The Angular Control for Virgo

Julia Casanueva
INFN Pisa

Introduction

Working point

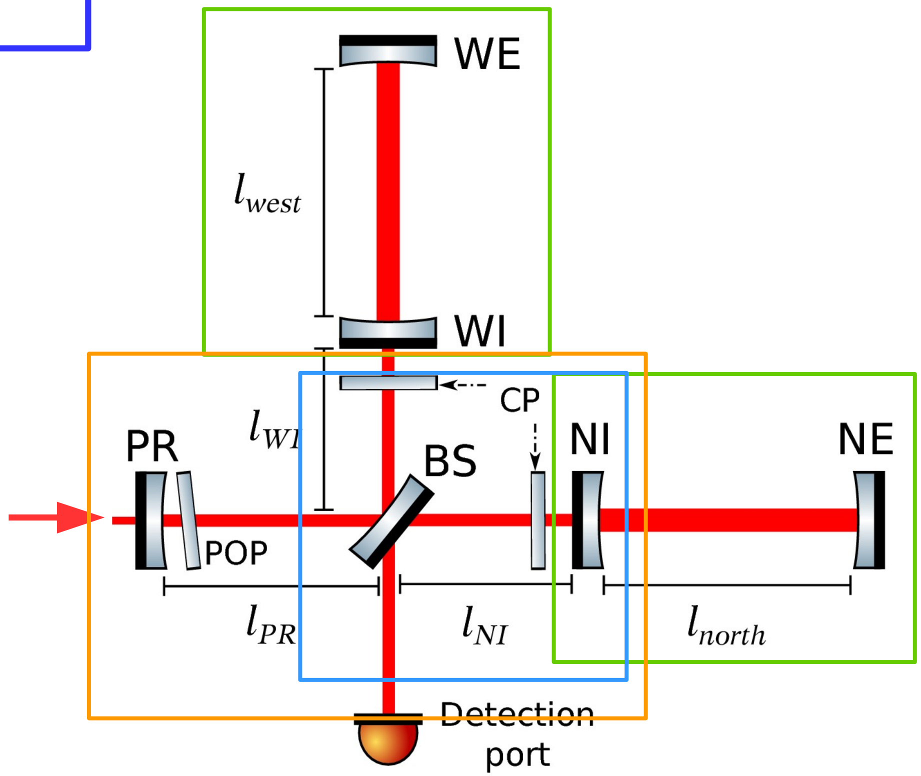
Working point of maximum sensitivity

- **Arm cavities** and **PRC** → *Resonance*
- **Michelson** → *Dark Fringe*

Estimation of the required precision

- PRM ~ $25 \cdot 10^{-9}$ rad
- Arm cavities ~ $2 \cdot 10^{-9}$ rad

VERY CHALLENGING!!

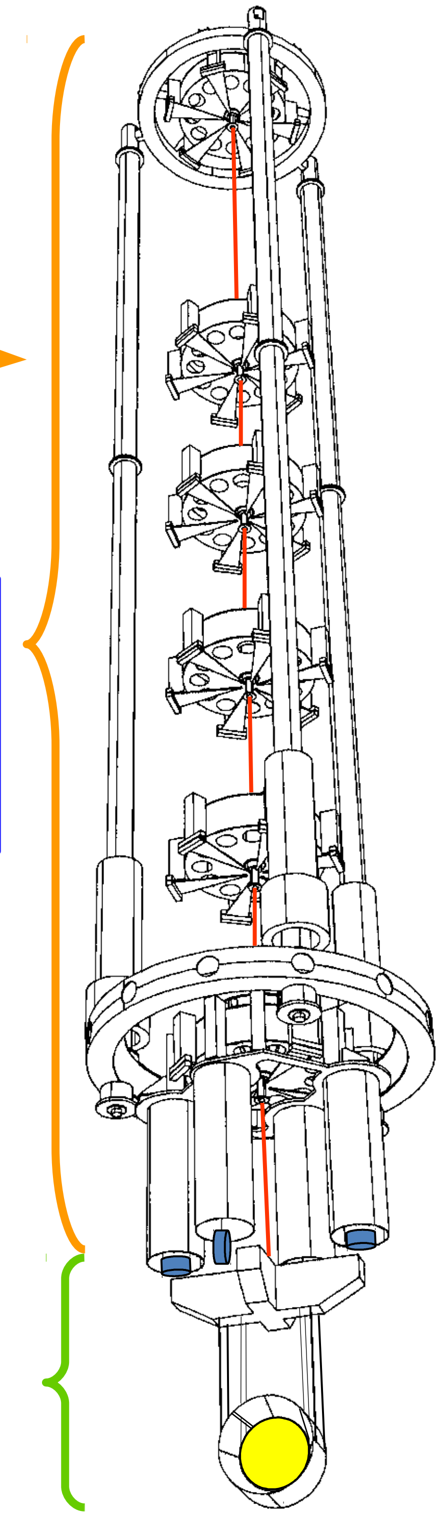


Seismic noise

- Dominant at low frequencies → **Superattenuator**
  - Factor 10^{12} of attenuation above 10Hz

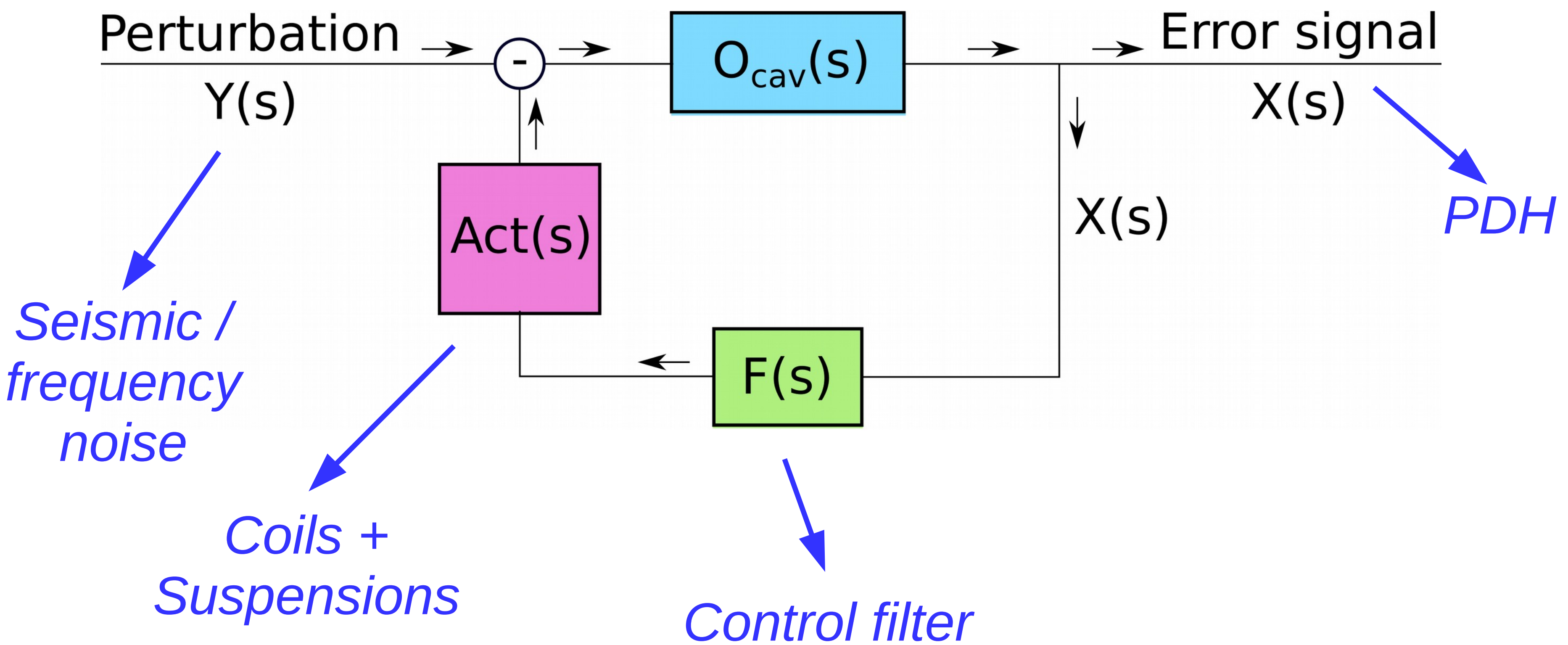
Residual seismic noise is **TOO HIGH** moves the mirrors both angularly and longitudinally → individual working point is crossed in a random way

- **Active control** is necessary to keep the ITF at its working point
  - *4 longitudinal* DOFs (lengths) + *frequency stabilization* (laser)
  - ***16 angular*** DOFs



Active control: feedback loop

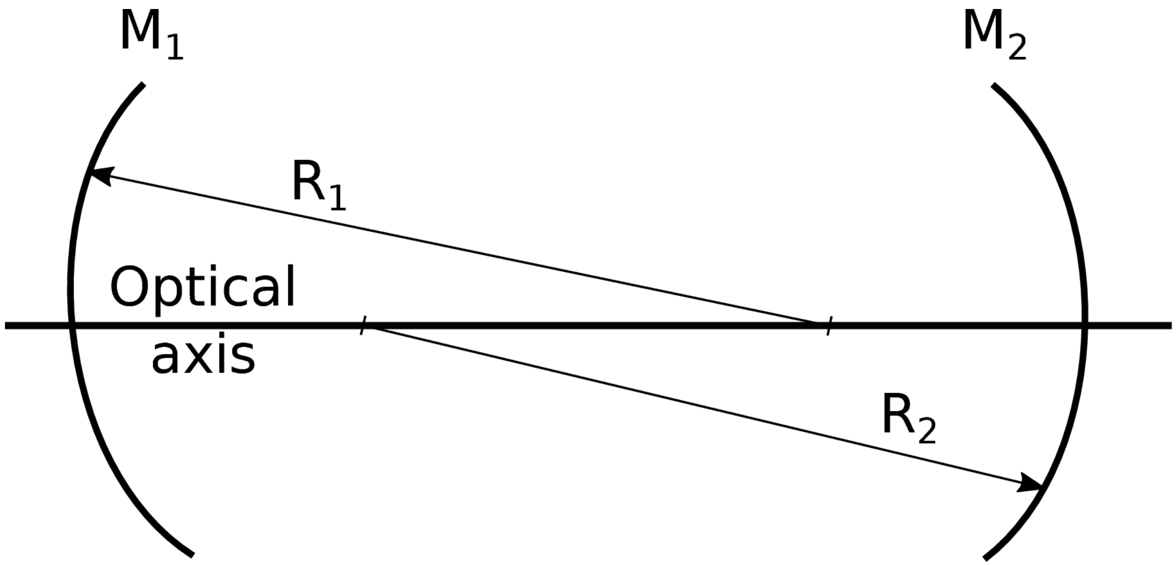
Control loops are composed of: **Plant** → Error signal → **Control Filter** → **Actuator** → **Plant**



Angular degrees of freedom

Optical Axis

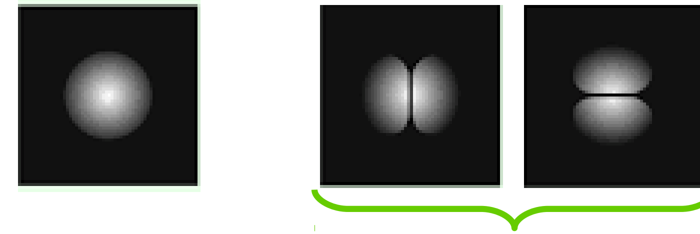
- An optical cavity is aligned when the *input beam and the optical axis are aligned so that no HOMs are generated* → all the power couples into the cavity



- **Optical axis** → line that intersects both centers of curvature

What happens in the presence of a misalignment?

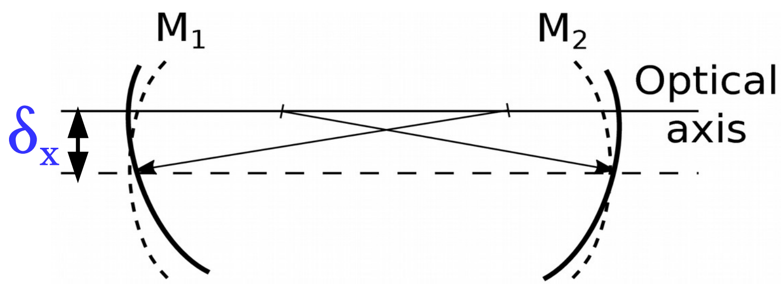
Angular control: HOMs



Fundamental mode

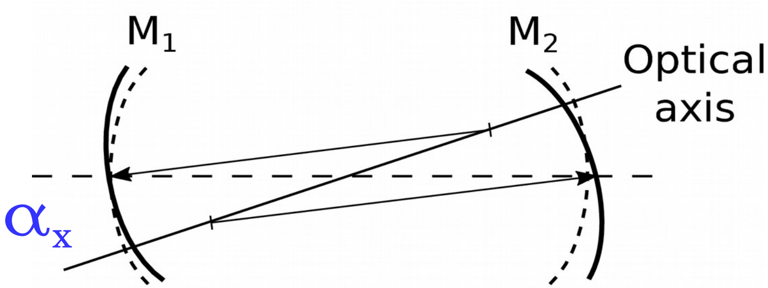
First modes

- Laser beam follows the **paraxial approximation** → described by a set of *Hermite Gauss modes*



- **Shift** of the optical axis

$$E(x+\delta_x) \approx A \cdot \left[H_0(x) + \frac{\delta_x}{w_0} \cdot H_1(x) \right]$$



- **Tilt** of the optical axis

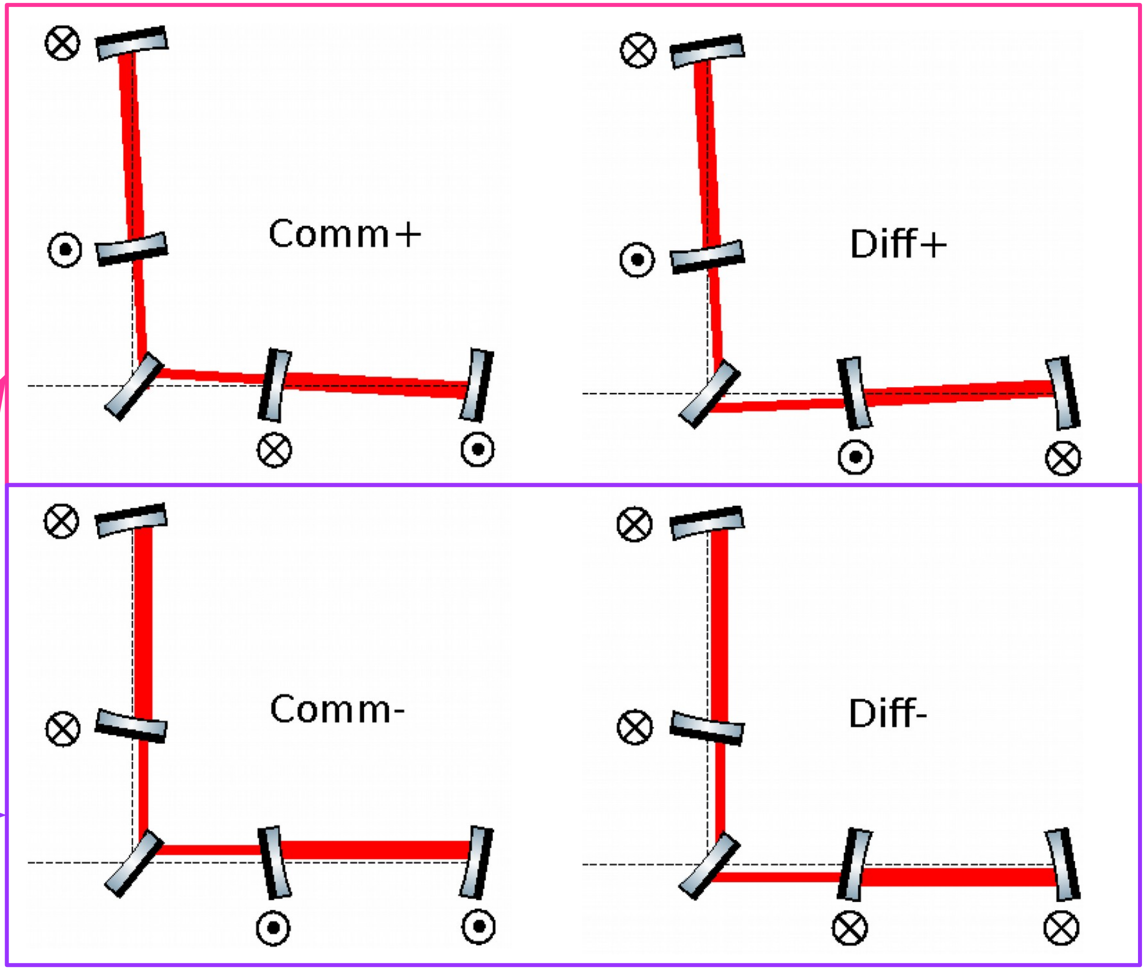
$$E(x+\alpha_x) \approx A \cdot \left[H_0(x) + i \cdot \frac{\alpha_x}{\theta_d} \cdot H_1(x) \right]$$

- **Higher Order Modes** *decrease the power of the fundamental mode* **AND** they can *couple inside the cavity*
- Misalignment changes the length of the cavity → *angular movements couple to the longitudinal control*

Interferometer angular DOFs

- There are (*6 mirror angular DOFs* **+** *2 input beam angular DOFs)* **x** *2 symmetry planes* **= 16 DOFs in total**

- **BS** mirror tilt
- **PR** mirror tilt
- Cavities tilt **(+)**: **Comm** and **Diff**
- Cavities shift **(-)**: **Comm** and **Diff**

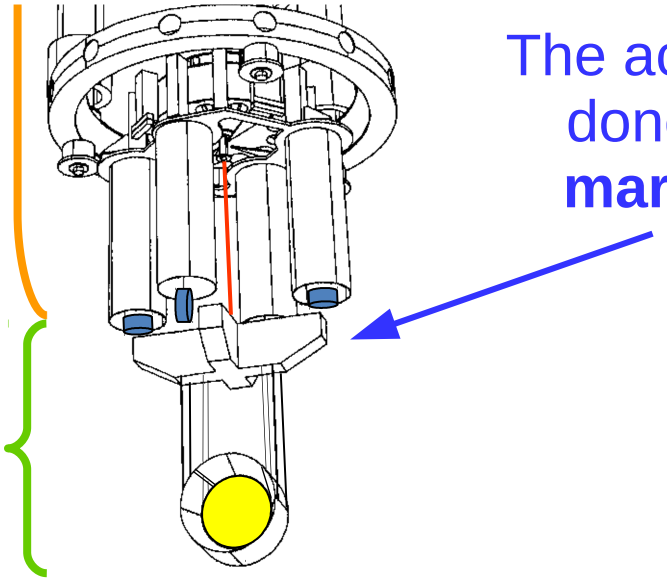


Angular error signals

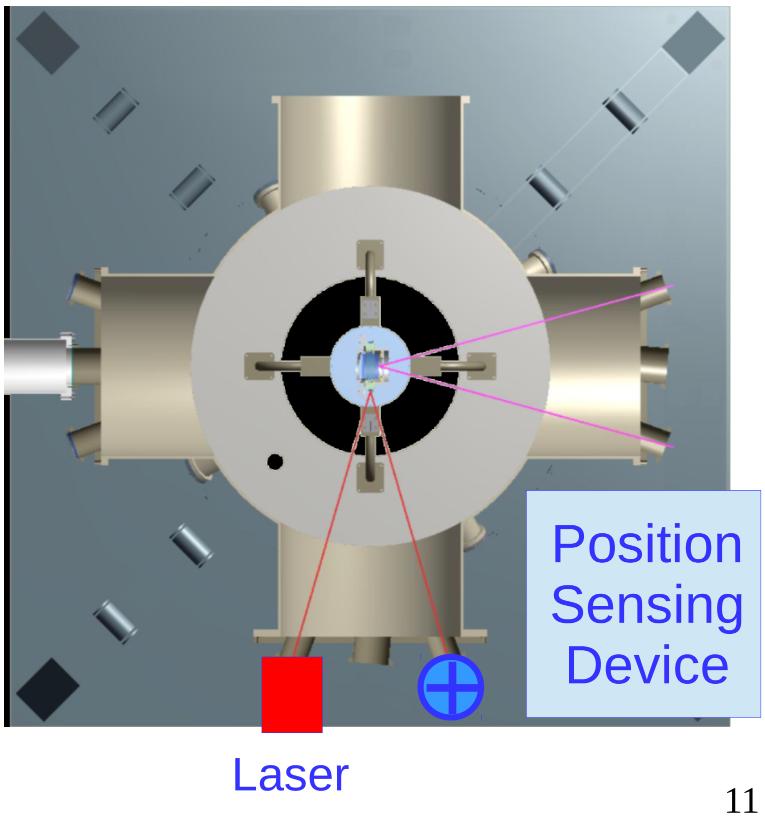
Pre-stabilization

No information on the Beam!

- Residual movement is too high to engage any control
  - Longitudinal movement → *Dampers*
  - Angular movement → ***Local controls*** *(Control up to ~3Hz)*
- Local controls use *optical levers* to monitor the angular position of the mirror *with respect to the tower*
  - Allow a control of ~0.5urad rms
  - Slow drifts (~1urad per hour)



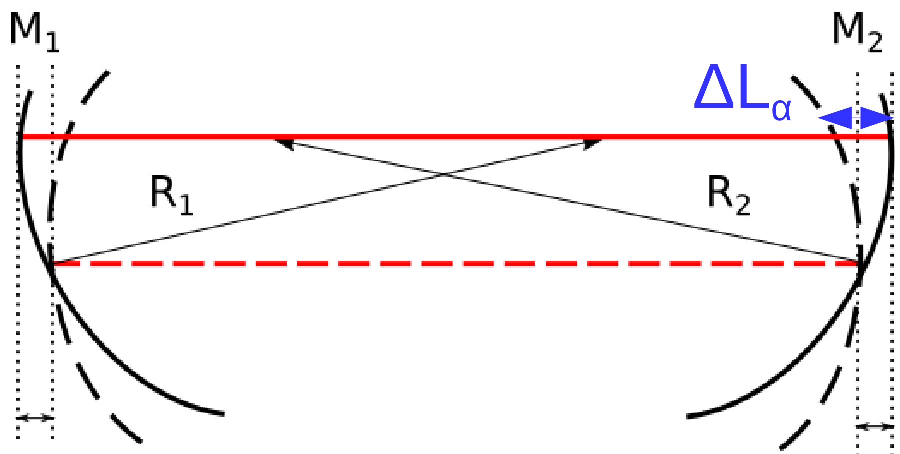
The actuation is done at the **marionetta**



Mechanical modulation

Global signal → information on Beam/Mirror alignment

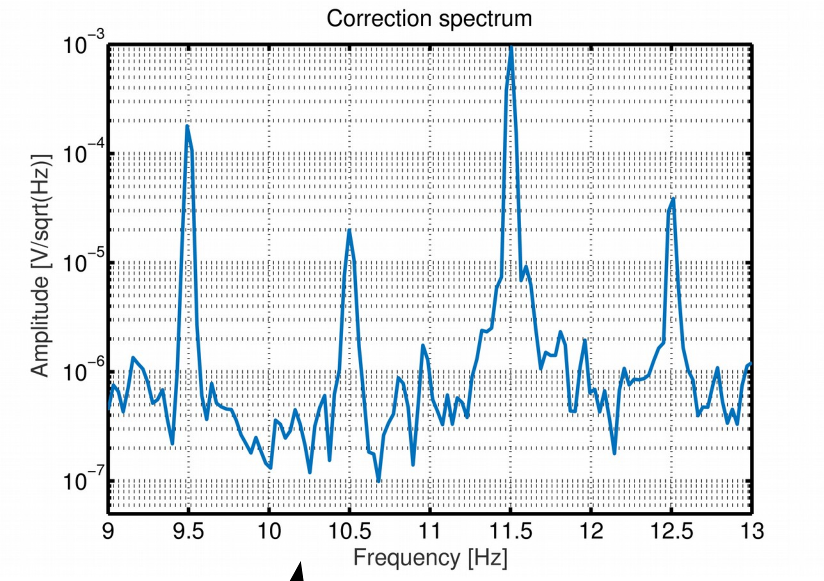
- **Target** → center the beam into the optics
  - Add a *tilting oscillation* to *each angular DOF* of *each mirror* at a different frequency $\omega_\alpha^{(DOF)}$
  - When the **optical axis is miscentered** there is a ΔL_α → frequencies *$\omega_\alpha^{(DOF)}$ appear on the longitudinal correction*



This control allows a precision ~0.5 urad rms and a band of ~ 30mHz

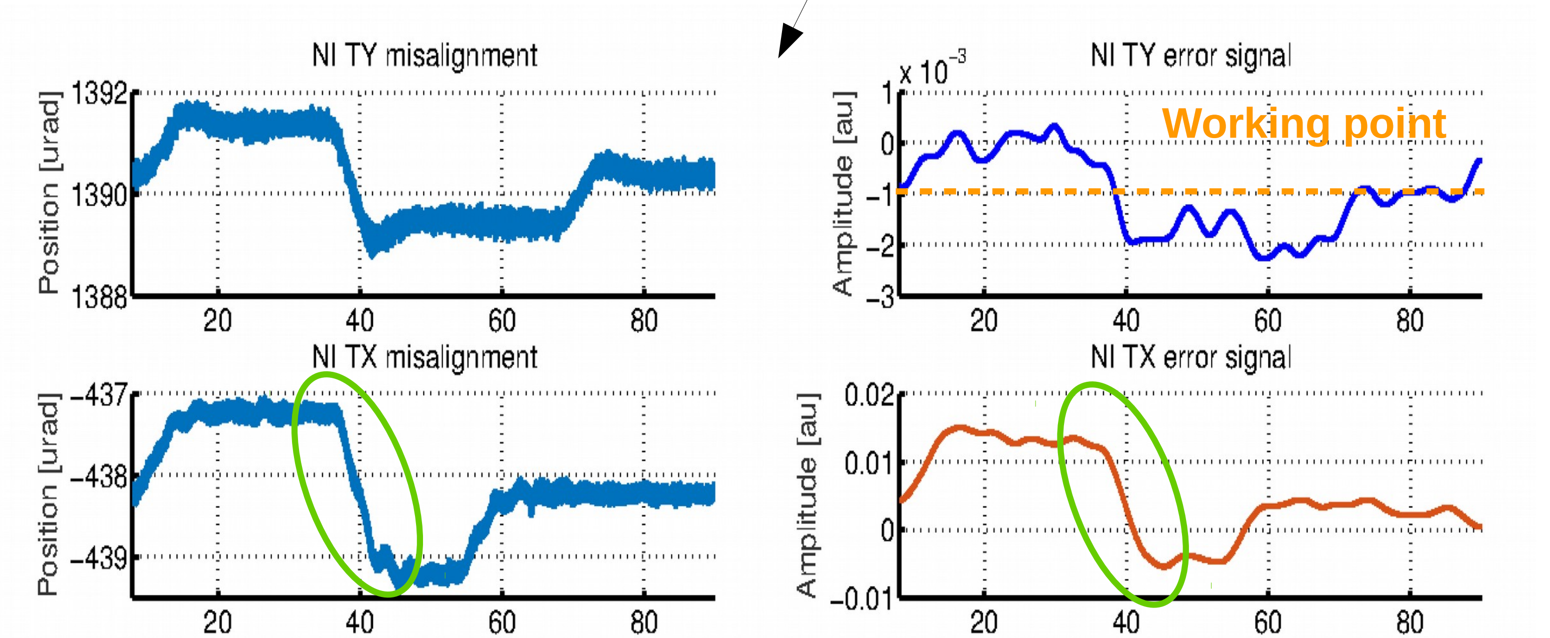
- The error signal is built by demodulating the longitudinal correction @ $\omega_\alpha^{(DOF)}$
- The **input beam alignment** impacts the power coupling inside the cavity → error signal uses the *P_{tr} by the cavity*

Mechanical modulation @ North arm



Modulation lines of North Arm

Demodulated error signals



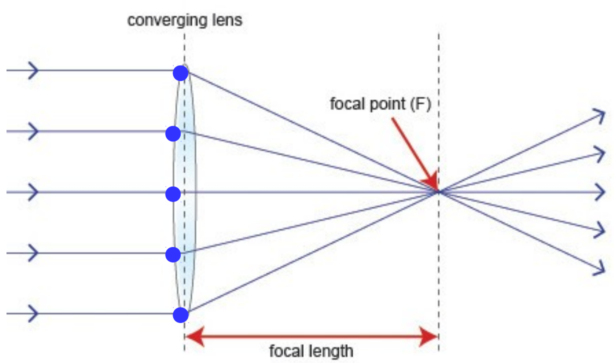
Julia Casanueva

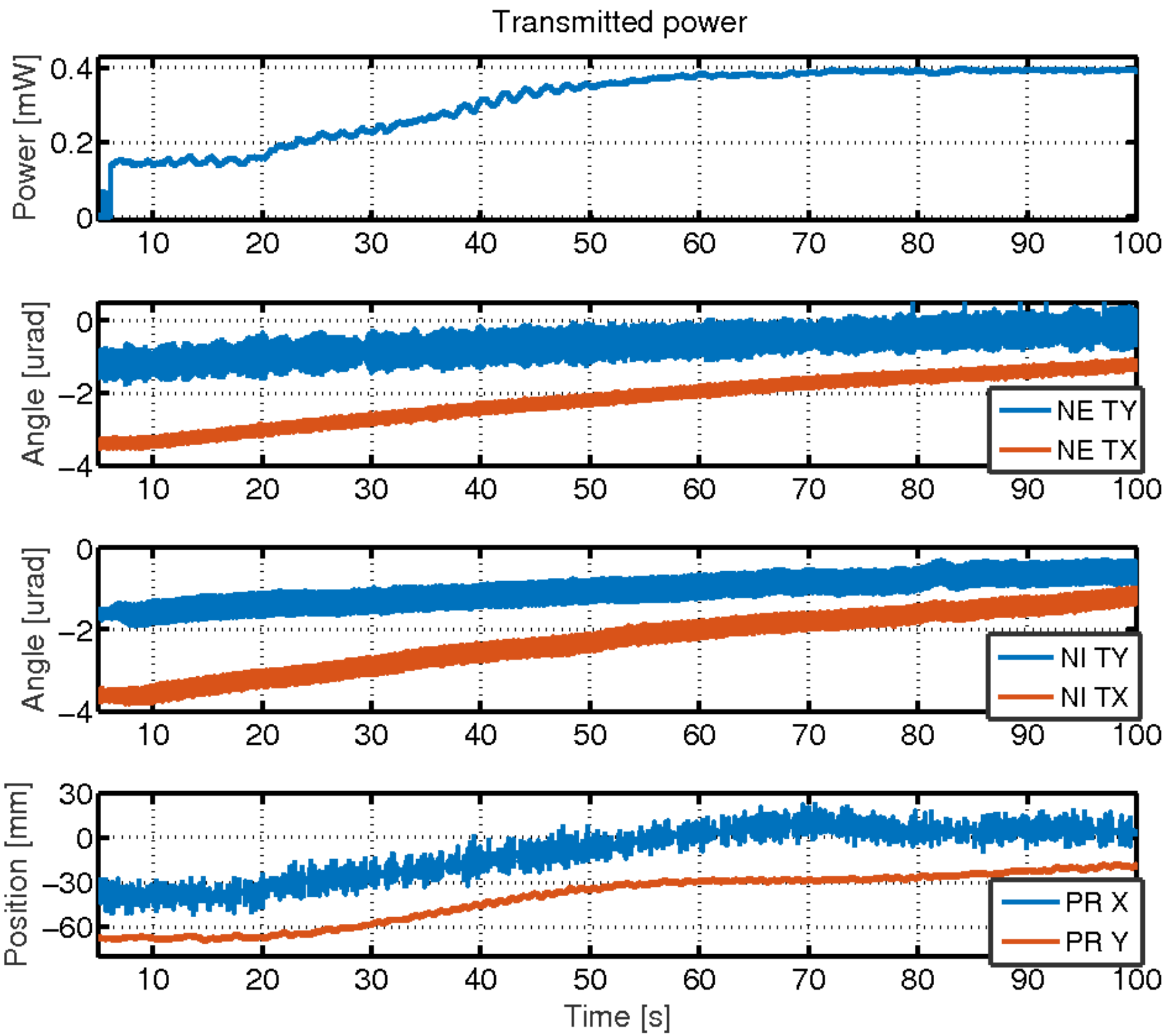
Mechanical modulation @ North arm

➔ To align the arm cavities we use the mechanical modulation previously described

Input Beam actuators:

- West arm: BS tilt
- North arm: PR translation





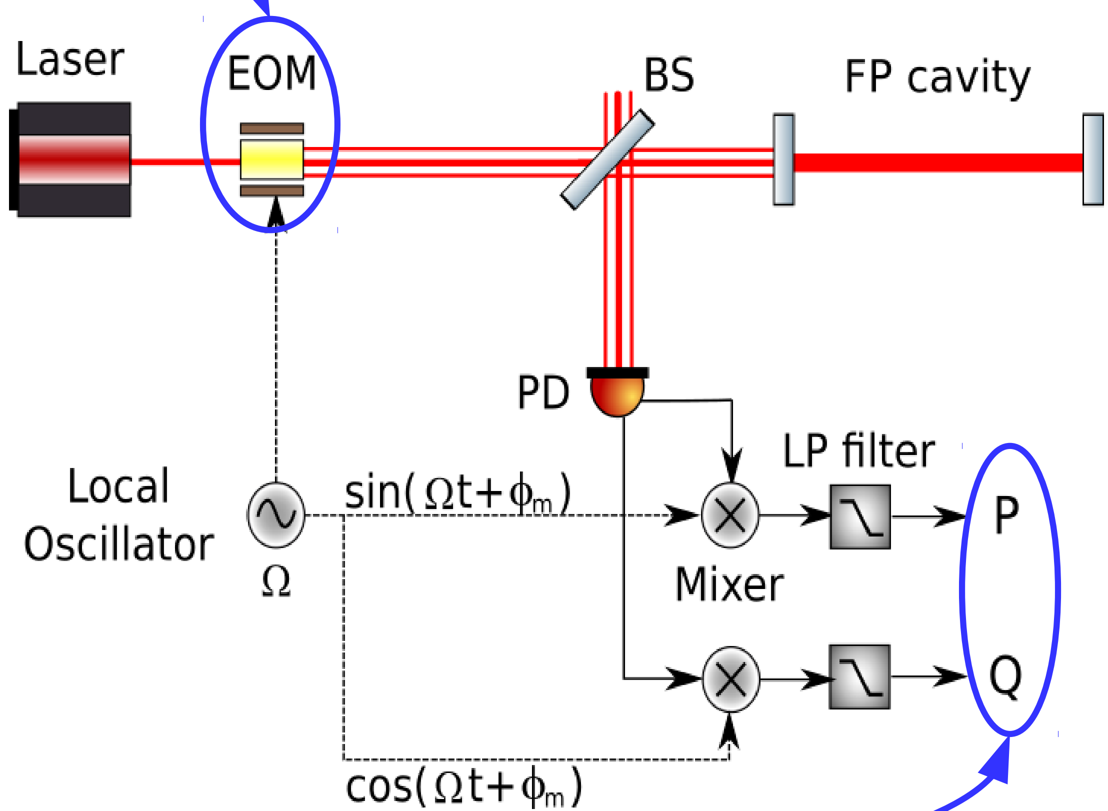
We can see how the mirrors move in order to reach the *maximum transmitted power*

Julia Casanueva

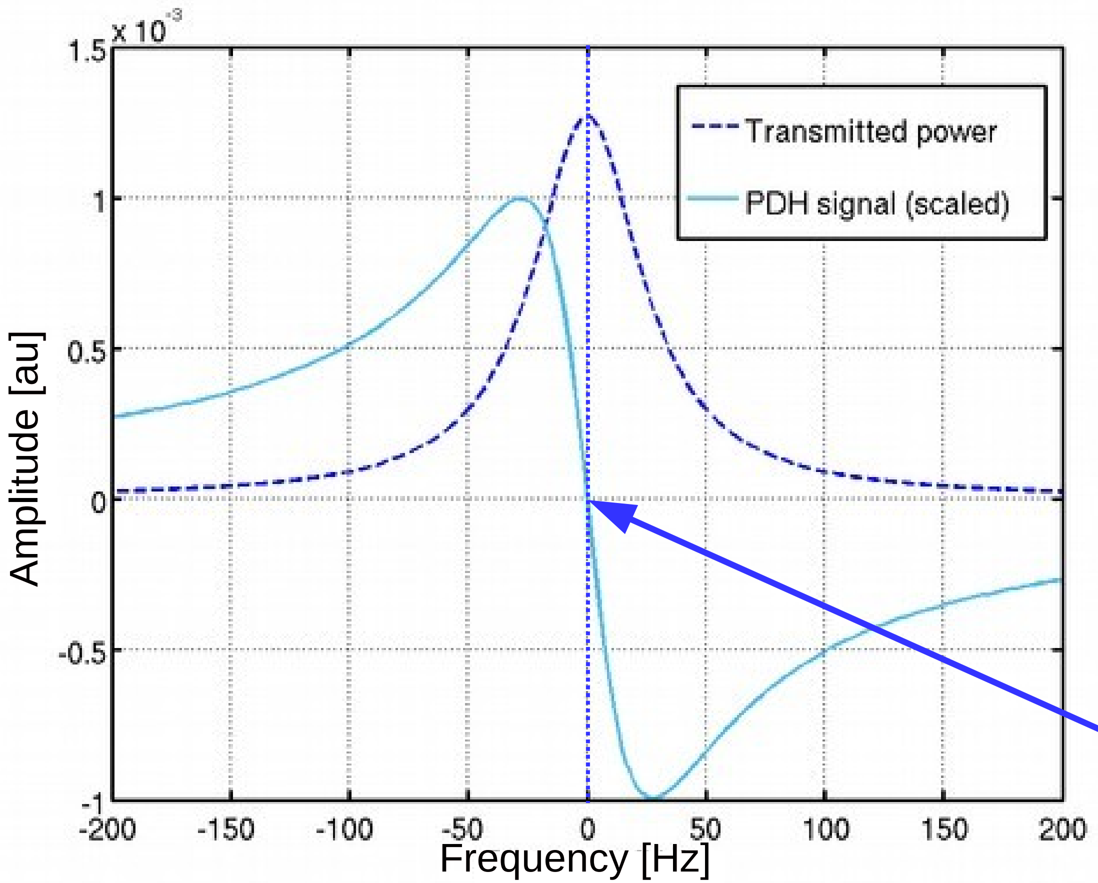
Phase modulation: Pound-Drever-Hall technique (PDH)

- **Error signal:** provides information about how far is the cavity length from the resonance position.

- Phase modulation: create *sidebands* around the carrier (ω_0) at ± the modulation frequency, Ω.
- **Error signal** → *beat note between carrier and non-resonant sidebands*
- **Demodulation:** select the interesting term
- Two signals: **in-phase** (P) and **in-quadrature** (Q)



Phase modulation: PDH technique



Good error signal fulfills:

- *Linear* around the working point
- *Bipolar*
- *Zero-crossing* at resonance

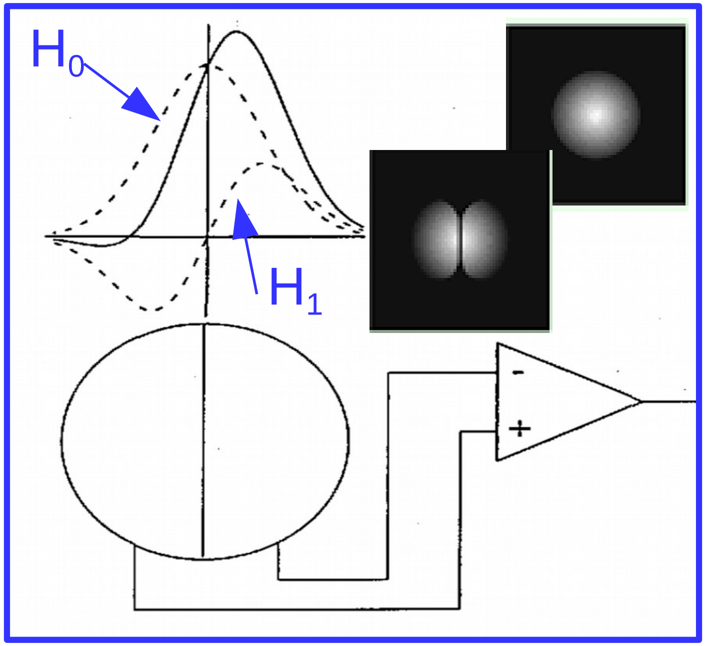
Working point

Phase modulation

Global signal → information on Beam/Mirror alignment

- **Phase modulation** → measure the spatial beam phase distribution (Ward's technique)
  - ➔ Reflected field contains the <u>*beat note*</u> between the ***HOMs*** produced and the ***fundamental mode*** (carrier and sidebands)
  - ➔ Demodulation is needed to select the interesting term, Ω
  - ➔ A special photodiode is needed since $H_0(x) \perp H_1(x)$ and integrating over the whole surface → 0

Quadrant photodiode (QPD) is divided in sectors → the difference between them gives us information on the *1st order mode ONLY!*

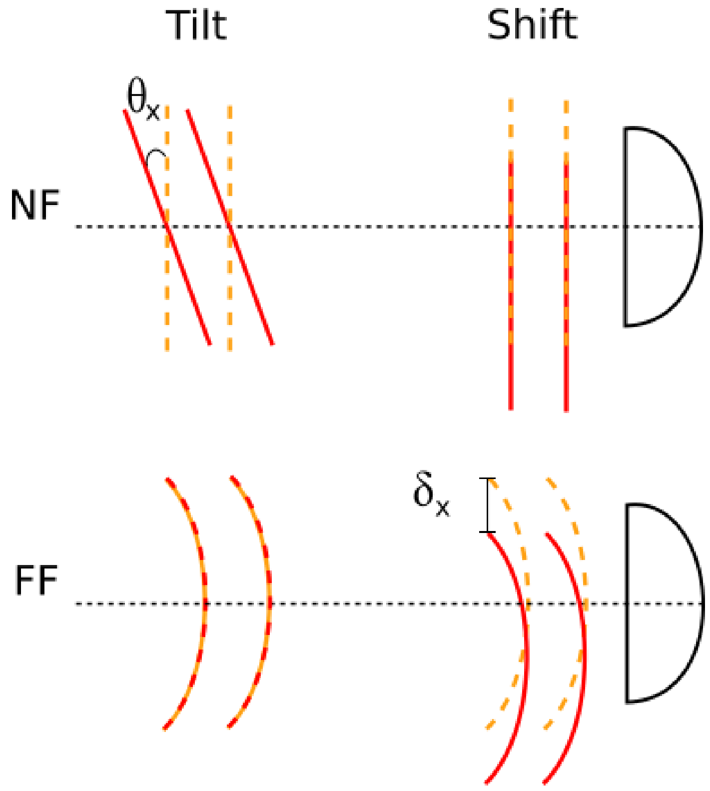


Phase modulation

- **Phase modulation** → measure the spatial beam phase distribution (Ward's technique)

  ➔ After demodulation ALL information is on one projection → *angular DOFs are mixed!!*

- Two QPDs are necessary:
  - **Near Field** → at the waist of the beam (plane-wave)
  - **Far Field** → radius of the beam converges to z (distance from the waist)

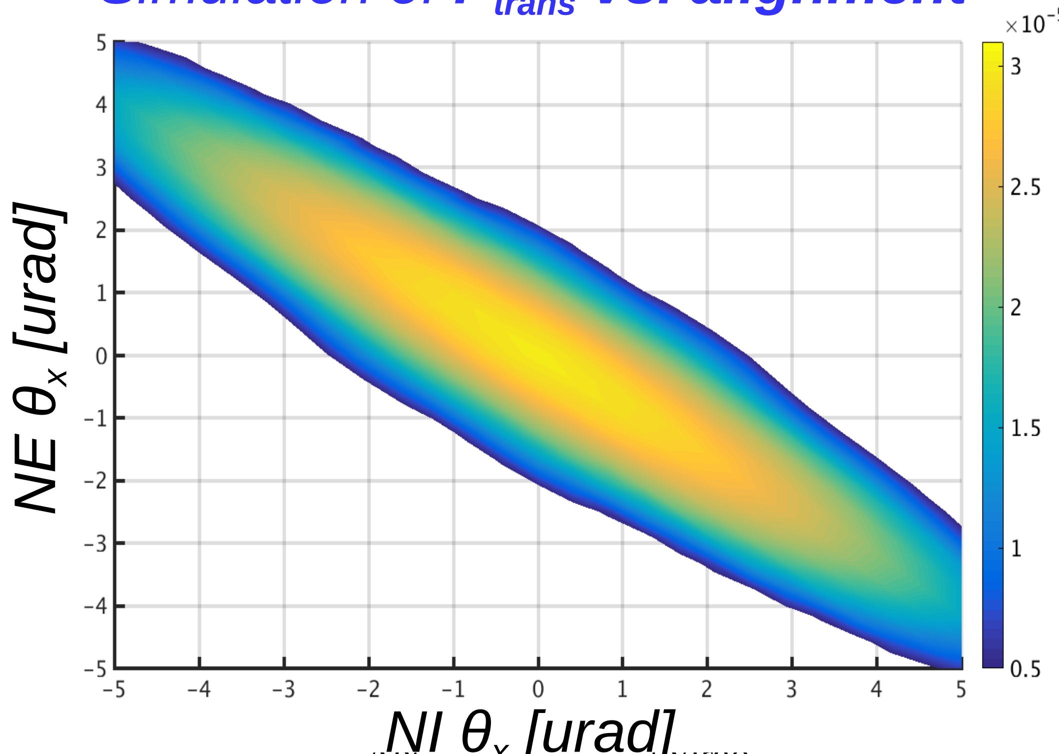


Actuation

Driving of angular DOFs

- The two mirrors of the cavities in the arms are **curved** → *angular DOFs do not correspond to the mirror angular positions*
  - It is necessary to find the *driving that decouples the angular DOFs* → **slope of the figure**

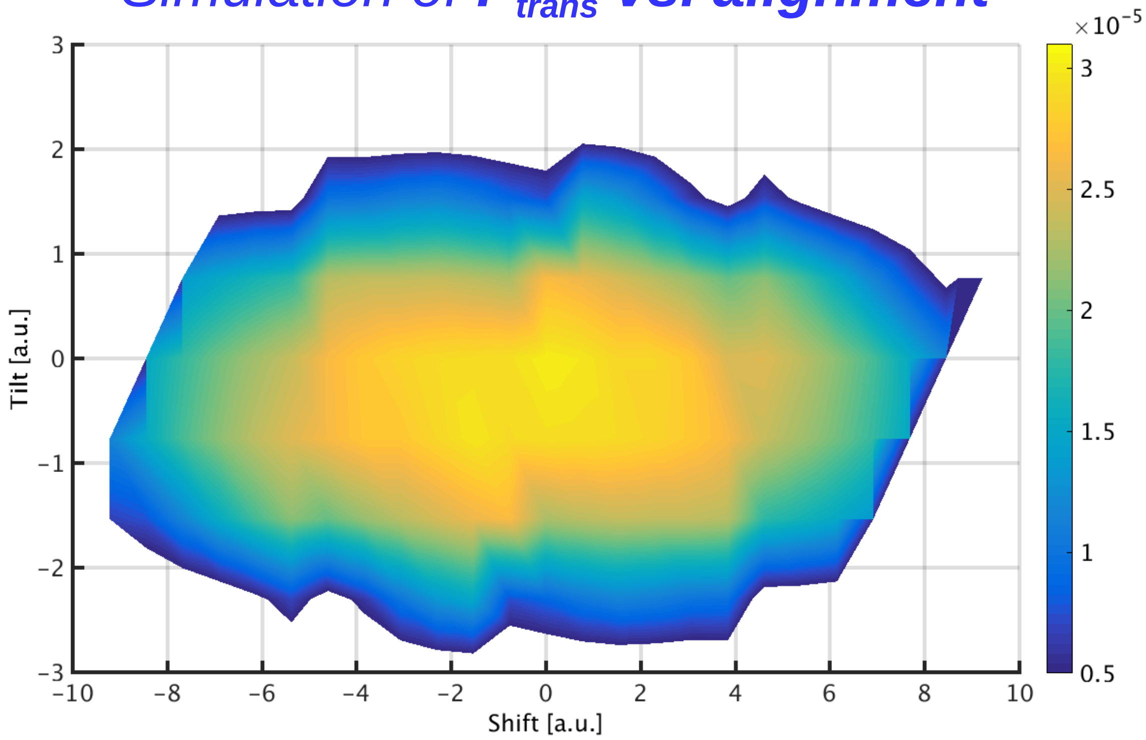
Simulation of ***P_{trans} vs. alignment***



Tilt / Shift sensitivity

- Arm cavities of Advanced Virgo → *more sensitive to Tilt than to Shift*
  - Important in terms of requirements → more stringent for tilt DOFs

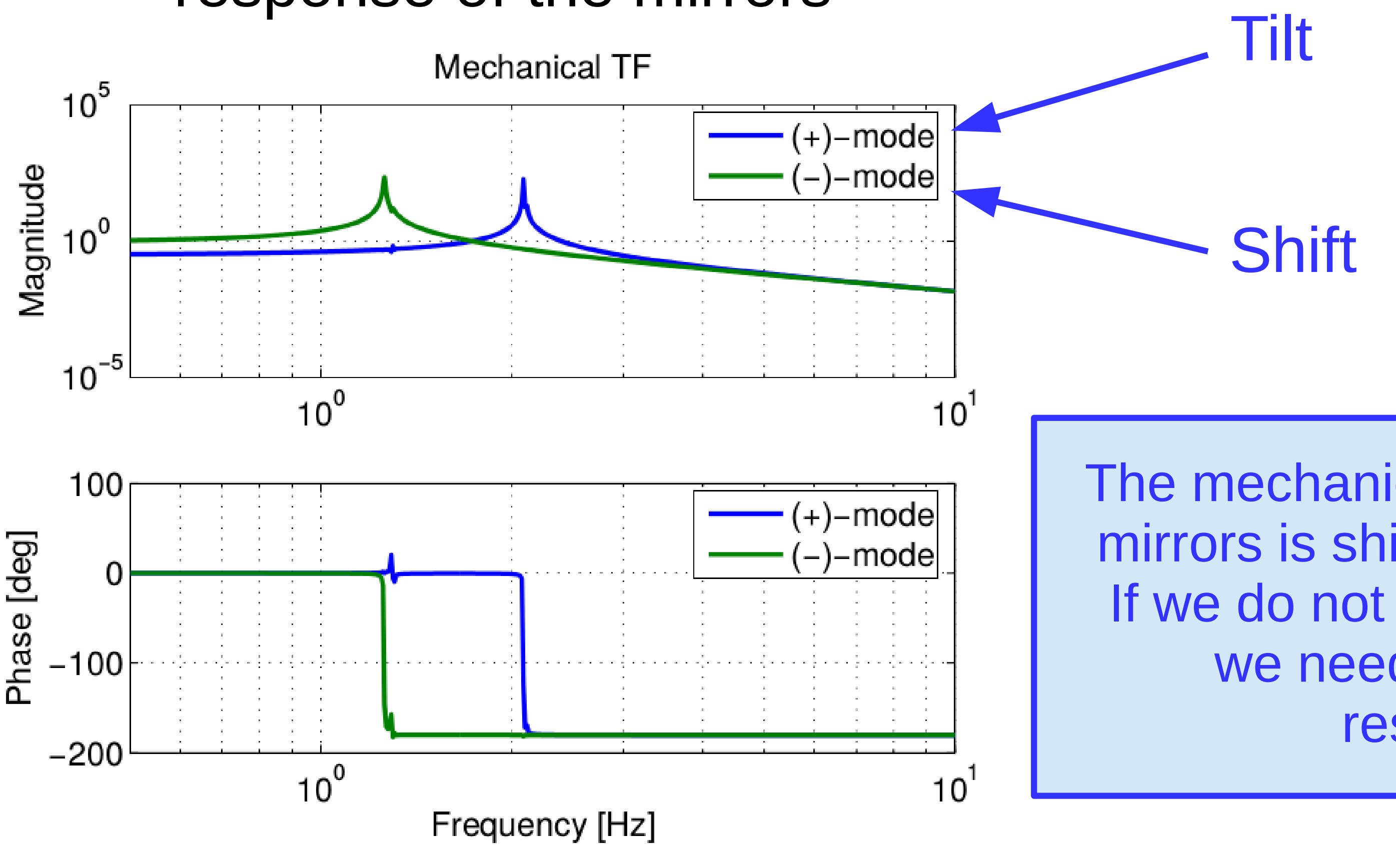
Simulation of P_{trans} vs. alignment



- Tilt ~ $1.5 \cdot 10^{-9}$ rad
- Shift ~ $10 \cdot 10^{-9}$ rad

Radiation pressure

- When there is a lot of power circulating inside a Fabry-Perot cavity → **Radiation pressure**
  - *Optical spring appears* → Modifies the angular mechanical response of the mirrors



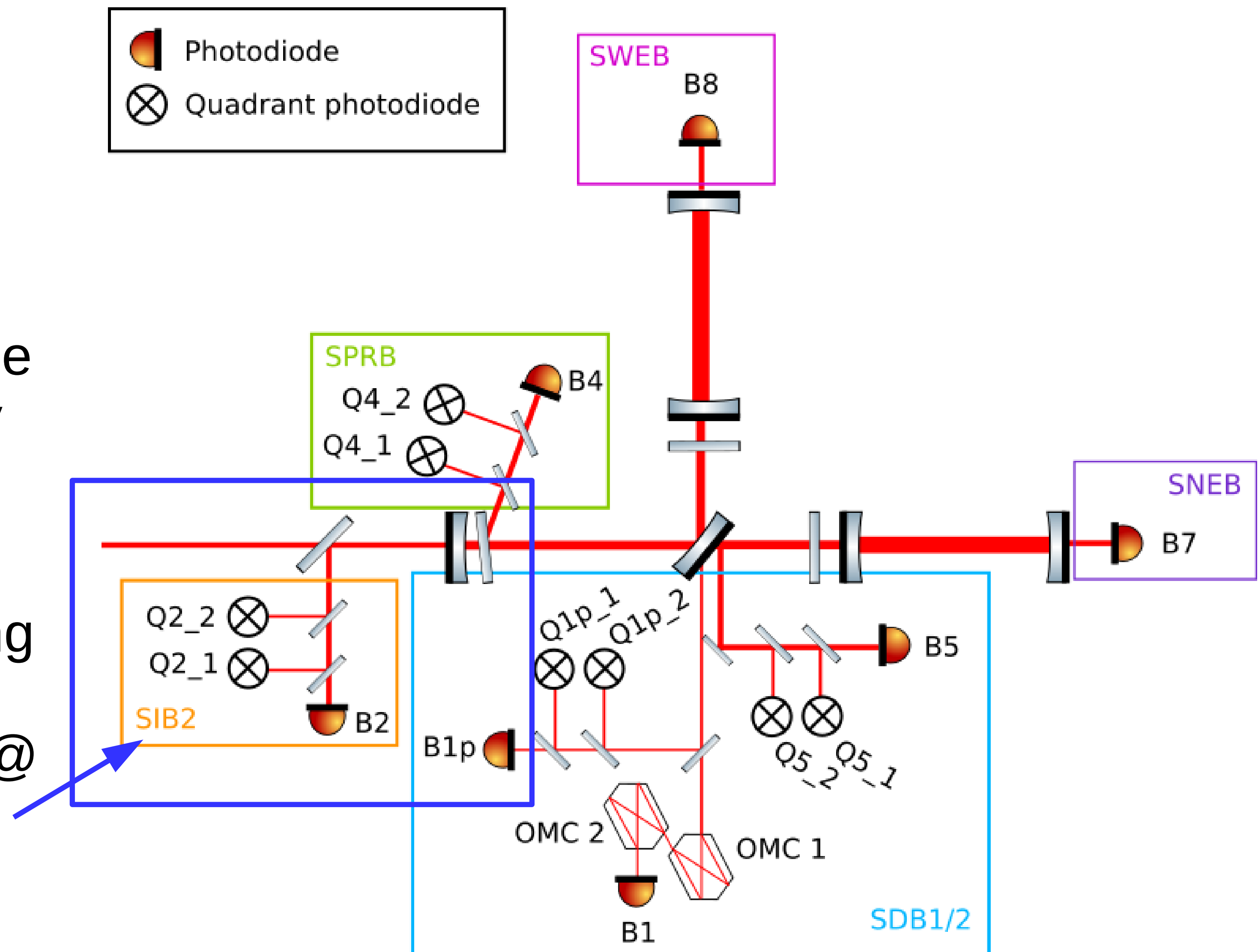
The mechanical resonance of the mirrors is shifted in frequency → If we do not decouple both dofs we need to deal with 2 resonances

Angular control strategy in Advanced Virgo

Angular control strategy

Alignment experiments **slow drifts** (~ tenths of minutes) → *not critical during control acquisition*

- **Strategy:** good *initial alignment* (mechanical modulation @ arms) + control the *critical DOFs* only (PR)
  - PR tilt → controlled using B2 QPD demodulated @ 8MHz



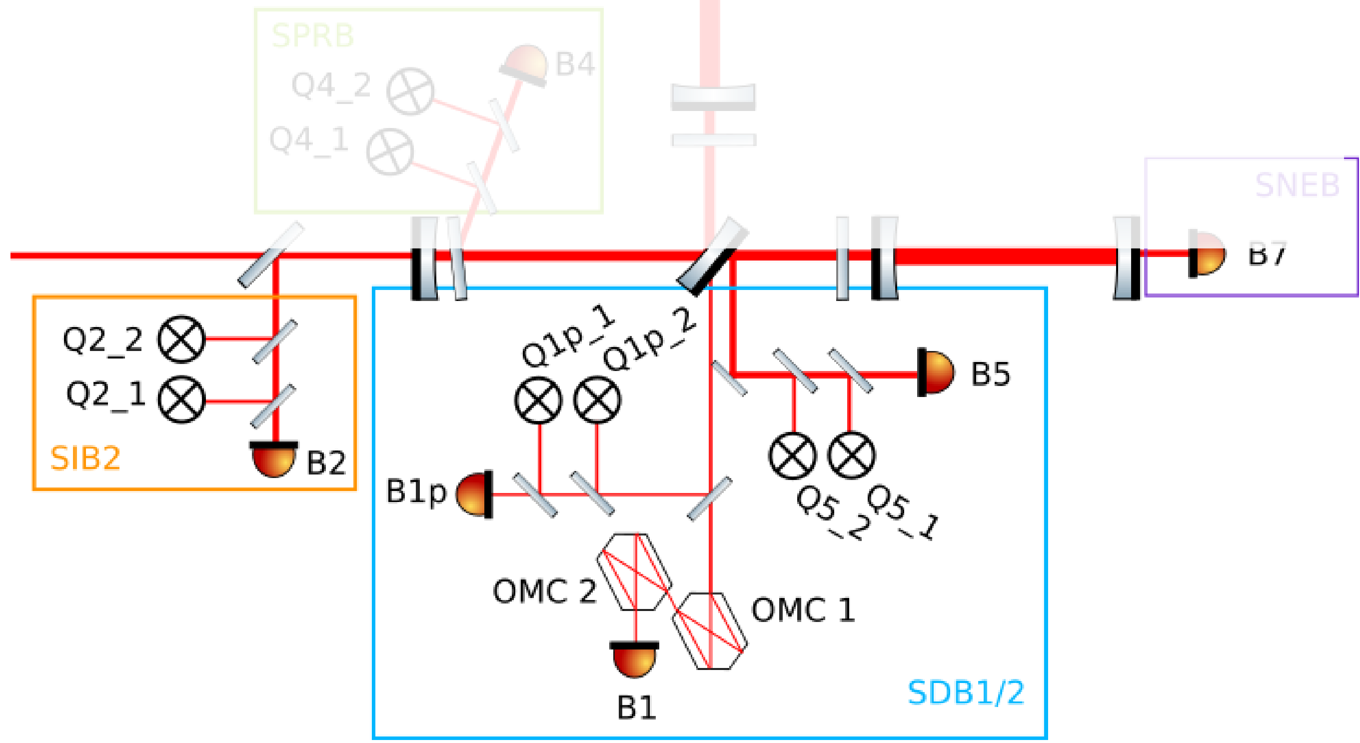
Alignment in Dark Fringe

1) **Define the ITF plane** → 3 points are needed (mechanical modulation)

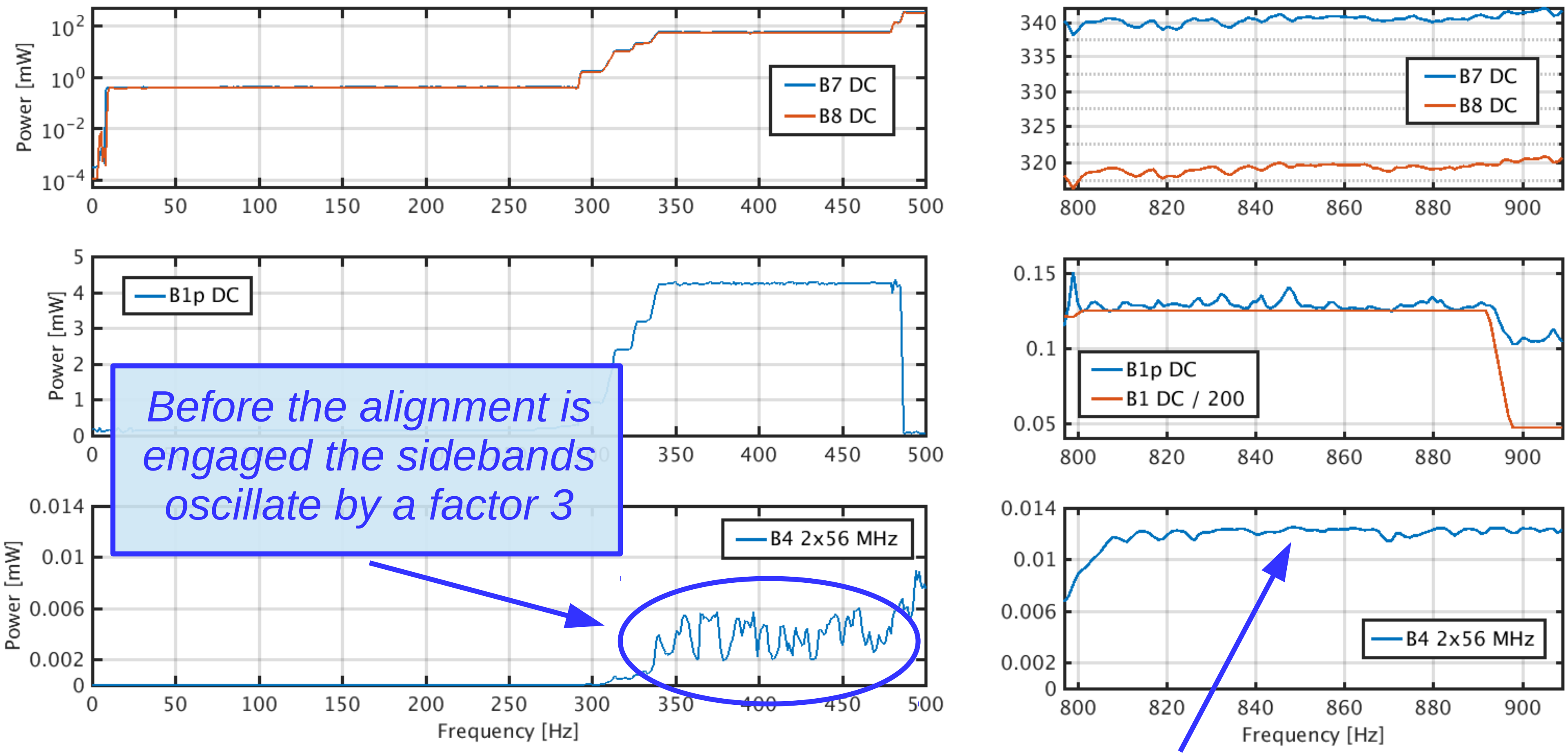
- **Working point of the Shift** of the cavities **(-)** is defined by the *center of the End Mirrors* *(up to ~30mHz)* → LCs up to 3Hz
- **COMM(+)** is defined using the c*enter of the WI mirror* → *B5 QPD DC up to 3Hz*

2) The rest of DOFs are controlled using QPDs

- PR tilt → B5 QPD @ 56MHz (I)
- BS tilt → B5 QPD @ 56MHz (Q)
- DIFF(+) → B1p QPD @ 56MHz
- PR translation (Input Beam tilt) → B2 QPD @ 8MHz



Alignment in Dark Fringe



Once the alignment is engaged the sidebands power stabilizes

Thank you!