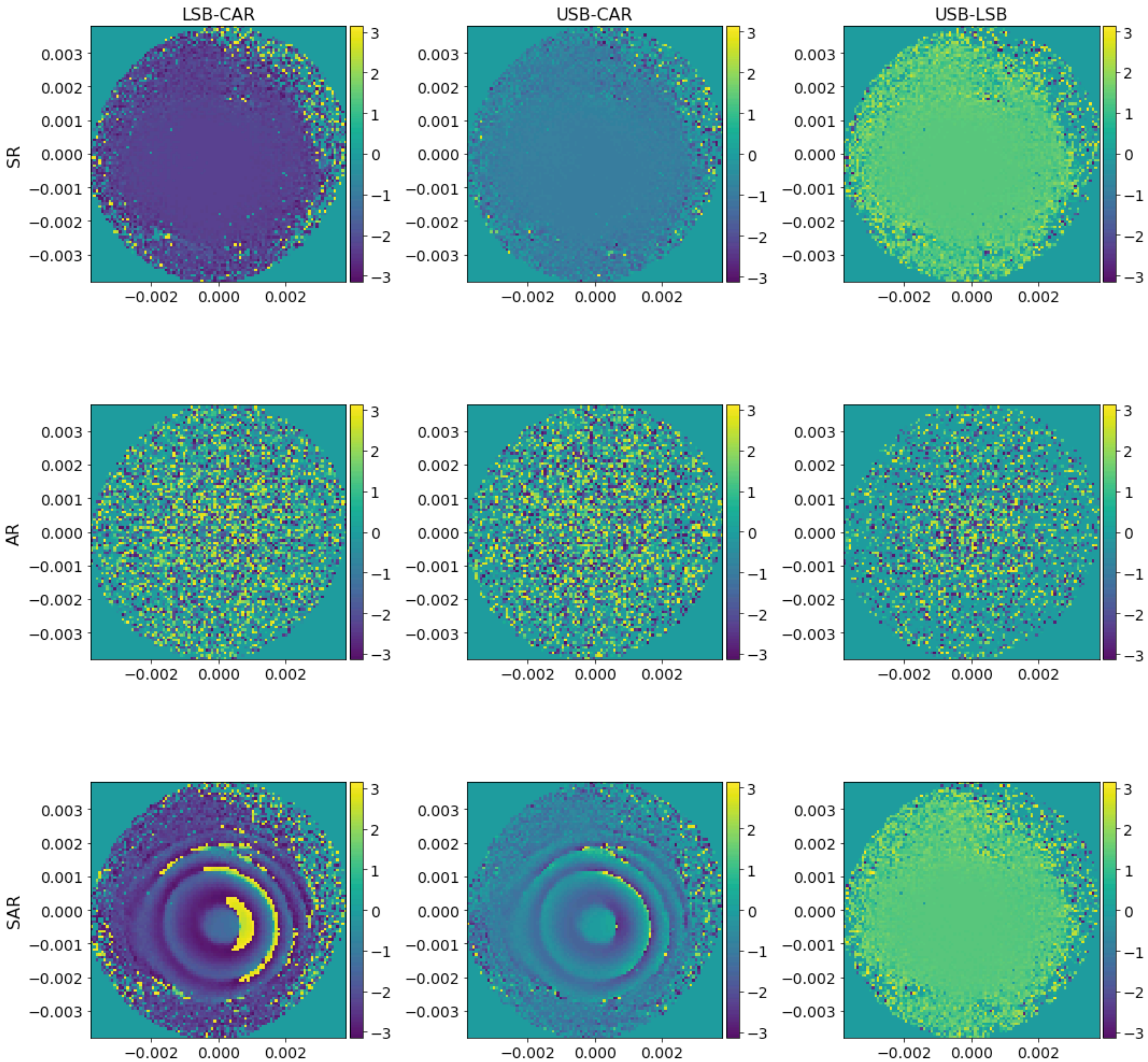


signal beam blocked
hence no sidebands



Interference of two TEM00 with different phases
(sidebands have flat wavefront)

Corresponding phase image



Aberration beam blocked
Only flat wavefronts -> constant phase

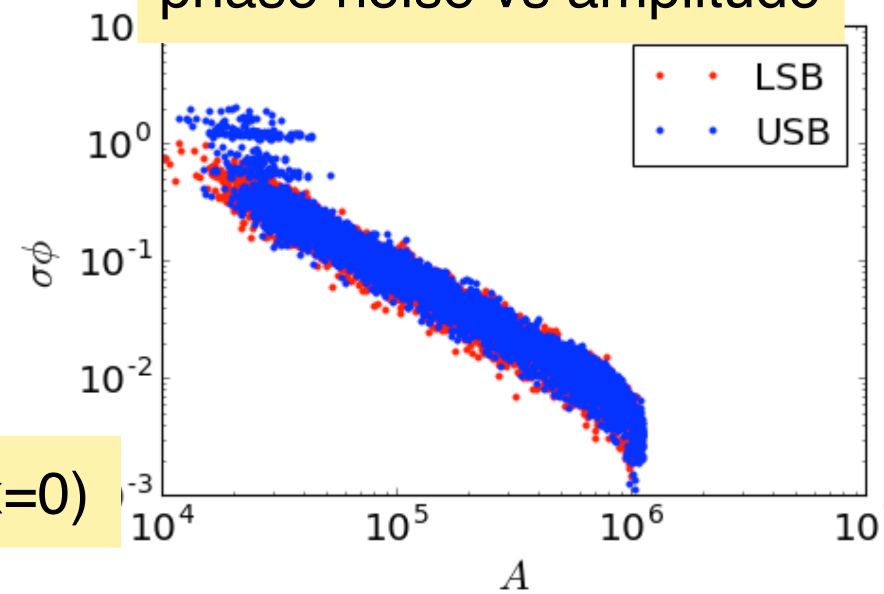
Signal beam (after EOM) blocked
hence no sidebands

Only carrier in aberration
beam has curved
wavefront

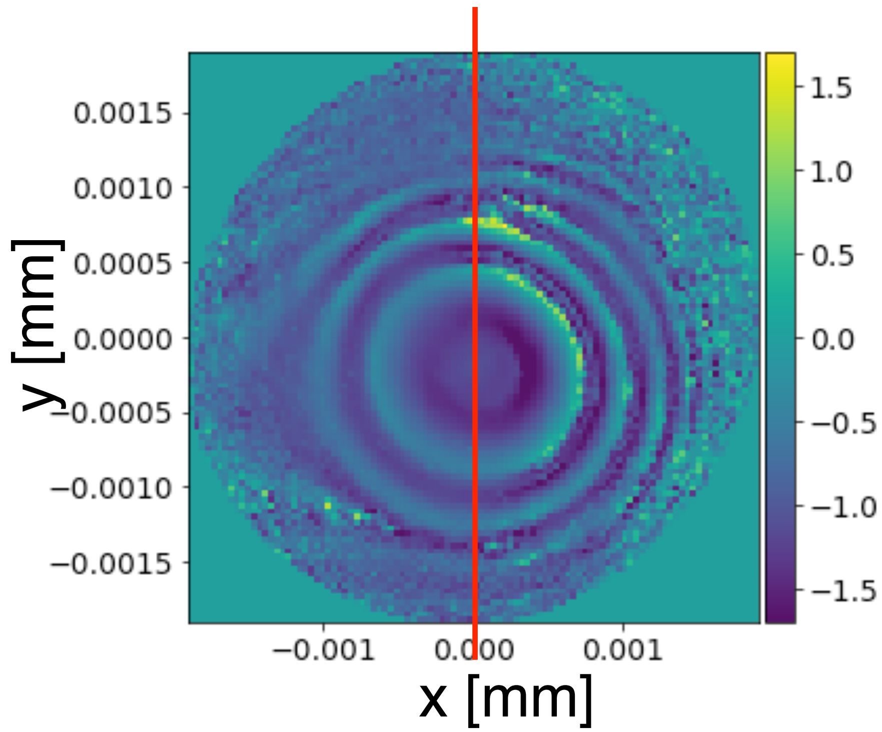
Phase resolution

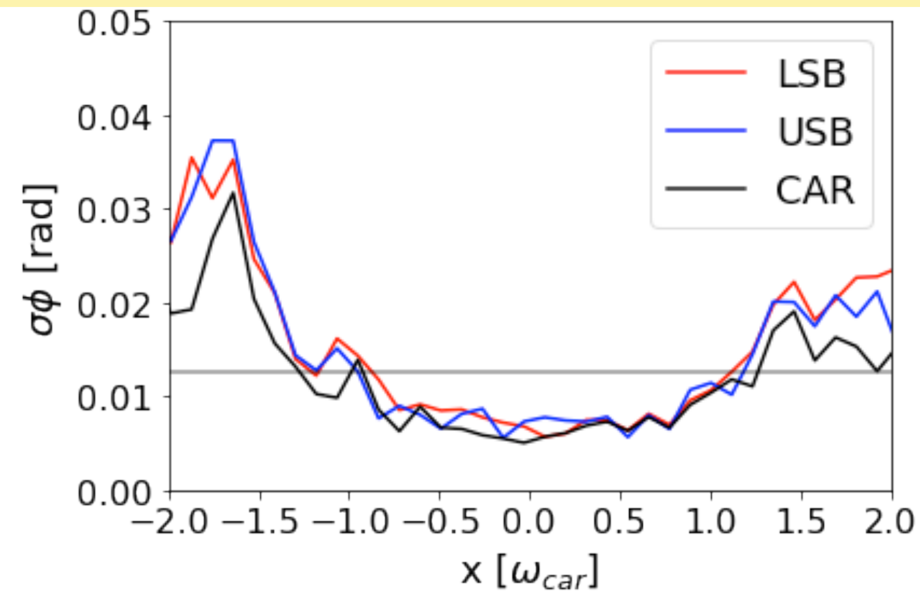
- Using differential phase images: LSB-carrier, USB-carrier
- Phase resolution determined from standard deviation of consecutive images
- Phase resolution is a function of beam intensity

phase noise vs amplitude



phase versus vertical position (at x=0)





phase noise vs expectation