The Phase Cameras of Advanced Virgo

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on behalf of the Virgo Collaboration

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Outlook

First experience with the Virgo phase cameras is shared:

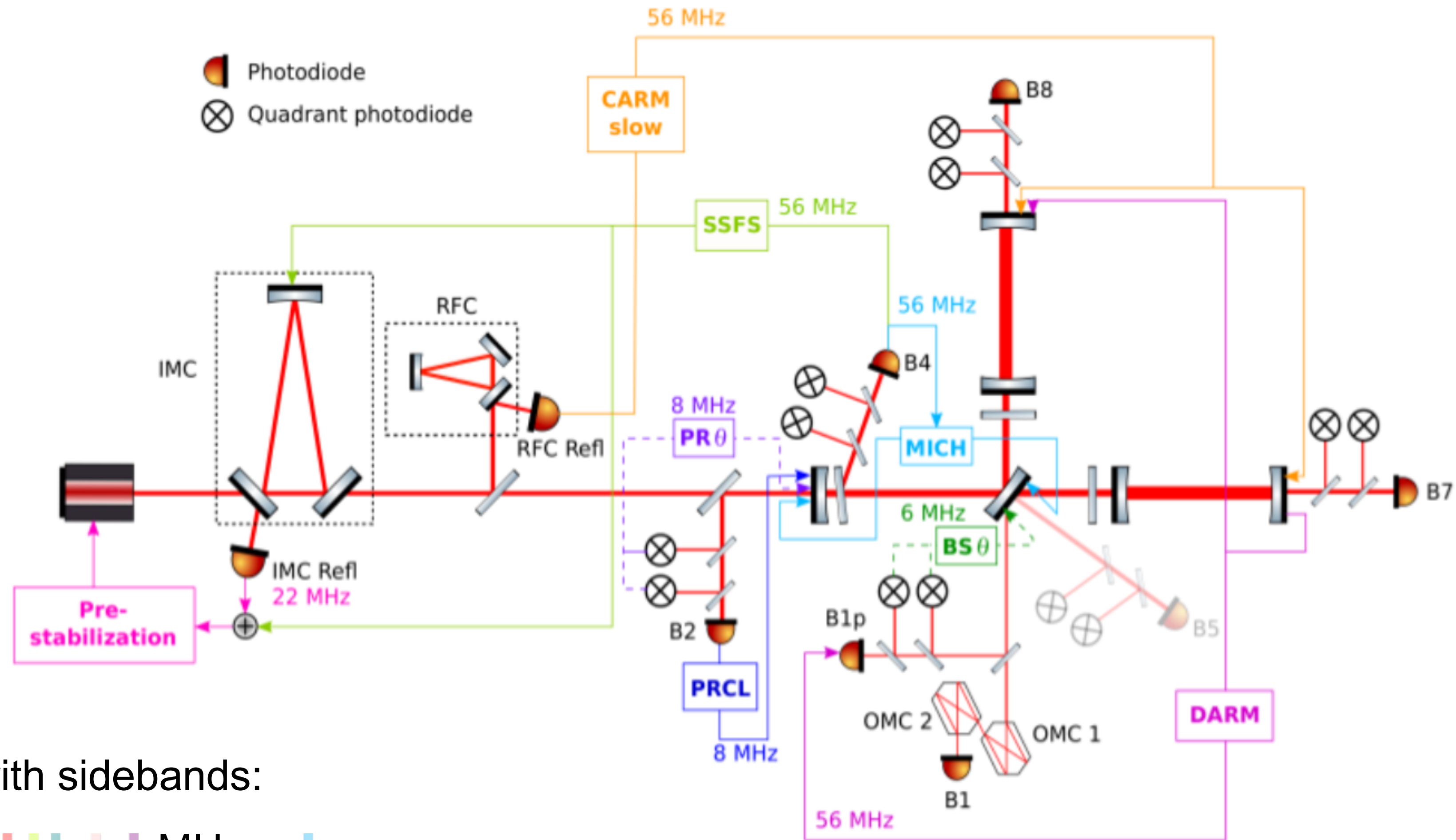
Motivation
- Design purpose for the phase cameras

Instrument
- The principle behind the phase cameras
- The integration in the Virgo detector

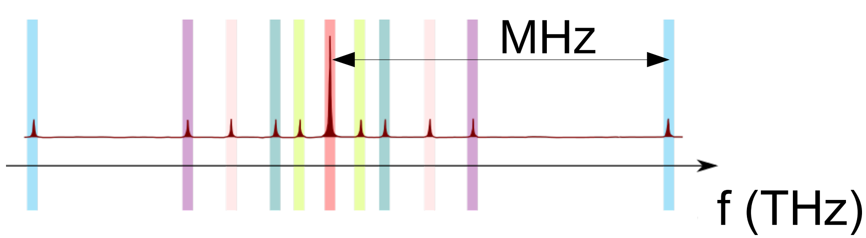
Commissioning
- Increasing the circulating power
- Increasing the input mirror curvature

Alignment controls

To successfully operate a GW detector the length and angles of the cavities needs to be controlled. The control schemes are designed for a Gaussian beam. Sideband frequencies are used to control various mirrors.



Carrier (red) with sidebands:

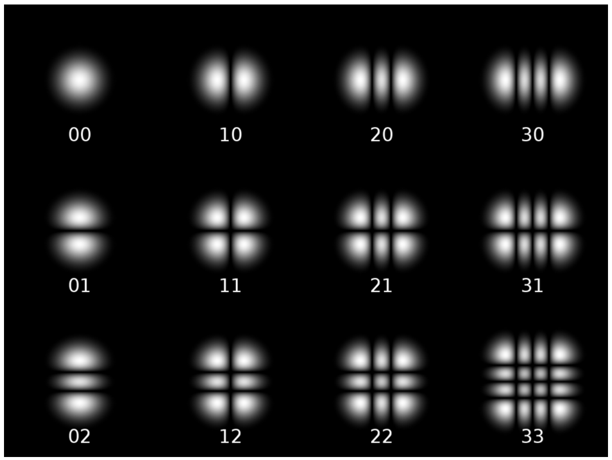


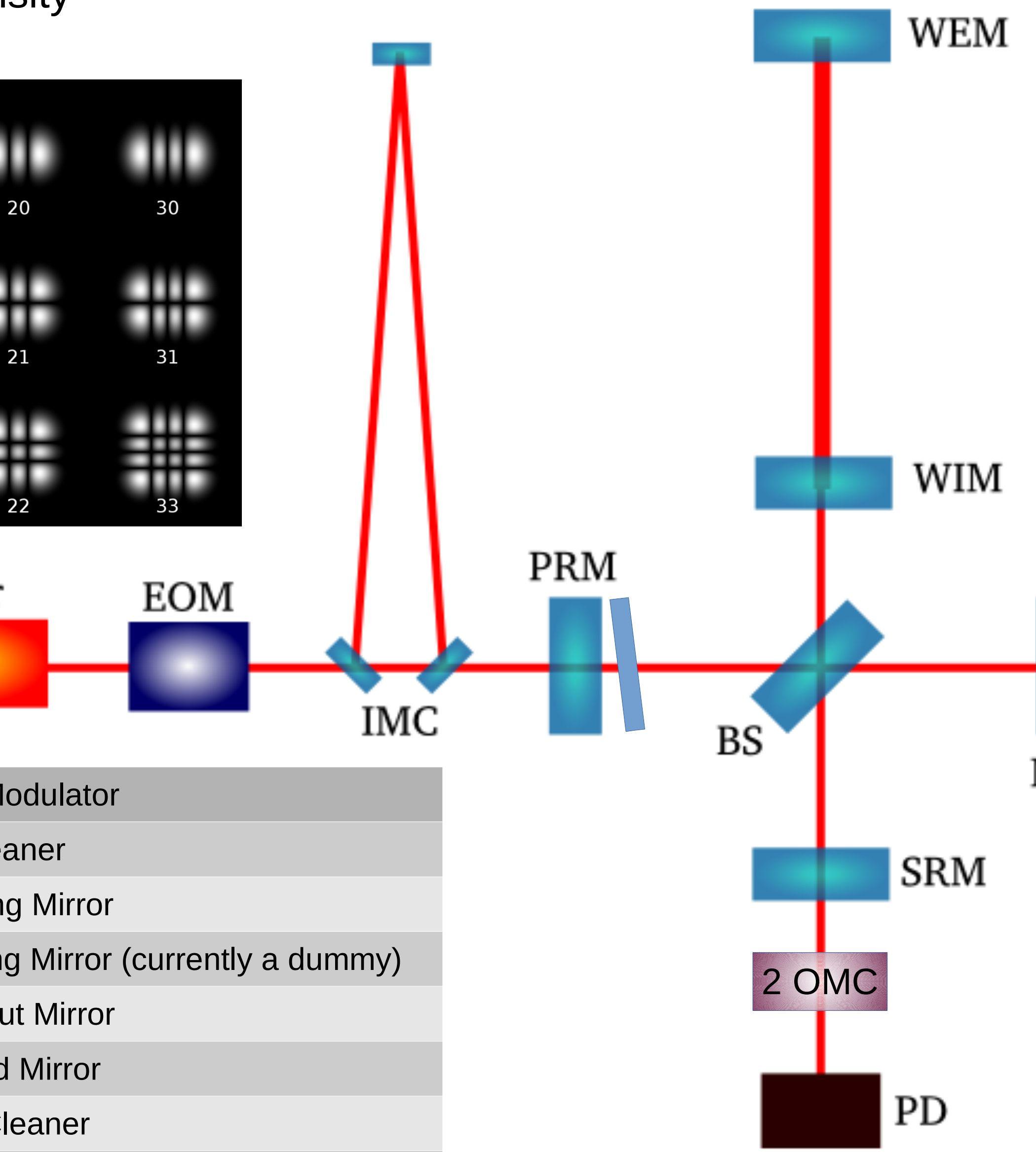
*Control scheme from thesis by Julia Casanueva Diaz

Overview AdV optics

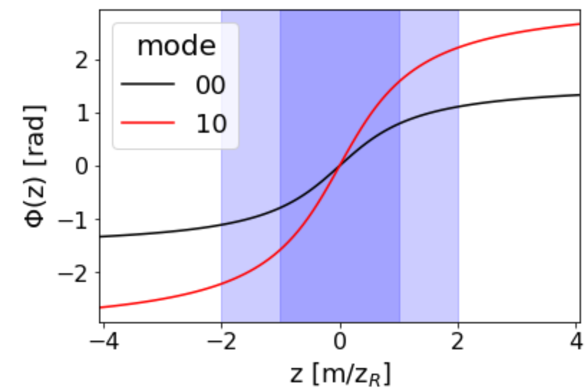
Higher order modes interfere with the controls and reduce the sensitivity of the detector.

Higher order modes have non-Gaussian intensity distributions:





And a different phase evolution (Guoy phase):



$$\Phi(z) = (l + m + 1) \cdot \arctan\left(\frac{z}{z_R}\right)$$

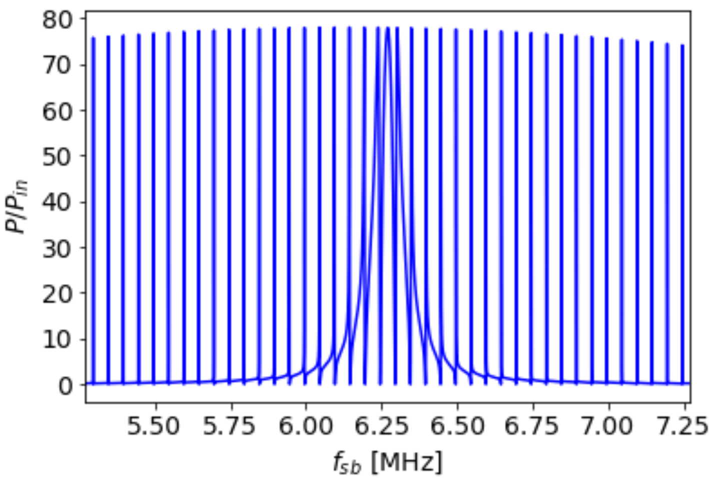
EOM	Electro-Optic Modulator
IMC	Input Mode Cleaner
PRM	Power Recycling Mirror
SRM	Signal Recycling Mirror (currently a dummy)
XIM	North/West Input Mirror
XEM	North/West End Mirror
OMC	Output Mode Cleaner
PD	Photodiode

After the IMC the light is in the fundamental mode (Gaussian beam)

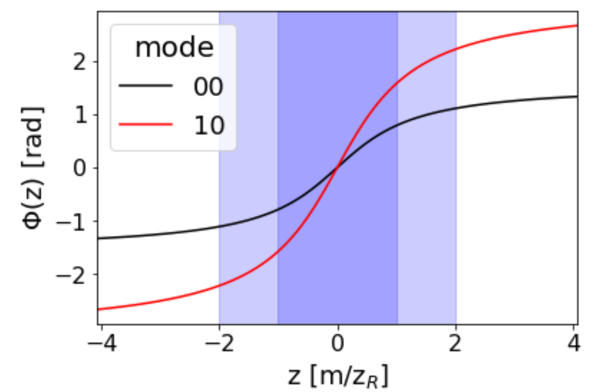
Overview AdV optics

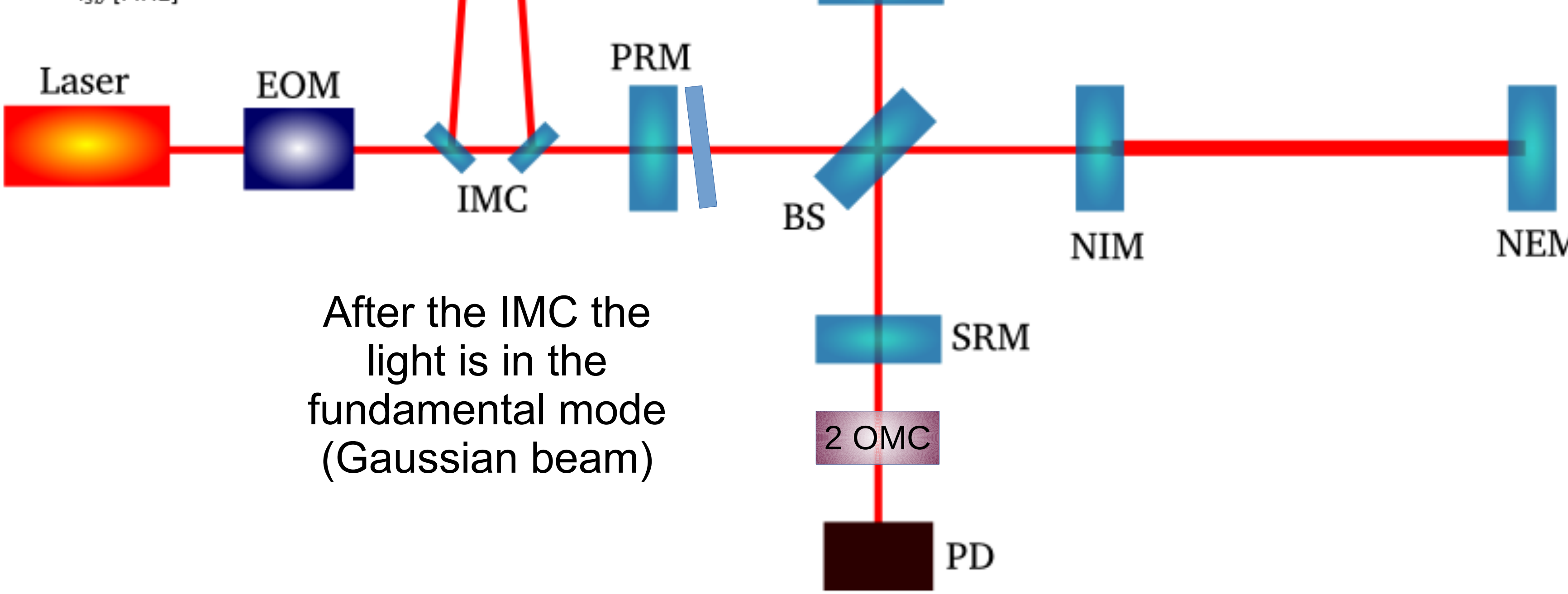
HOMs can resonate in the central interferometer, but not in the arms.

Resonance width of the arms is 112 Hz, while the resonance width of the central interferometer is 0.1 MHz.



Guoy phase of higher order modes falls within the resonance.

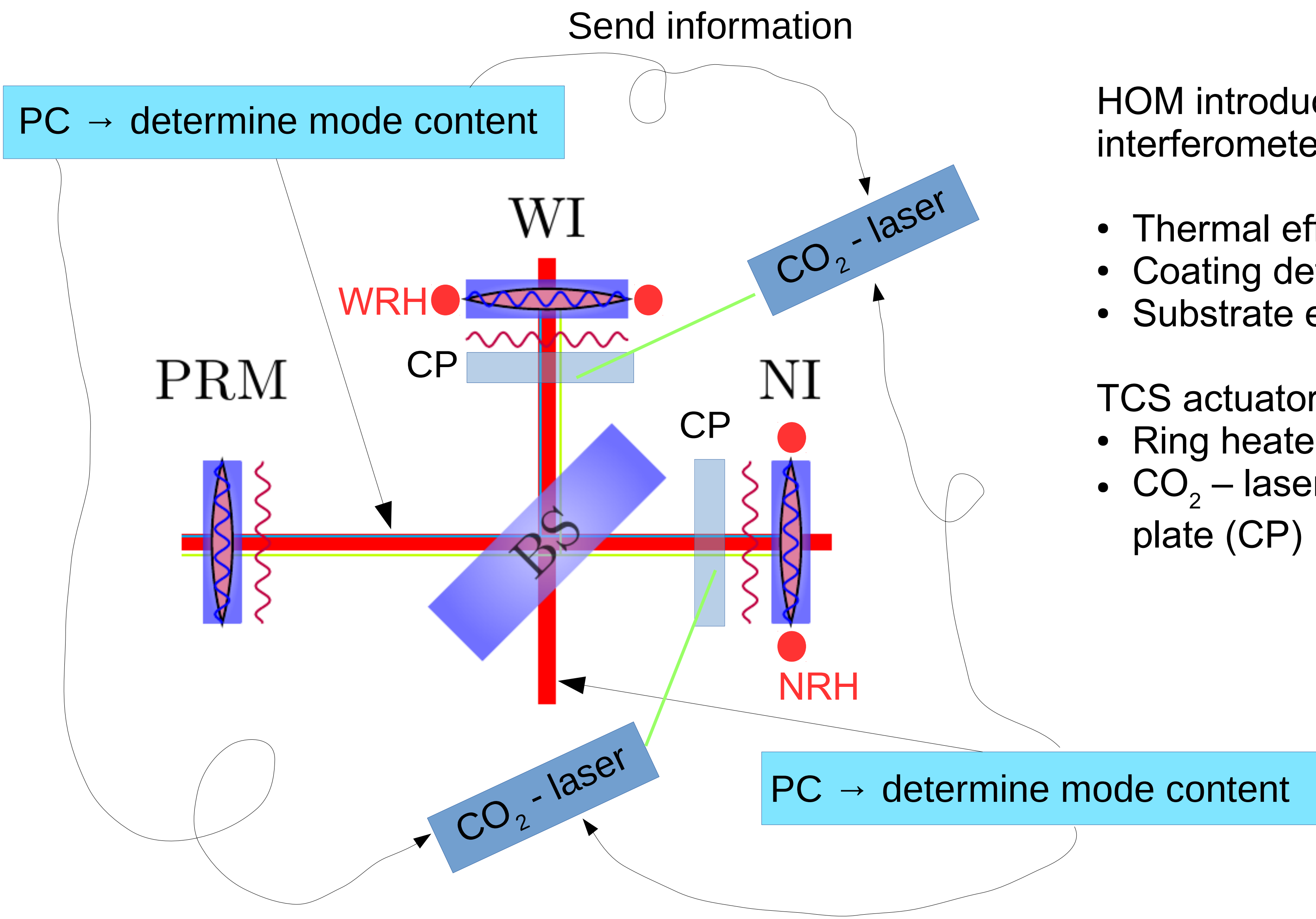




After the IMC the light is in the fundamental mode (Gaussian beam)

TCS

After sensing the HOM with the phase camera they are counteracted with the thermal compensation system (TCS). The TCS employs a CO2-laser and compensation plates (CP) to alter the optical path length of the various fields inside the PRC.



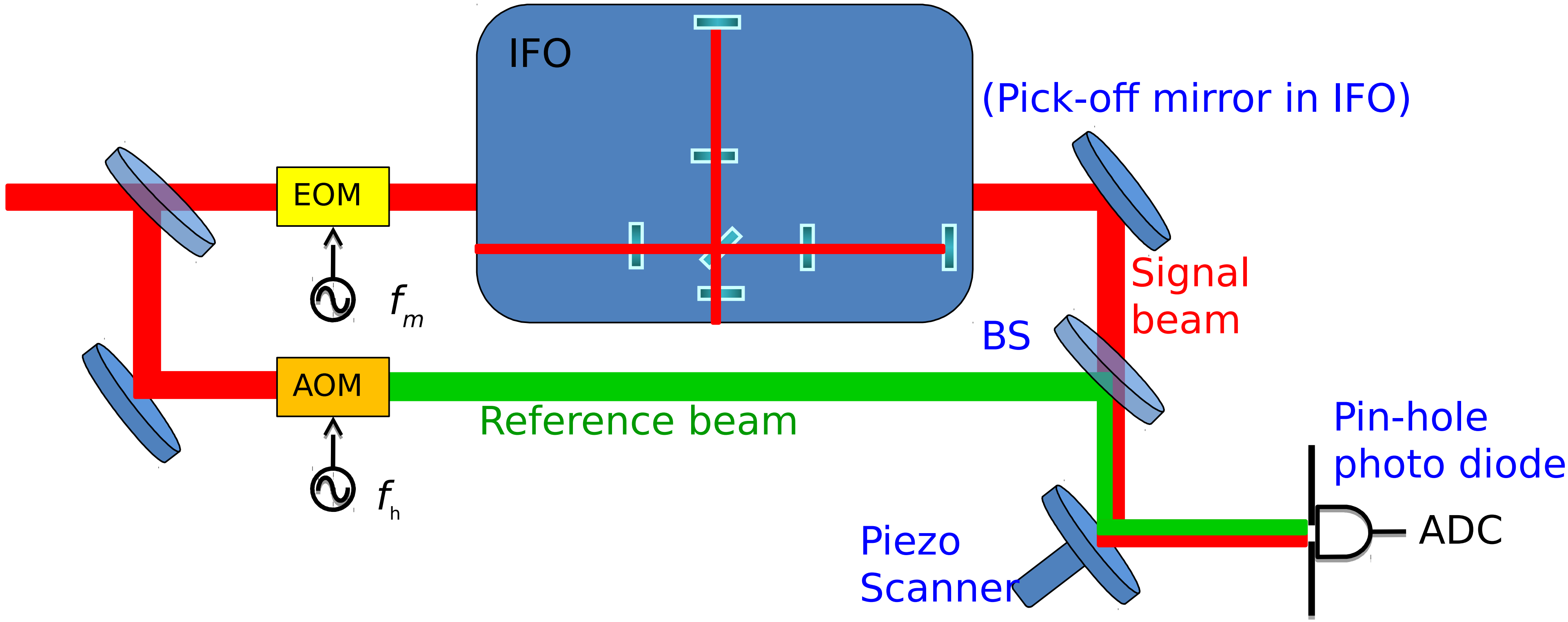
HOM introduced inside the interferometer by:

- Thermal effects (thermal lens)
- Coating defects
- Substrate errors

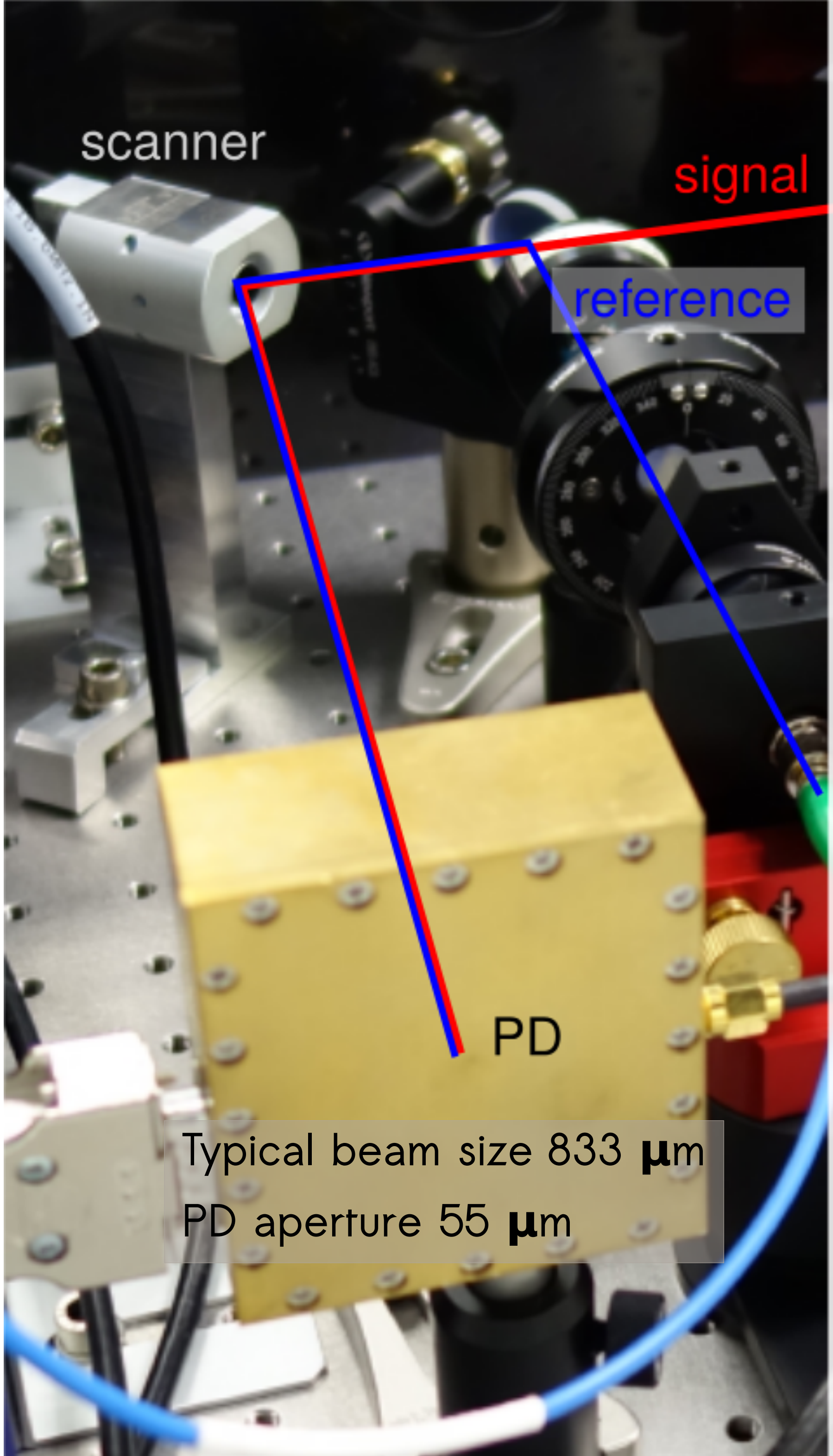
TCS actuators:
- Ring heaters (RH)
- CO_2 – laser on compensation plate (CP)

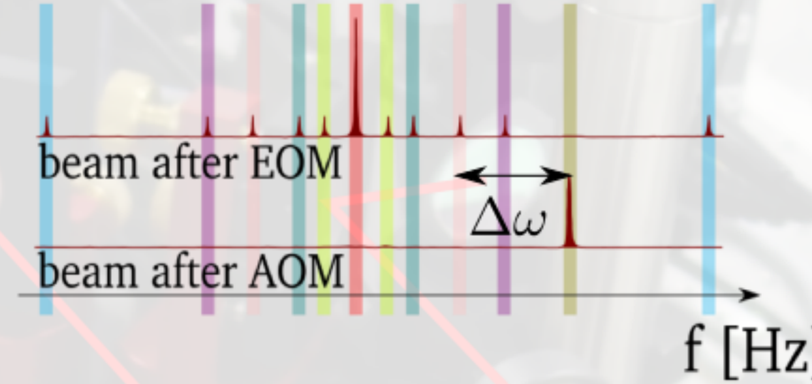
*the TCS system is provided by V. Fafone’s group of Università degli studi di Roma Tor Vergata

Phase camera schematic diagram



- Acousto-optic modulator (AOM) gives 80 MHz frequency shift (heterodyne)
- Mixing of test beam with reference beam on beam splitter (BS)
- Scanner moves beam over pinhole photo diode





Current in PD:

$$I(t) = \mathrm{DC-offset} + \mathrm{amplitude} \cdot \sin(\Delta\omega t + \mathrm{phase})$$

Sampling with ADC (14 bit resolution, 500 MS/s)

Demodulation in FPGA

Scan the laser front with Archimedean spiral to get phase and amplitude maps.

ADC: Intersil ISLA214P50
FPGA: Xilinx Virtex-7 XC7VX485
PD, photodiode: OSI optoelectronics FCI-InGaAs-55
PD, amplifier: Hittite HMC799LP3E
scanner: PI-S334

Picture: preliminary setup at EIB

Demodulation

$$\text{Sample current for each pixel (ADC, 500 MHz, 14 bit)}:$$
$$I(\vec{x},t) \propto C_1 + C_2 \cdot \sin[\Delta\omega_{\mathrm{sb,h}} t + \Delta\Psi + \Delta R]$$

$$\text{Demodulate by multiplying with the respective } \Delta\omega_{\mathrm{sb,h}} \text{ in the FPGA}$$
$$p \equiv I(\vec{x},t) \cdot \sin[\Delta\omega_{\mathrm{sb,h}} t]$$
$$= C_1 \cdot \sin[\Delta\omega_{\mathrm{sb,h}} t] + C_2 \cdot (\cos[\Delta\Psi + \Delta R] - \cos[2\Delta\omega_{\mathrm{sb,h}} t + \Delta\Psi + \Delta R])$$

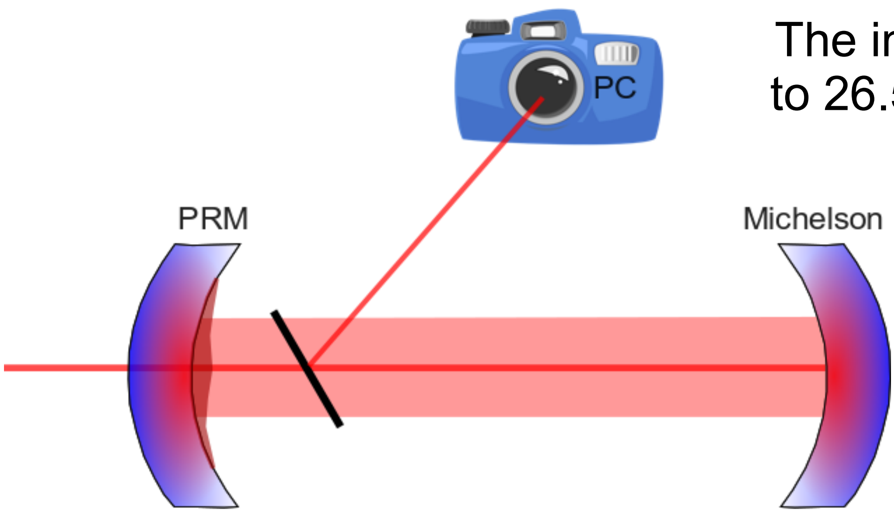
$$q \equiv I(\vec{x},t) \cdot \cos[\Delta\omega_{\mathrm{sb,h}} t]$$
$$= C_1 \cdot \cos[\Delta\omega_{\mathrm{sb,h}} t] + C_2 \cdot (\sin[\Delta\Psi + \Delta R] - \sin[2\Delta\omega_{\mathrm{sb,h}} t + \Delta\Psi + \Delta R])$$

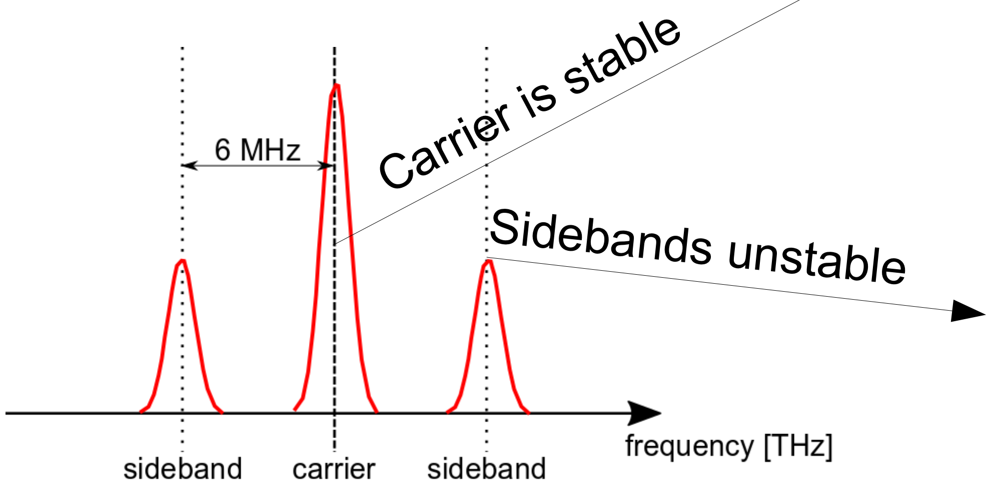
$$\text{Lowpass} - \text{filter to obtain}:$$
$$p = C_2 \cdot (\sin[\Delta\Psi + \Delta R])$$
$$q = C_2 \cdot (\cos[\Delta\Psi + \Delta R])$$

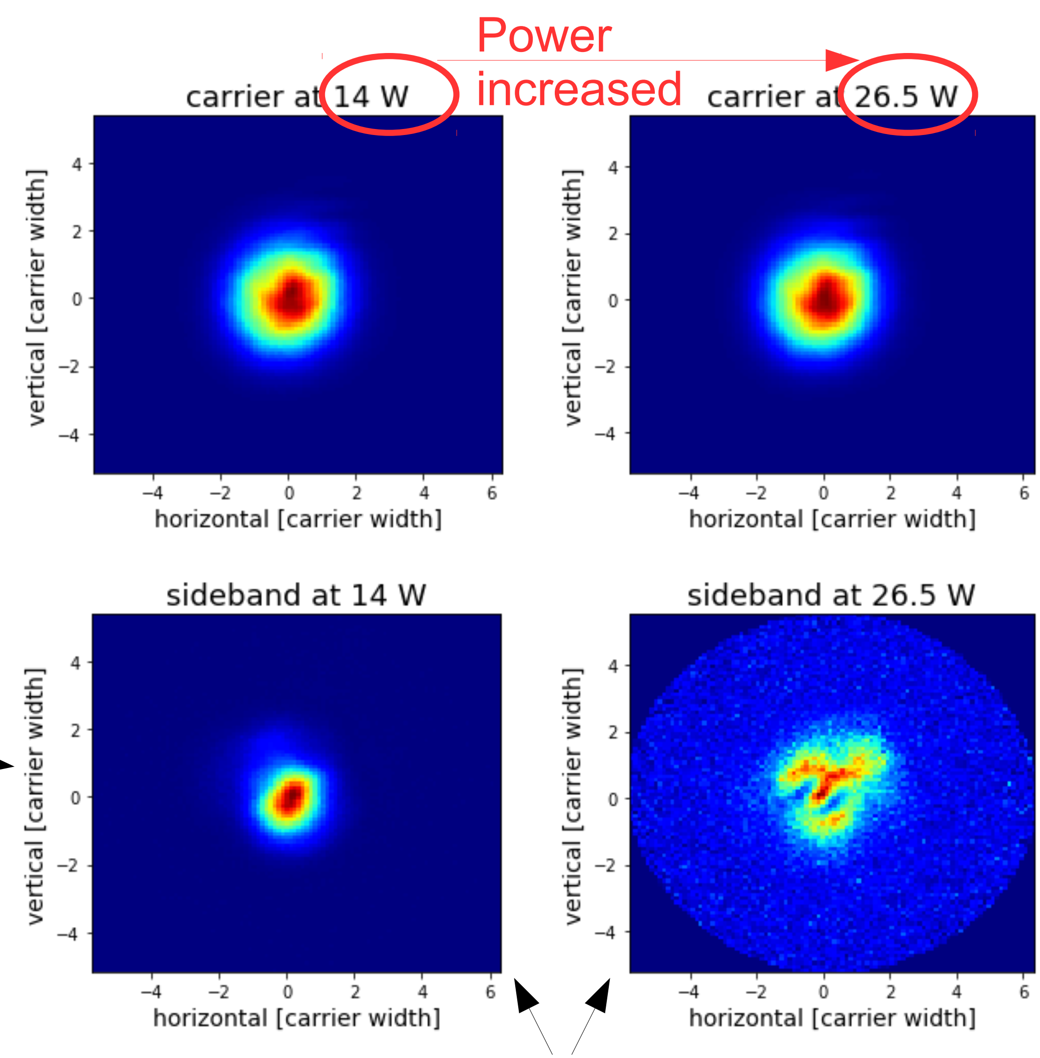
$$\Delta\Psi + \Delta R = \arctan\left[\frac{q}{p}\right]$$
$$C_2 = \sqrt{p^2 + q^2}$$

Phase camera in action

The input power to the interferometer is increased from 14 W to 26.5 W. This makes mirrors thermally expand and changes the resonance condition.





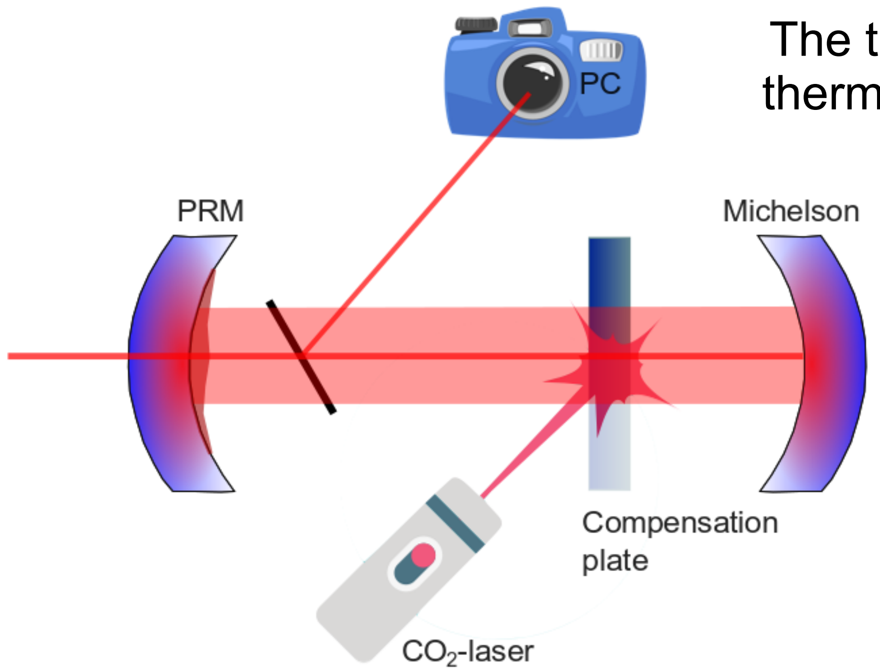


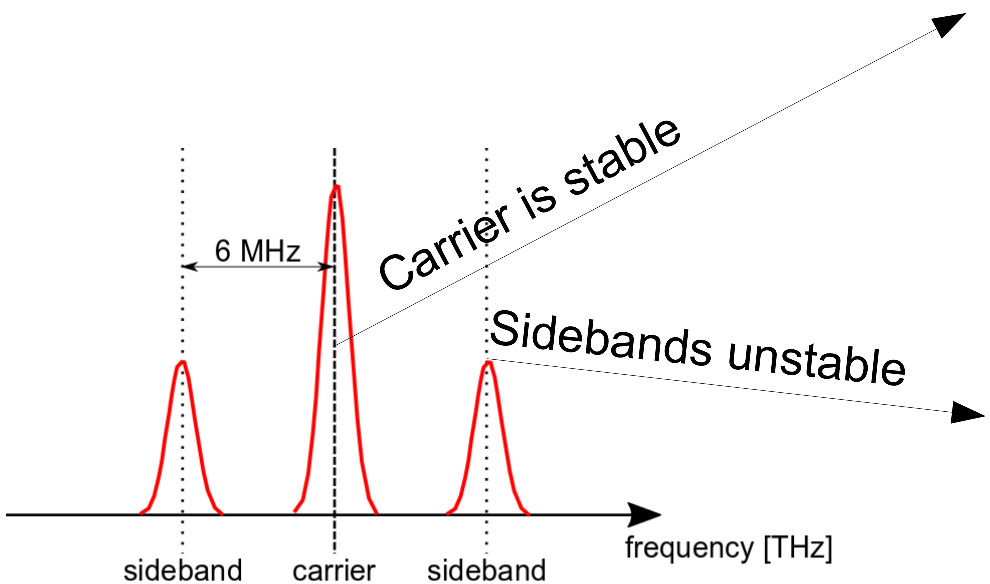
Carrier: field for GW detection
Sidebands: fields used to control the interferometer

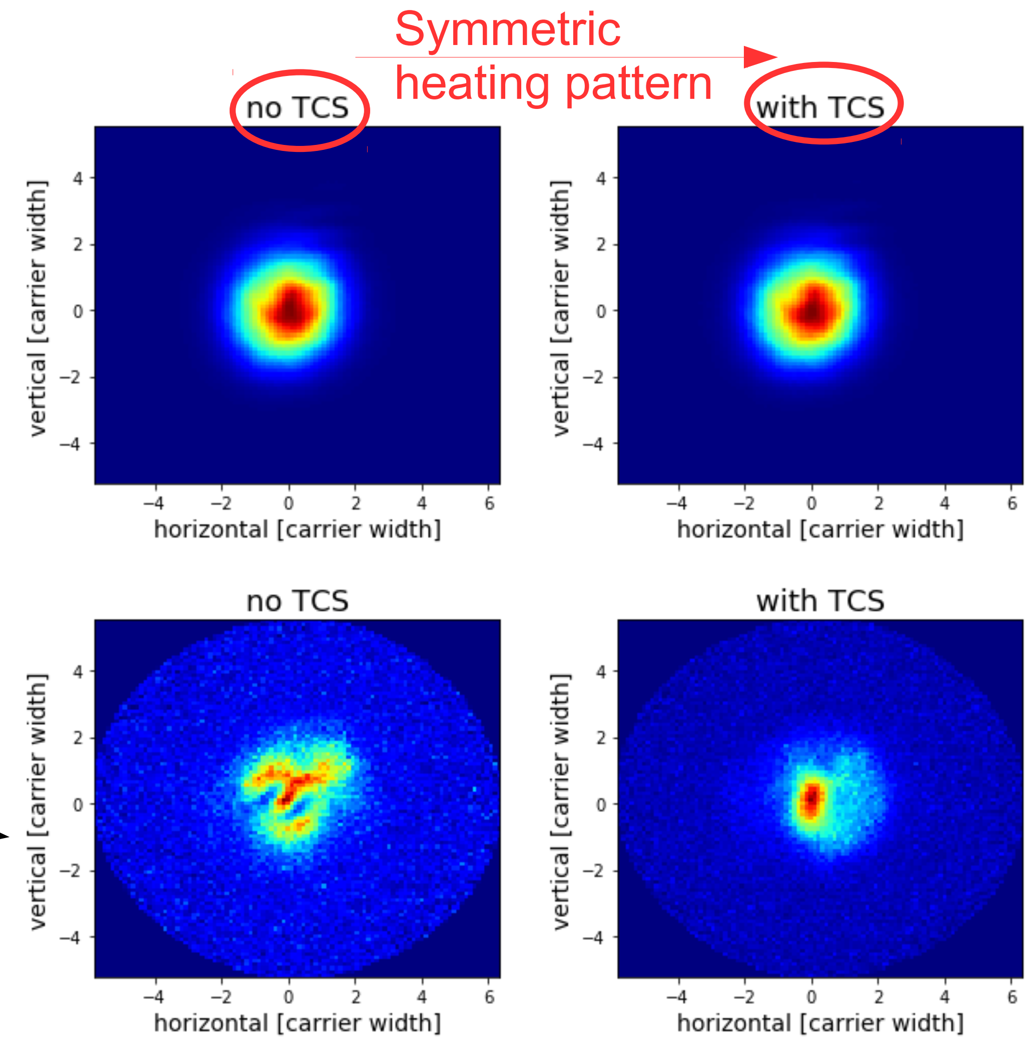
Change in noise floor because sideband amplitude is reduced, not thermal effect.

Phase camera in action

The thermal expansion of the mirrors is counteracted by the thermal compensation system. The compensation plates are heated to recover the sideband shape.

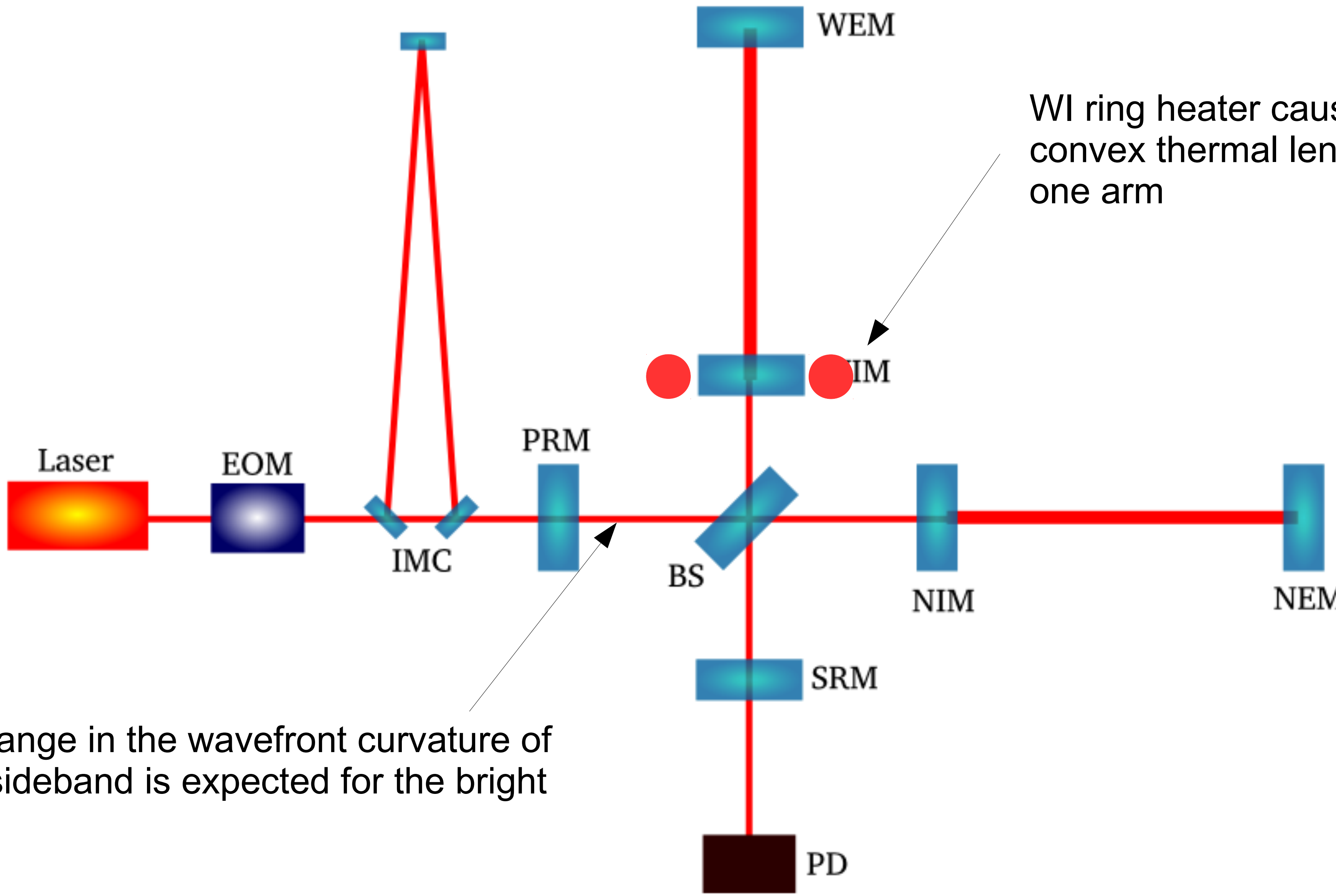






Changing the wavefront

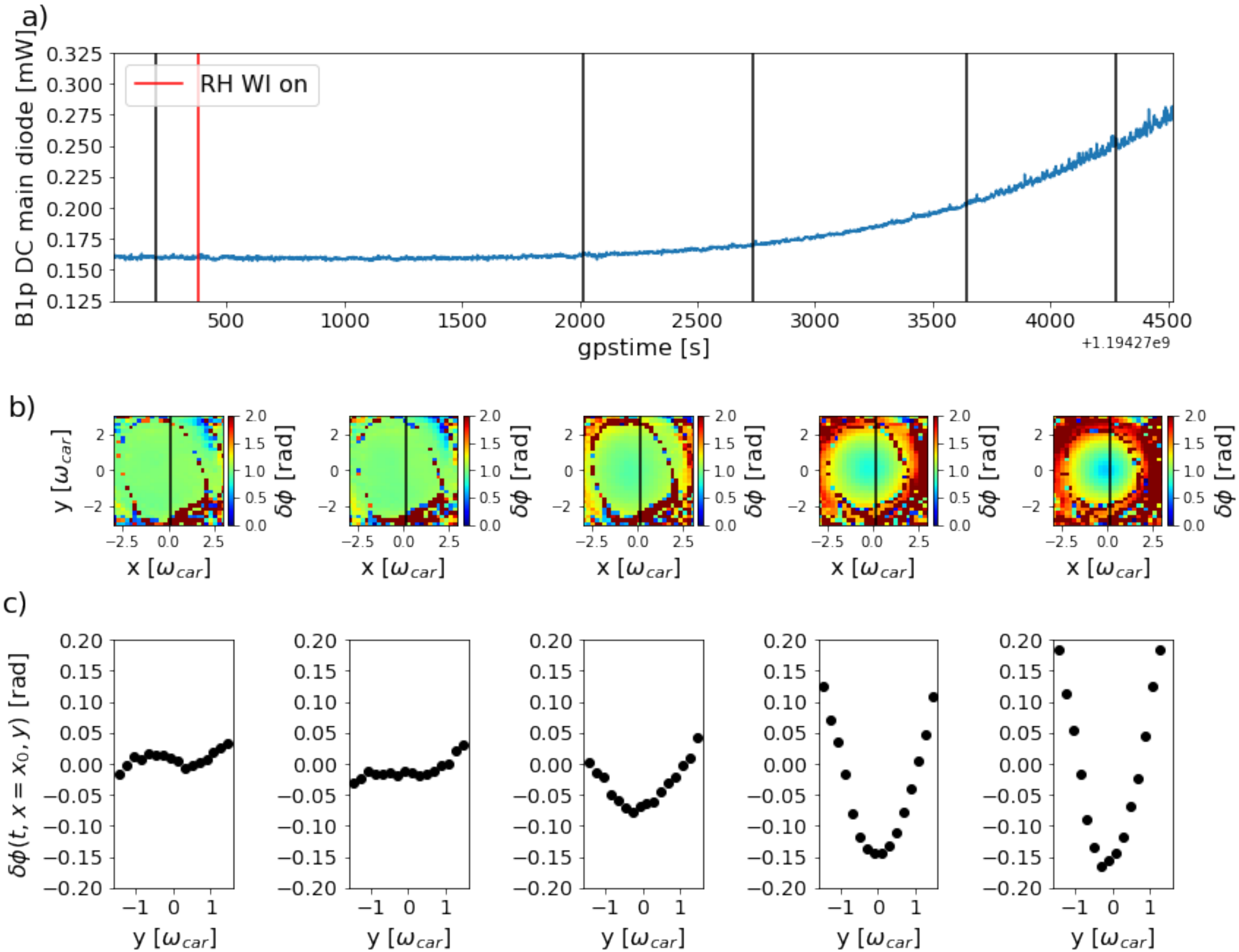
Ring heaters are actuators used to recover the mirror curvature after it is heated by a beam passing through. For this test a ring heater has been turned on without there being a need for it.



WI ring heater causes a convex thermal lens in one arm

A change in the wavefront curvature of the sideband is expected for the bright port

Changing the wavefront



Interferometer condition worsens → more power at the dark port

Wavefront of the sideband starts to curve

Cross section of the wavefront for better visualization

Current status

2 phase cameras are operational

Data has been taken with and without TCS

Currently busy analysing the data, cross checking the results with OSCAR, an FFT based simulation tool

Outlook

Next step will be the construction of an error signal for the TCS

And for the long term an improved phase camera based on the experiences with the current one

Backup slides

Paraxial approximation

Helmholtz equation $\nabla^2 \vec{X} + k^2 \vec{X} = 0$

For a beam propagating in the z-direction define $\vec{X}(\vec{x}) = \vec{U}(\vec{x}) \cdot e^{ikz}$

The Helmholtz equation becomes

$$\nabla^2 \vec{X} + k^2 \vec{X} = \left(\partial_x^2 U + \partial_y^2 U + \partial_z^2 U + 2ik\partial_z U\right) \cdot e^{ikz} = 0$$

Paraxial approximation $|\partial_z^2 U| \ll |2ik\partial_z U|$

Paraxial Helmholtz equation

$$\nabla_\perp^2 U + 2ik\partial_z U = 0$$

Equation generally used to describe laser beams

Putting everything together $\vec{E}(x, y, z, t) = U(x, y, z) \cdot e^{ikz} \cdot e^{i\omega t}, \text{ where } \omega \equiv \frac{kc}{\sqrt{\epsilon\mu}}$

Hermite-Gaussian modes

Any basis of R^2 is equivalent for the plane perpendicular to the propagation direction, but in general:

1. Cartesian coordinates useful for alignment → Hermite-Gaussian modes
2. Polar coordinates useful for thermal lensing → Laguerre-Gaussian modes

Hermite-Gaussian modes:

$$|U_{lm}(x,y,z)| = U_0 \frac{\omega_0}{\omega(z)} H_l\left(\frac{\sqrt{2}x}{\omega(z)}\right) H_m\left(\frac{\sqrt{2}y}{\omega(z)}\right) e^{-\frac{x^2+y^2}{\omega^2(z)}}$$

$$\arg\left(U_{lm}(x,y,z)\right) = -\frac{k(x^2+y^2)}{2R(z)} - \Phi(z)$$

where

$$\omega(z) = \omega_0 \cdot \sqrt{1+\left(\frac{z}{z_R}\right)^2}$$ Beam width

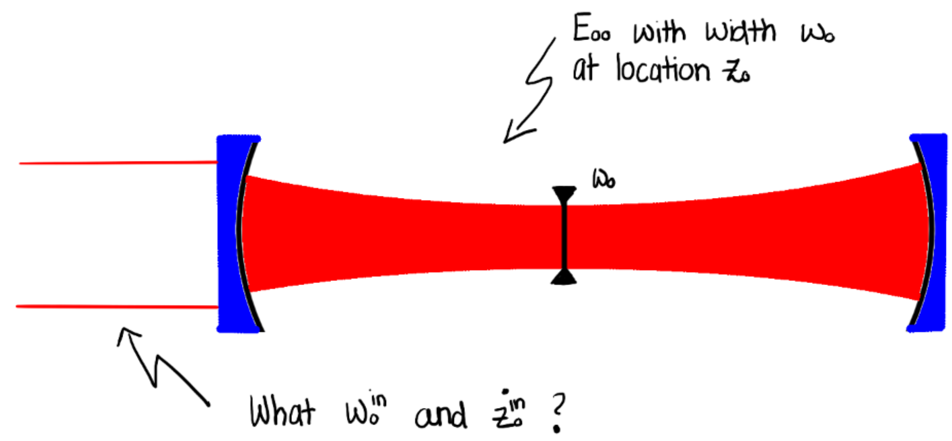
$$R(z) = z \cdot \left(1+\left(\frac{z_R}{z}\right)^2\right)$$ Wavefront curvature

$$\Phi(z) = (l+m+1)\cdot \arctan\left(\frac{z}{z_R}\right)$$ Guoy phase

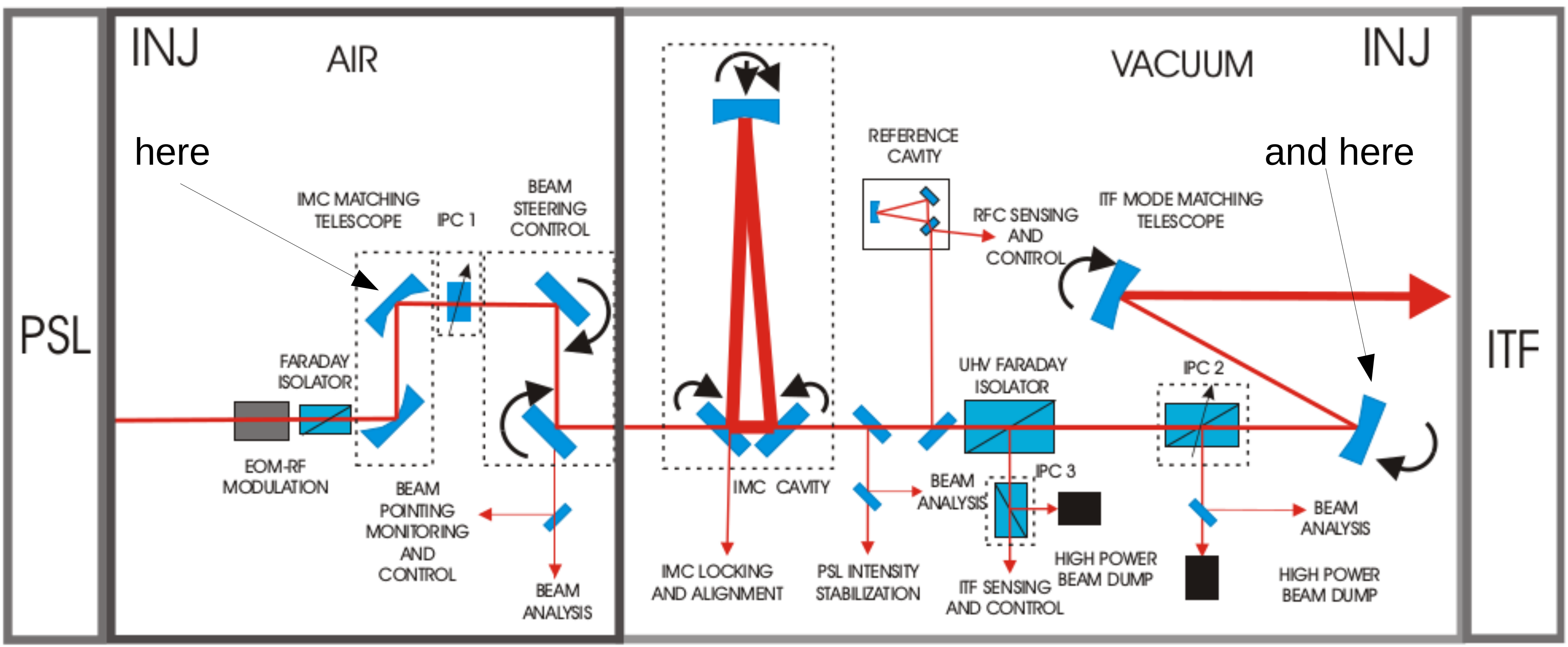
$$z_R = \frac{\pi\omega_0^2}{\lambda}$$ Rayleigh range

Mode matching

Mode matching is the method with which an input beam is formed by a telescope such that all the power is transferred in the eigenmode of choice (for AdV 00 mode).

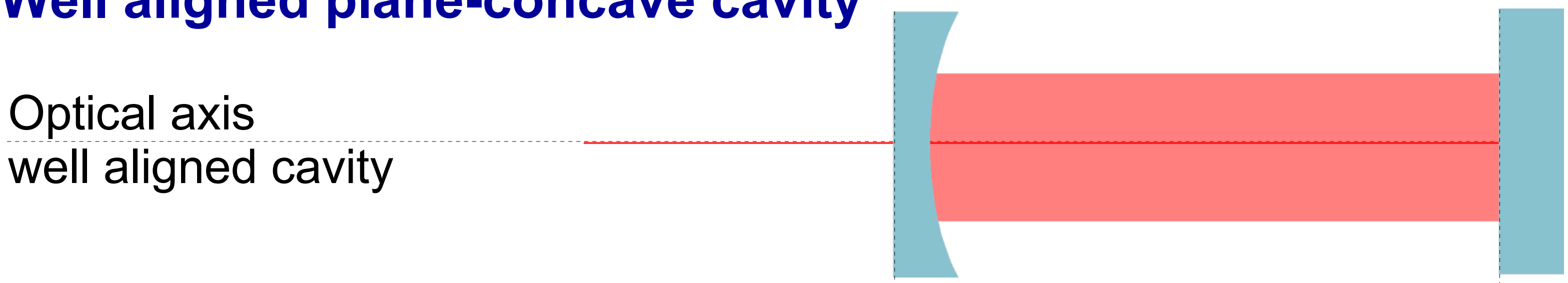


Two examples of mode matching telescopes from the injection system:

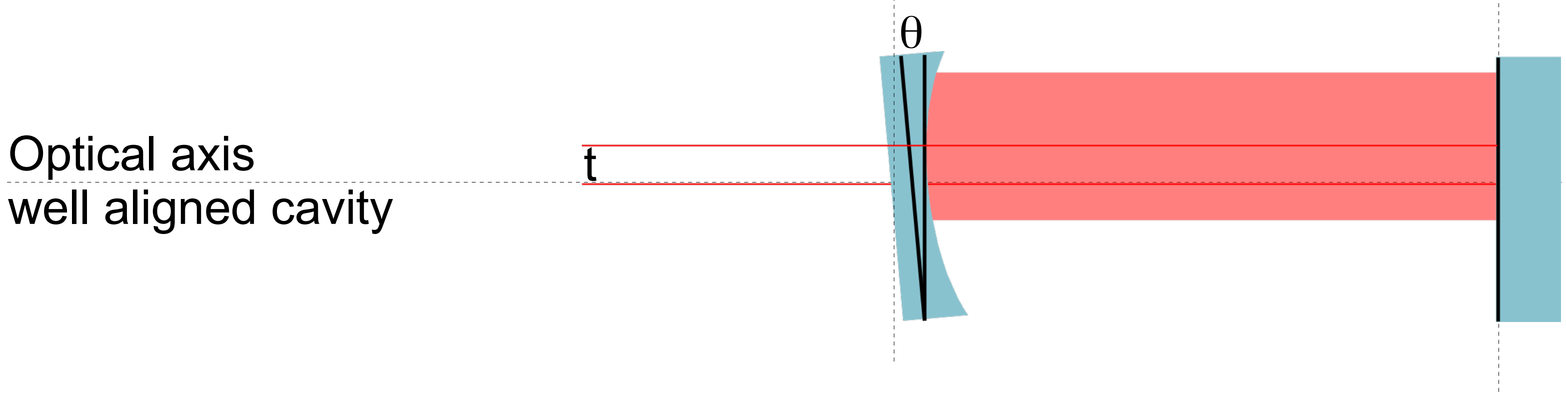


Example bad mode matching

Well aligned plane-concave cavity



Misaligned plane-concave cavity: input mirror misaligned

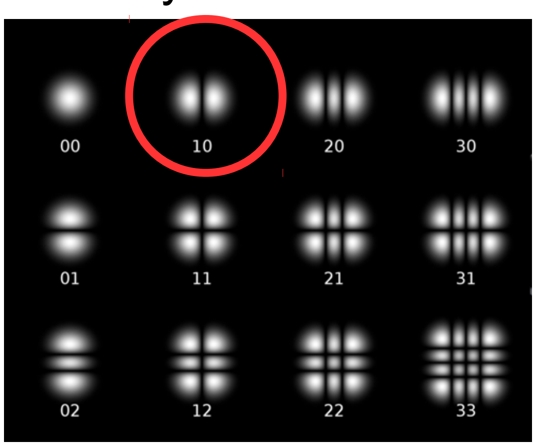


$$\vec{E}(x,y,z) = \vec{U}_{00}(x-\Delta x, y, z)e^{ikz}e^{i\omega t}$$

$$= (\vec{U}_{00}(x-\Delta x, y, z) + \frac{\Delta x}{\omega_0}\vec{U}_{10}(x-\Delta x, y, z))e^{ikz}e^{i\omega t}$$

10 mode carries information on the alignment → quadrants

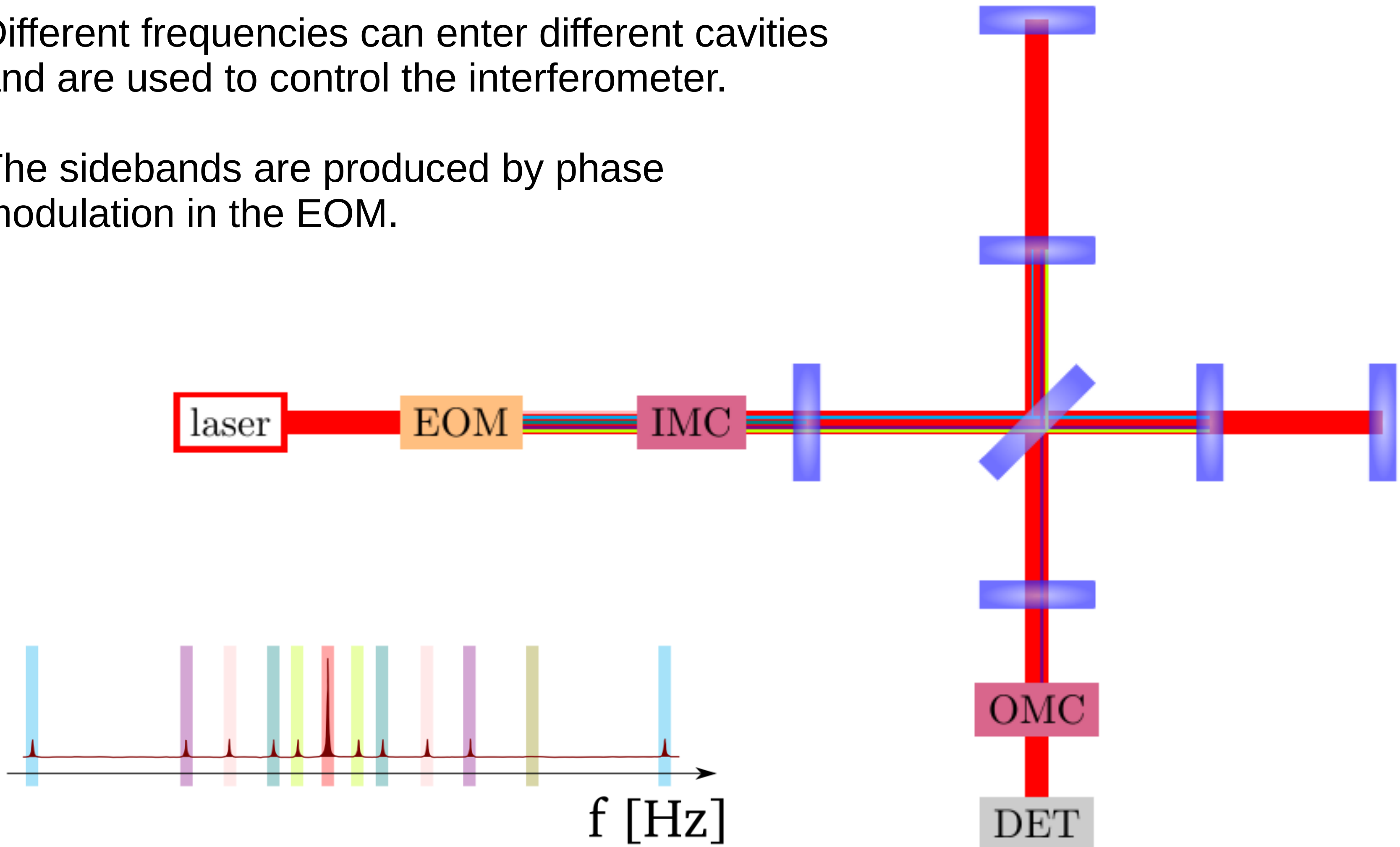
Intensity HOMs:



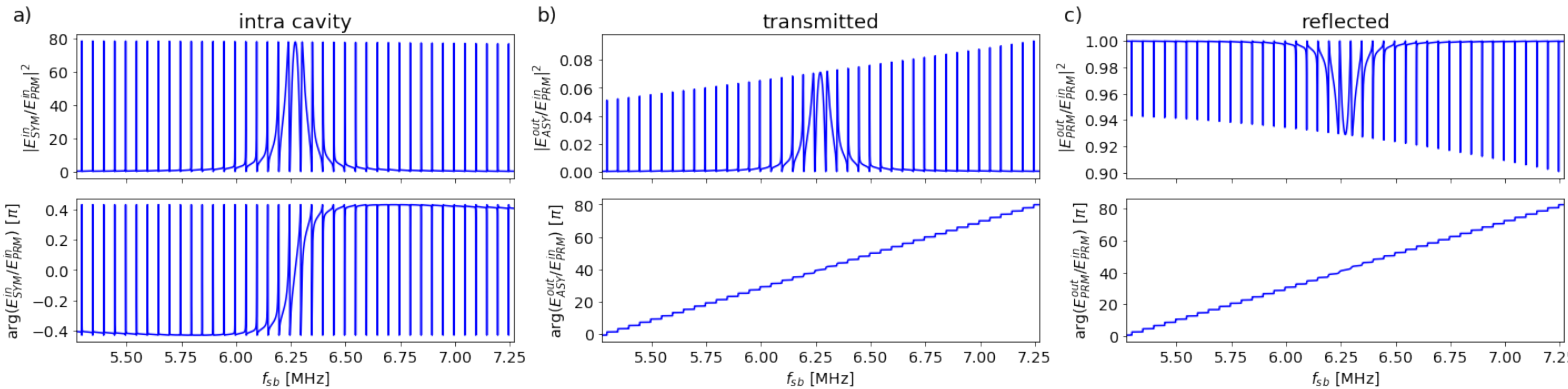
Sidebands for the alignment

Different frequencies can enter different cavities and are used to control the interferometer.

The sidebands are produced by phase modulation in the EOM.



PRC – marginally stable cavity



Resonance width PRC: 0.1 MHz → kL = 0.025 rad
Resonance width arms: 112 Hz → kL = 0.007 rad

(round trip phases less than 2kL are resonant)

Round trip phase (after the kz term has been used to get the fundamental mode resonant)

$$\Phi(2L) = (l + m + 1)\arctan(\frac{2L}{z_R})$$

→ 1 mrad for PRC (smaller than the resonance width)
→ 1.5 rad for arms (larger than the resonance width)

→ so many higher order modes in the PRC that the error signals for the alignment can start to drift