Lock acquisition in Advanced Virgo: Guided Lock, SSFS and Automatic Alignment

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Interferometer **S**ensing and **C**ontrol

TARGET:

Bring the interferometer to its working point in a reliable and controlled way

PROBLEM:

- Residual seismic noise (*~1μm rms, ~1μm/s*) moves the mirrors both angularly and longitudinally → working point of each DOF 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* (Cavities, PR and BS)

Longitudinal DOFs (LSC)

Working point of maximum sensitivity:

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

Longitudinal Degrees Of Freedom

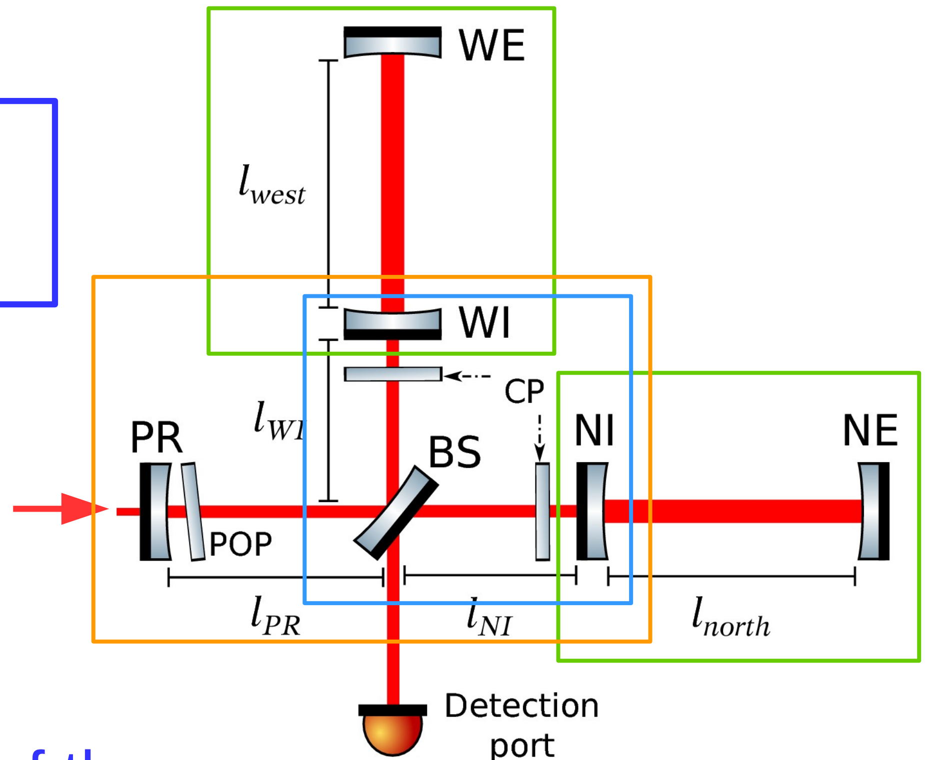
$$CARM = \frac{l_{north} + l_{west}}{2}$$

$$DARM = \frac{l_{north} - l_{west}}{2}$$

$$MICH = l_{NI} - l_{WI}$$

$$PRCL = l_{PR} + \frac{l_{NI} + l_{WI}}{2}$$

Estimation of the required control



- CARM ~ $4 \cdot 10^{-14}$ m
- DARM ~ $6 \cdot 10^{-12}$ m
- MICH ~ $2 \cdot 10^{-9}$ m
- PRCL ~ $7 \cdot 10^{-11}$ m

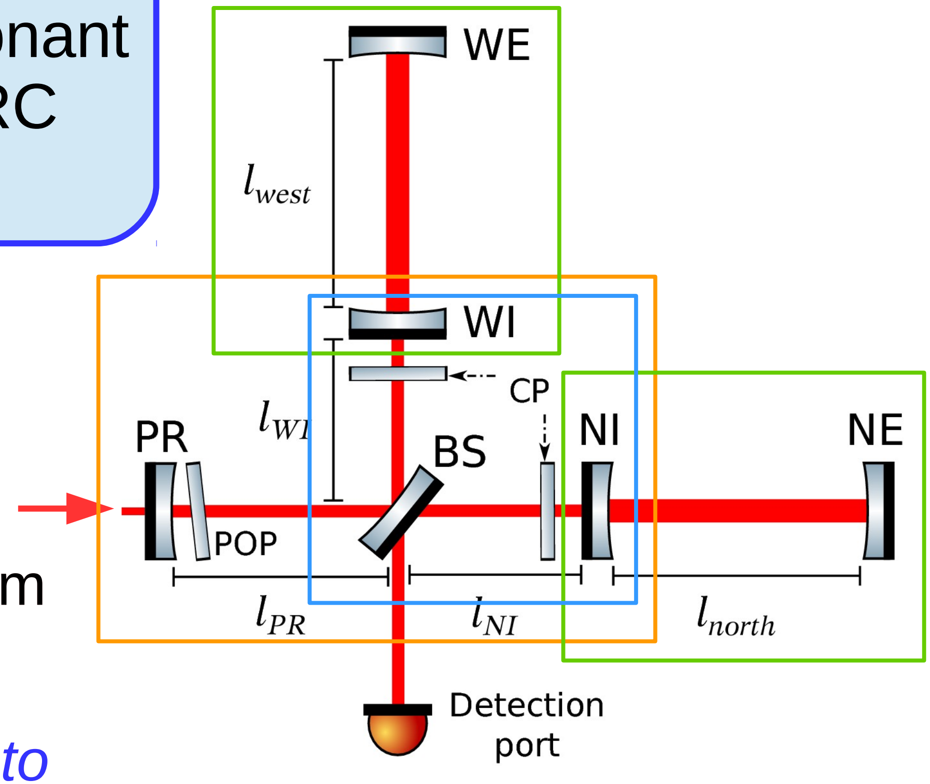
Longitudinal DOFs (LSC)

How do we build the error signals?

Ω_1 = 6 MHz
Ω_2 = 8 MHz

Arm cavities (Ω_1):
- Anti-resonant in the cavities
- Resonant in the PRC

PRC (Ω_2):
- Anti-resonant in the PRC



Error signal at the Detection port:
sidebands have to reach the Detection port even in Dark Fringe (carrier)

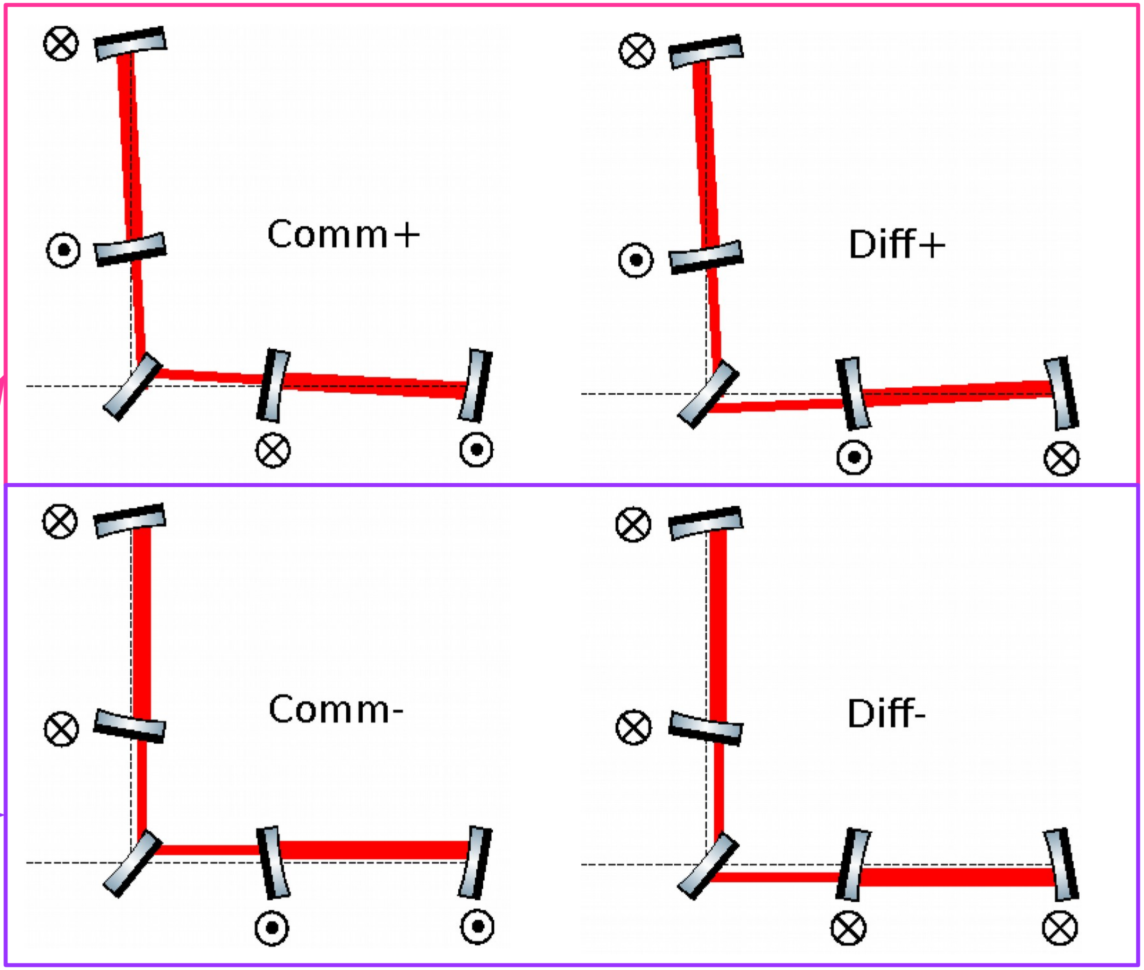
- *Schnupp asymmetry*: $\Delta_S = l_{NI} - l_{WI}$ = 23cm
- Interference condition depends on frequency so the *sidebands can "leak" to the Detection port:*

$$k_s = k_c + k_\Omega \rightarrow E_{det}(DF_c) \propto \sin(\pm\Omega\Delta_S/2)$$

Angular DOFs (ASC)

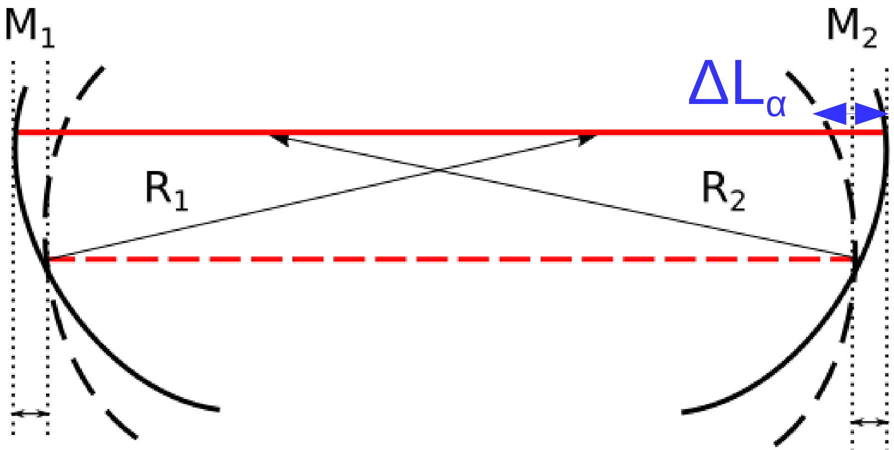
➔ There are (*6 mirror angular DOFs* **+** *2 input beam angular DOFs*) **x** *2 symmetry planes* **= 16 DOFs in total**

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



Angular control: error signals

- **Mechanical modulation** → 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*



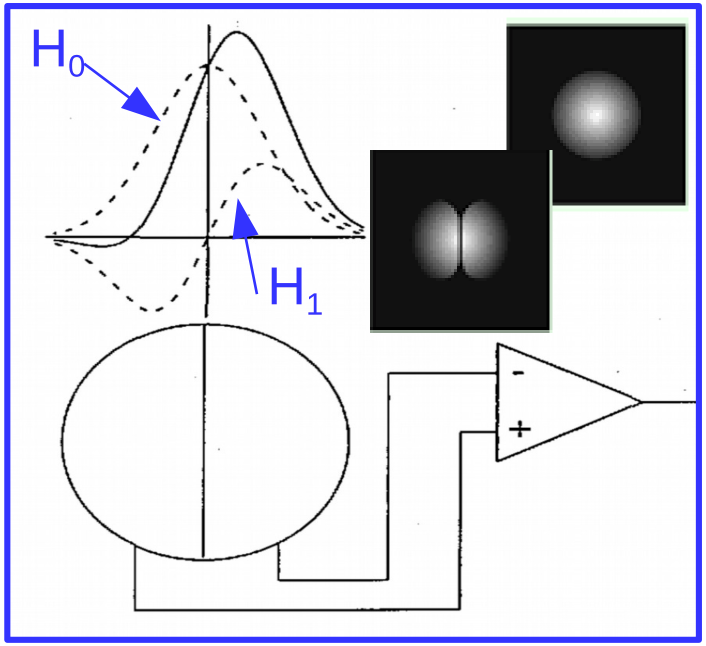
This control allows a precision ~0.5 urad and a band of ~ 30mHz

  - 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*

Angular control: error signals

- **Phase modulation** → measure the spatial beam phase distribution (Ward's technique)
  - ➔ Reflected field contains the *beat note* 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

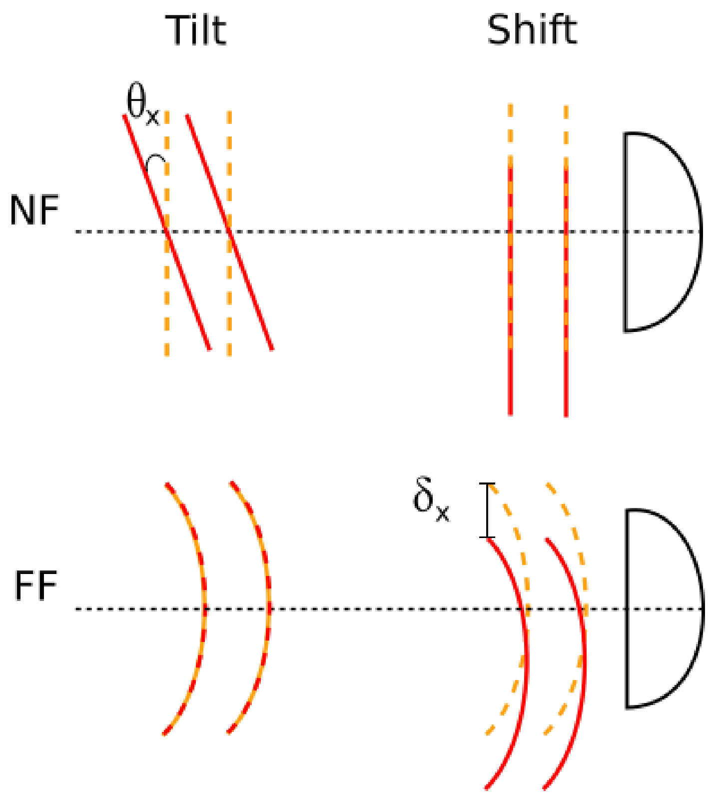
Quadrant photodiode (QPD) is divided in sectors → the difference between them gives us information on the *1st order mode ONLY!*



Angular control: error signals

- **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)



Longitudinal control strategy

➔ The linear region of the error signals is very narrow, the mirrors position changes randomly and the DOFs are very coupled → their control *can not be engaged simultaneously*

- **Misalign PR mirror** → only 3 DOFs to control, *less coupling.*

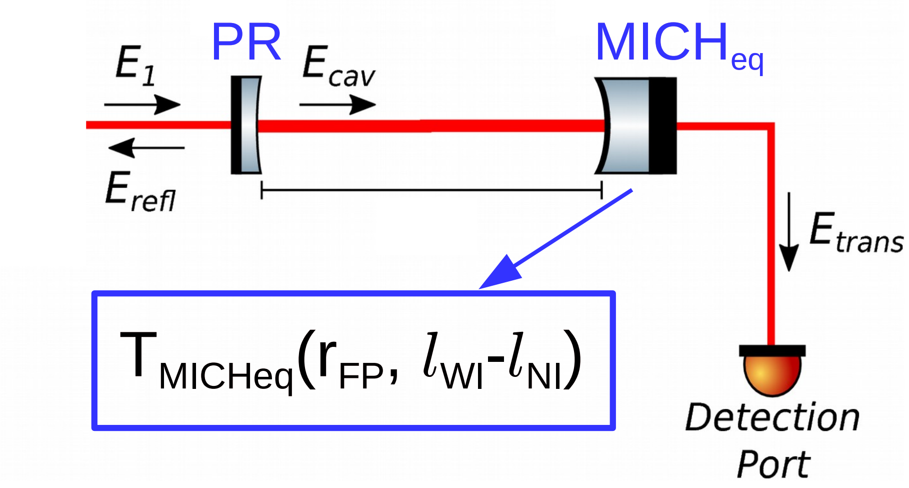
1) Control the **arm cavities** independently

2) Control the **Michelson** in **Half-Fringe**

3) **Align the PR** mirror → all DOFs under control

4) Bring the **Michelson towards dark fringe**

➔ The whole interferometer can be seen as a **compound FP cavity**



The finesse of the PRC increases towards the Dark Fringe → **Variable Finesse**

Angular control strategy

- Alignment experiments **slow drifts** (~ tenths of minutes) → it is not so critical during the control acquisition
- Strategy adopted was:
  - Good initial alignment of the cavities → *mechanical modulation*
  - The PR mirror alignment is engaged as soon as it is aligned → ***critical due to the marginally stable nature of the PRC***
  - The full angular control is not engaged until *Dark Fringe!*

> Notice that the ***shift of the input beam*** is the only DOF that is ***not controlled*** since we do not have the proper actuators!

Power Recycling Cavity stability

- An optical cavity is **stable** when it exists a beam that can resonate inside it.
  - **Geometrical** considerations only:

$$0 < g_1 g_2 < 1$$

$$g_1 = 1 - \frac{L}{R_1}$$
$$g_2 = 1 - \frac{L}{R_2}$$

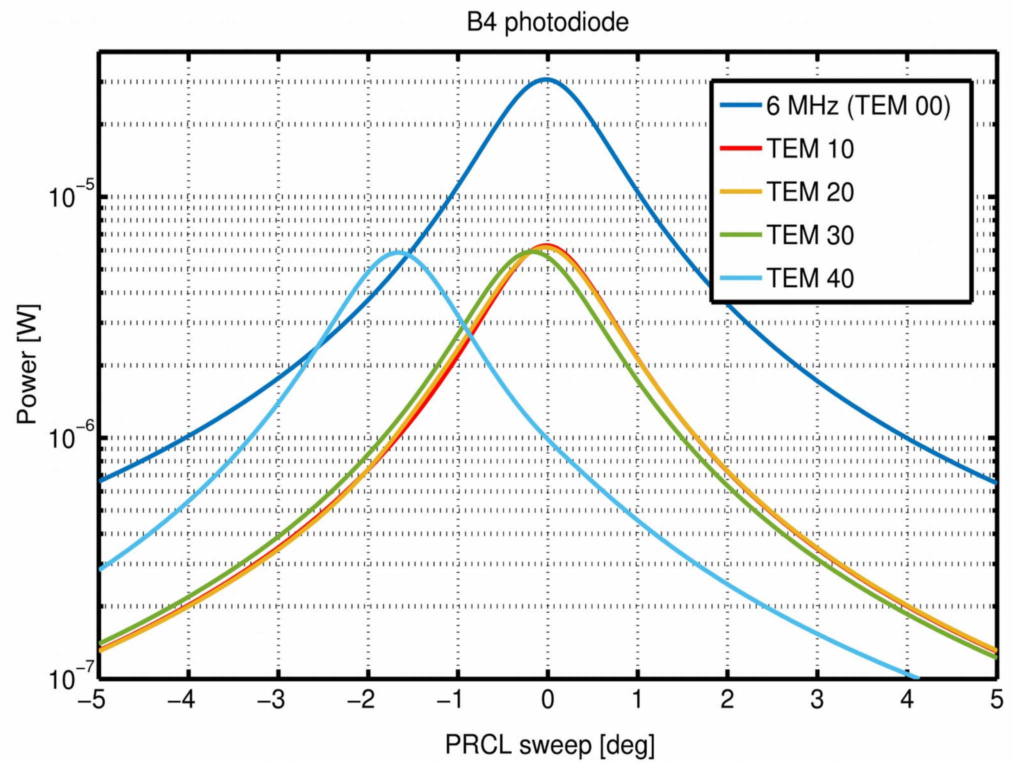
Cavity Length

Mirror Radius Of Curvature

- PRC is *marginally stable* → **$1 - g_1 g_2 \sim 0.19e\text{-}5$**

WHAT DOES IT MEAN ?

- **HOMs resonate very close to the fundamental mode** (degeneracy) → very sensitive to *misalignments, mismatch* and/or *optical aberrations*
- Very *high coupling of HOMs* inside the ITF



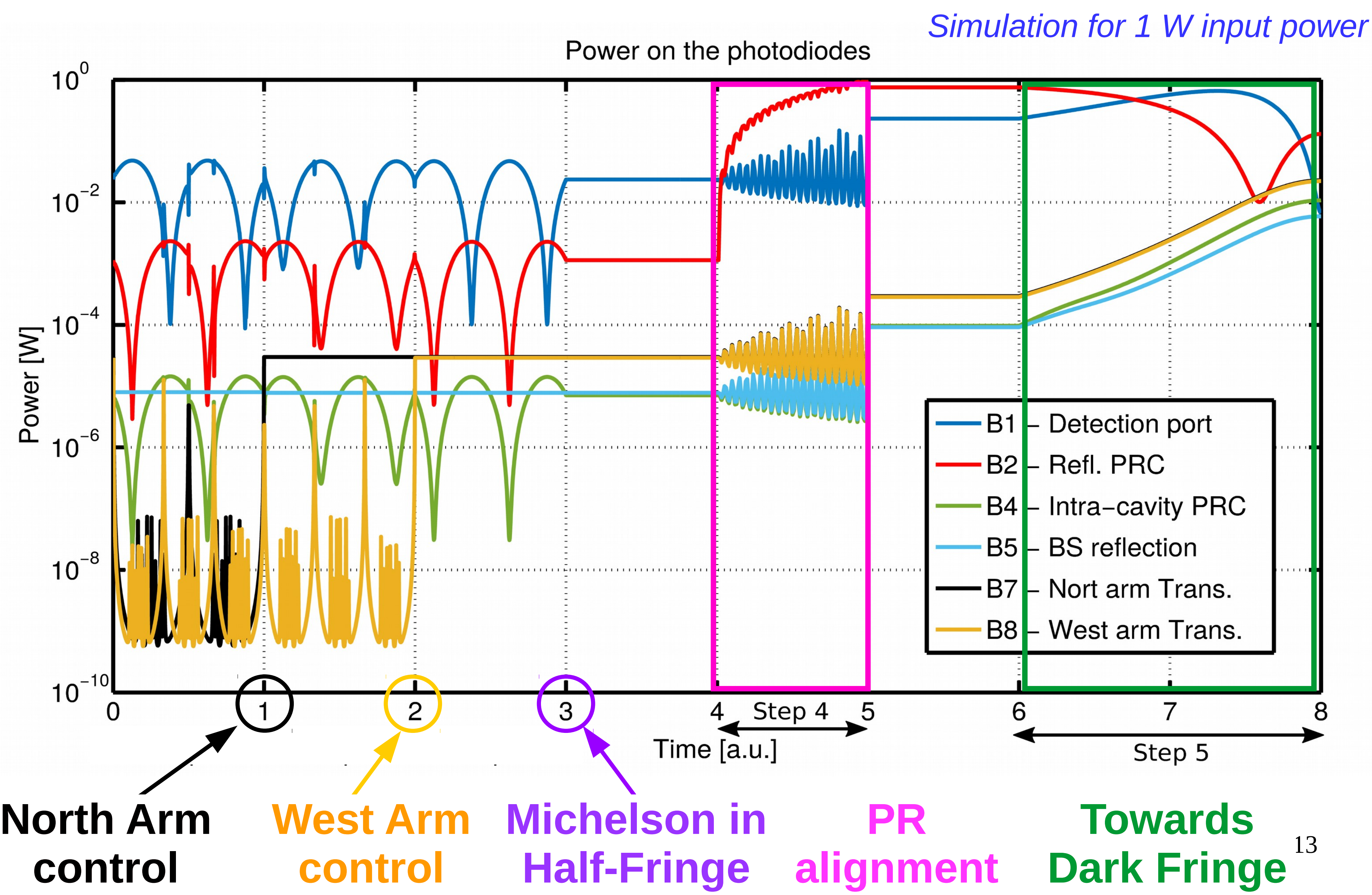
High modulation frequency

- *Arm cavities are very good "mode cleaner" for the carrier* → the sidebands are only resonant on the PRC!
- Simulations showed that for *typical misalignments,* the Optical Gain of the error signals decrease very fast (~80% for 0.5 urad) → **feedback loop can not survive!**
- Alignment of PR is "critical" to minimize the formation of HOMs **BUT** the *alignment error signals* are good only if the *1st HOMs are dominant!*

Error signal is the beat note between the HOMs produced and the fundamental mode

SOLUTION: Add a ***higher RF modulation frequency*** (6x9 = 56MHz) that sees a ***lower finesse*** of the PRC and so it is ***less sensitive to misalignment and mismatch***

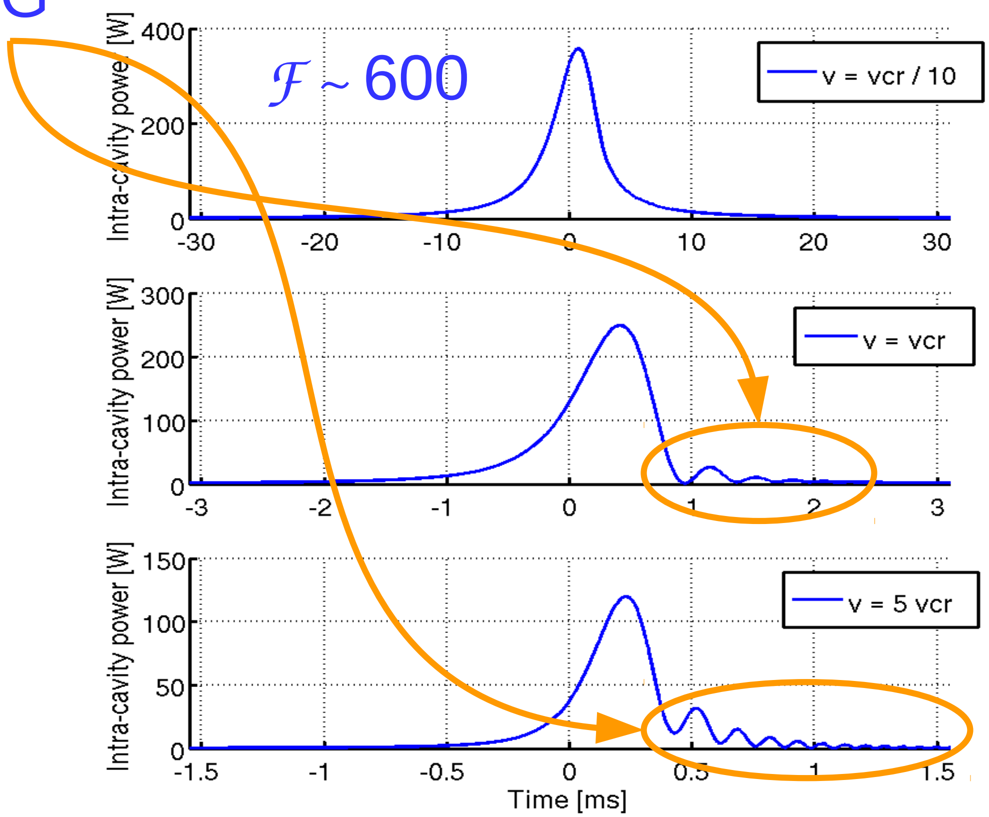
Control acquisition sequence



Arm cavities' lock

- Due to the high finesse of the cavities (450) → dynamical effects
- When the beam reaches a ***moving mirror*** → **Doppler effect**
- It *accumulates each round-trip*, when the effect is ~δν the EM field gets distorted → RINGING

$V_{critical}$ is ~0.4 µm/s for AdV arm cavities ***vs.*** 1µm/s of residual motion



Effect on the error signal:
Wrong zero-crossing / *multiple* zero-crossing / *asymmetrical* around working point...

✗ It can not be used!

Guided Lock

Measure the *resonance crossing velocity* **online** and apply a *single extended impulse* with the *maximum force* available in order to bring the cavity *back to the resonance* but with a *lower velocity*

➔ To estimate the velocity online the method proposes to use the *PDH's slope*

$$v_{\mathrm{meas}} = C \left(\frac{\partial}{\partial t} \frac{S_{\mathrm{PDH}}}{S_{\mathrm{DC}}} \right)^{P}$$

✗ *Needs* ***calibration*** *and a power law* ***correction for high velocities!***

Alternative for velocity estimation:

➔ **Time** that the transmitted power takes to pass from *10% to 40% of the cavity power on resonance*

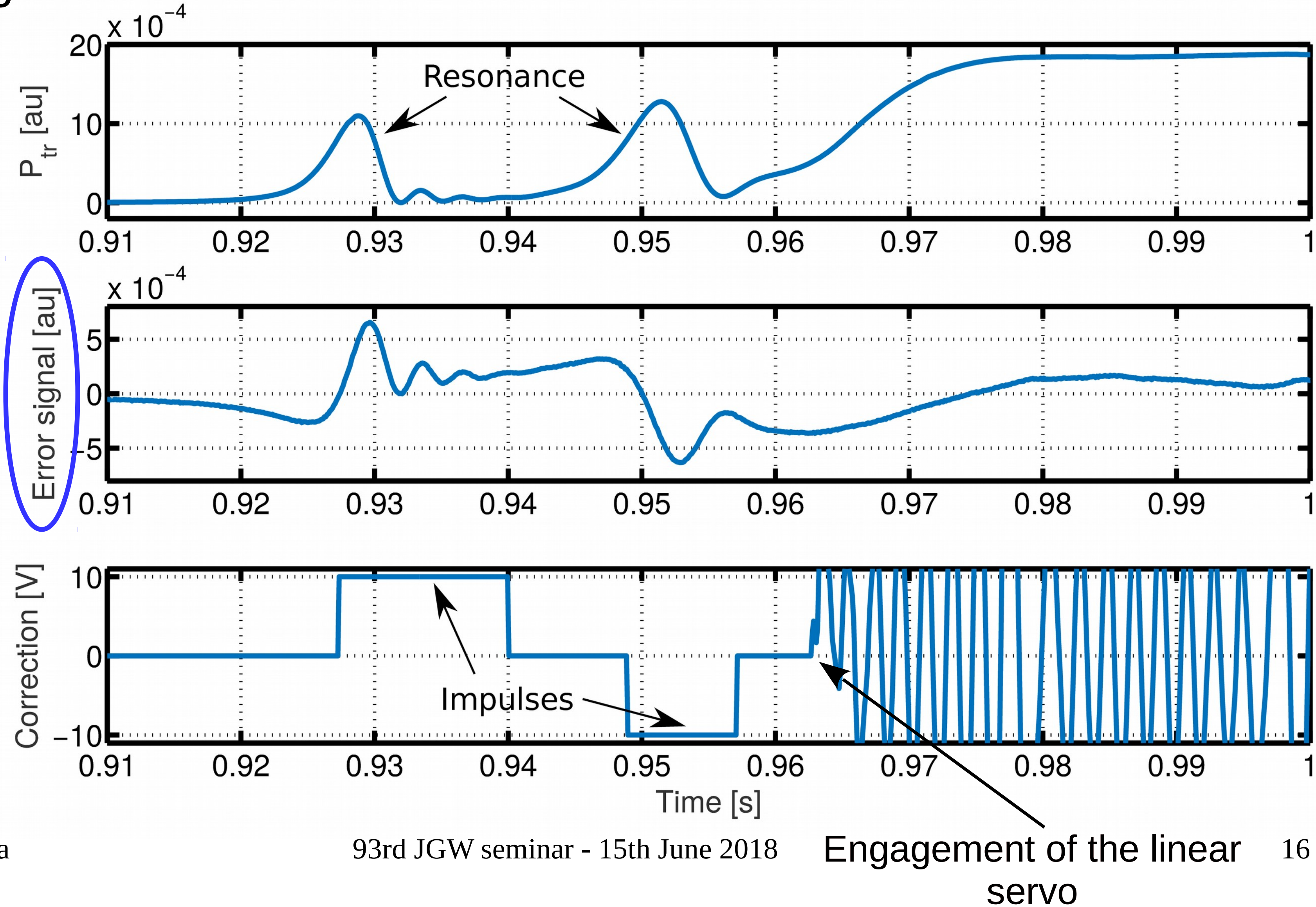
➔ **Simulations** showed that: $v \propto 1 / t_{10\text{-}40}$

Guided Lock

➔ Real case of the control acquisition of the **North arm cavity** using Guided Lock

North Arm:
B7 6MHz

West Arm:
B8 6MHz



Second Stage of Frequency Stabilization

Common DOF (CARM) ⇨

Seismic noise (*low frequency*) **+**
Frequency noise (from laser, *full freq. band*)

$$\delta\Phi \propto (\nu \cdot \delta L + L \cdot \delta\nu)$$

PARTICULARITIES:

1) **Common Mode Rejection Factor**: in practice there are *asymmetries between the cavities* (finesse, losses…)
   → extra frequency noise leaking so *better control is needed*

2) The **bandwidth** of this control needs to be *higher (up to kHz)* due to the laser contribution
   → *mirrors are not good actuators* (limited bandwidth)

3) Frequency noise **couples to all the sensors** (dominant noise)
   → *pre-stabilization* of the laser is needed to control the ITF

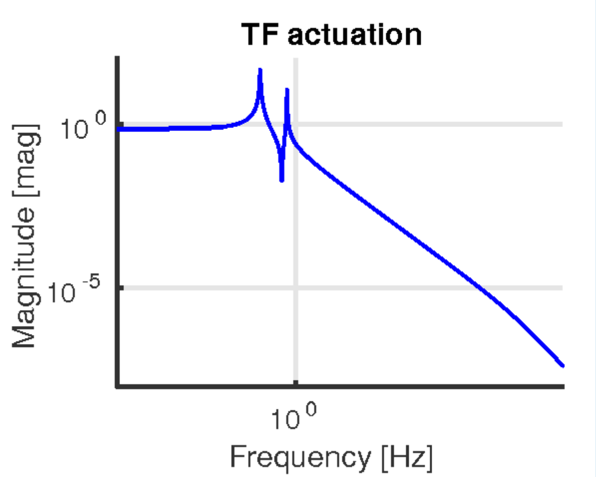
CMRF and Mirrors TF

- **Common Mode Rejection Factor**: in practice there are *asymmetries between the cavities* (finesse, losses…) → extra frequency noise leaking so *better control is needed*
  - If the *ITF is perfectly symmetric* the common noise is completely canceled → **No coupling to DARM!**
  - If there is *asymmetries* the coupling to DARM is:

$$CMRF \cdot \tilde{f}$$

Frequency noise

How much of the common noise we are able to reject in spite of the asymmetries



- The **bandwidth** of this control needs to be *higher* *(up to kHz)* due to the laser contribution → *mirrors are not good actuators* (limited bandwidth)

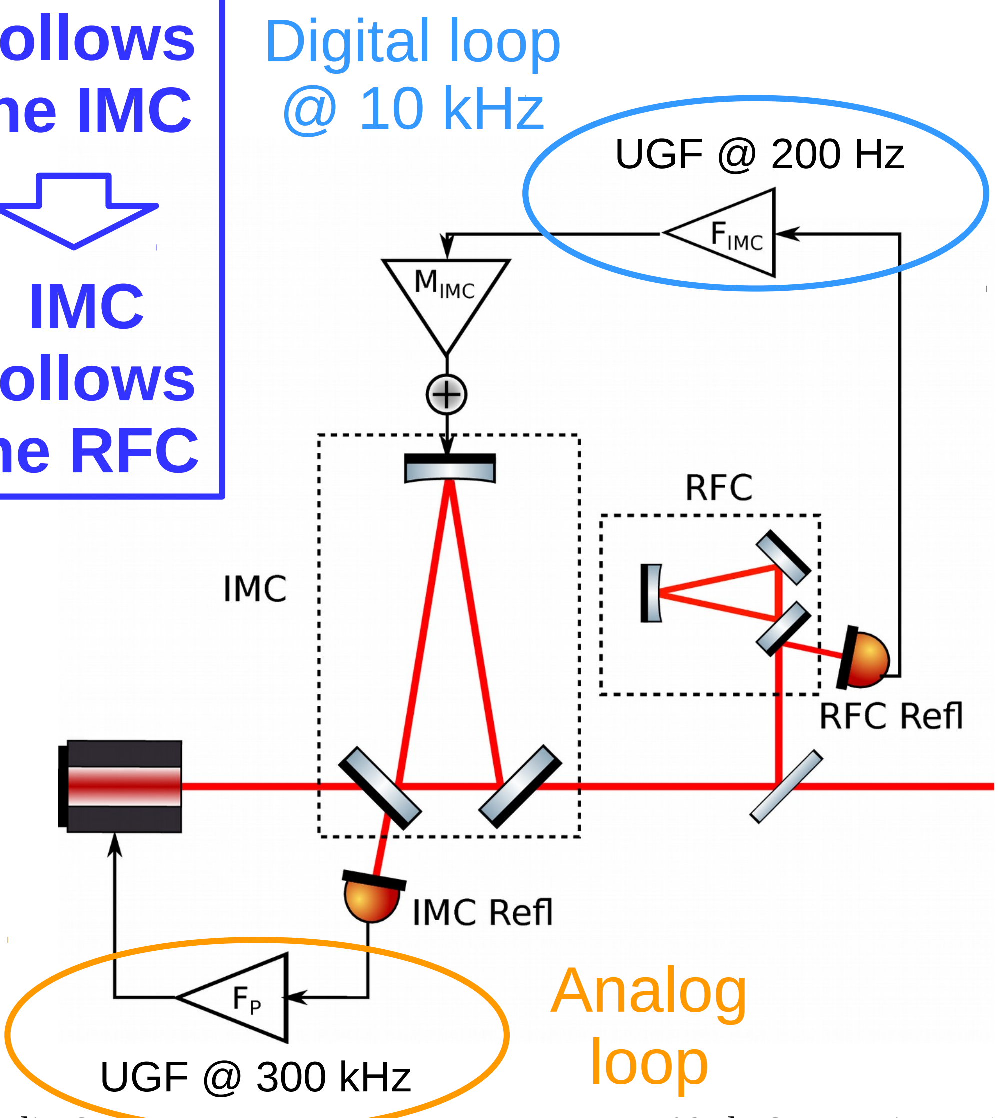
Frequency pre-stabilization

Laser follows the IMC

⇩

IMC follows the RFC

➔ **Pre-stabilization:** *independent from the ITF*



➔ **Reference Cavity** (RFC): reference at *low frequency*

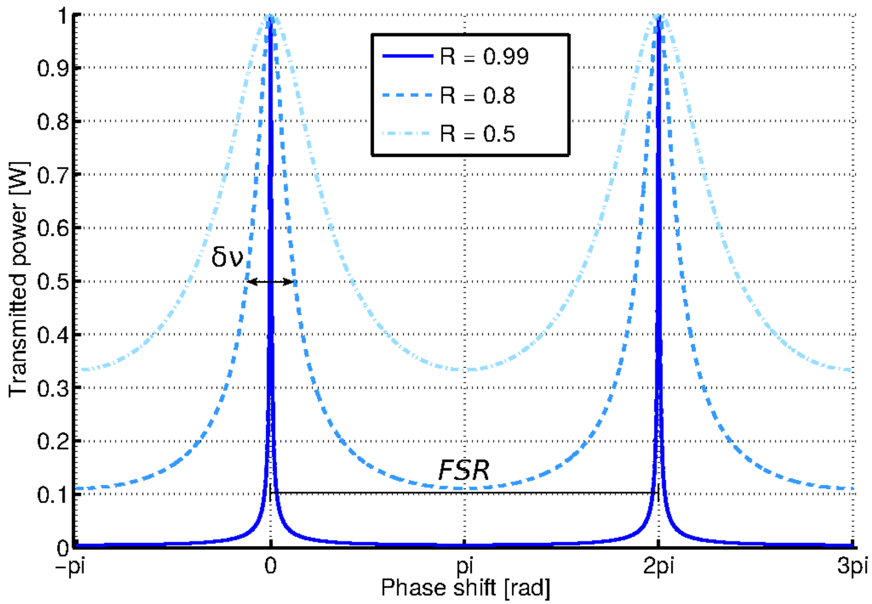
- ➔ **U**ltra **L**ow **E**xpansion material
- ➔ Monolithic cavity ~30 cm

➔ **Input Mode Cleaner** (IMC): reference *above 200 Hz*

- ➔ Suspended mirrors
- ➔ Length ~ 150 m

SSFS

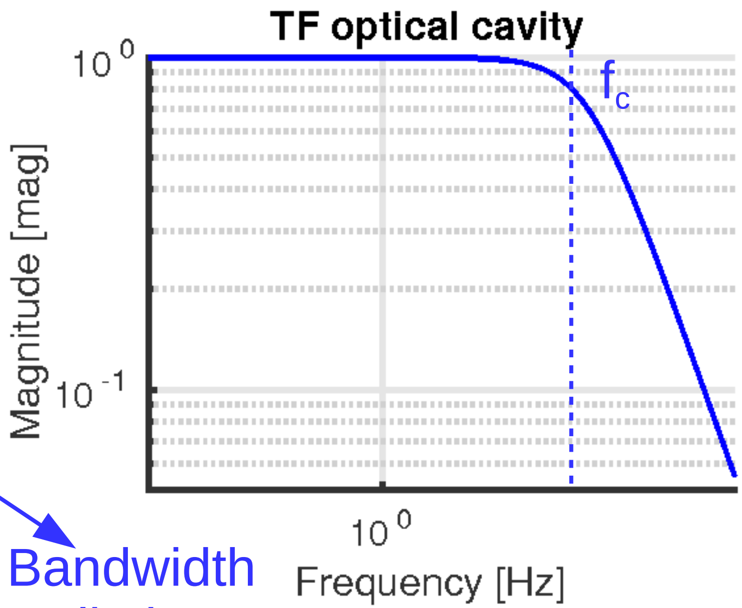
➔ **Second Stage of Frequency Stabilization (SSFS):** replace the RFC and the IMC by the Arms → CARM error signal @ **B4 56MHz**



$$f_c = \delta\upsilon/2$$

$$\delta\upsilon = \frac{FSR}{F}$$

Bandwidth limit!



➔ **Input Mode Cleaner** (IMC):

- ➔ FSR ~ 1MHz
- ➔ f_c ~ 500Hz

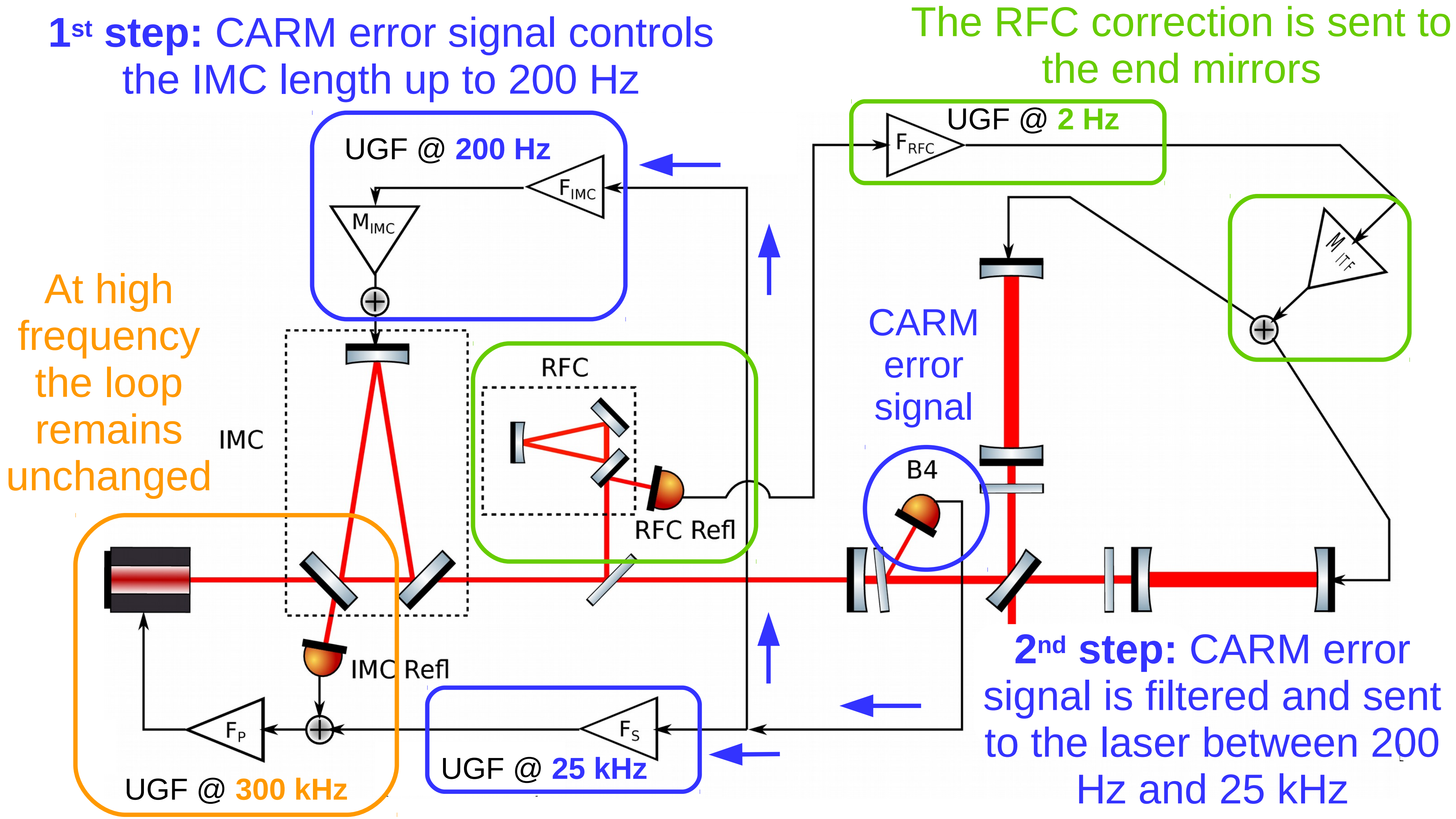
Arms are a *better cleaner* **BUT** within a *lower bandwidth*

➔ **Arm cavities:**

- ➔ FSR ~ 25kHz
- ➔ f_c ~ 50Hz

SSFS architecture

➔ **Second Stage of Frequency Stabilization (SSFS):** replace the RFC and the IMC by the Arms → CARM error signal @ **B4 56MHz**

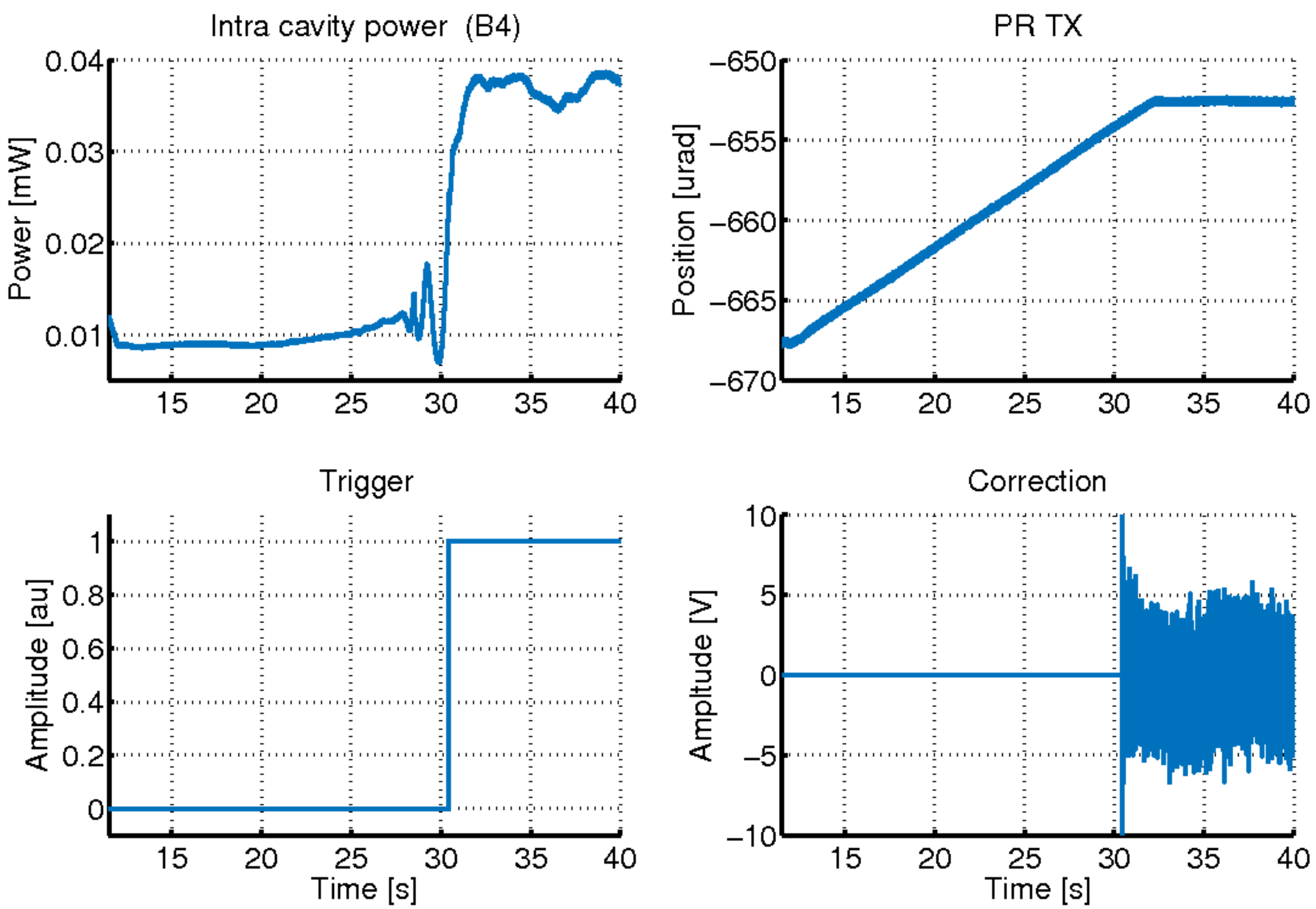


PR mirror alignment

- When we ***align the PR mirror*** all the powers in the ITF suffer a violent increase in a few seconds

The error signal used is **B2 8MHz**

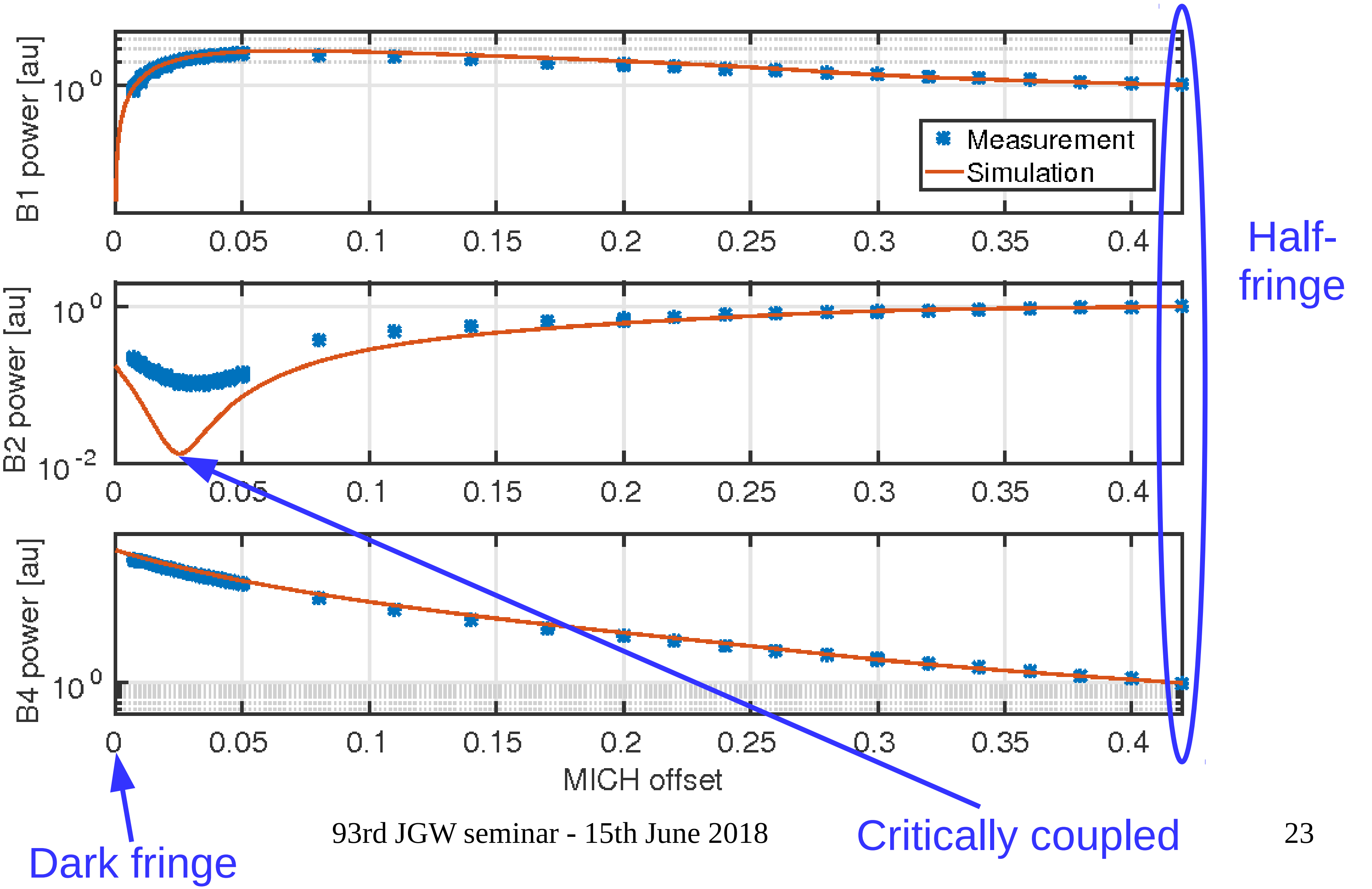
At this point the PR tilt loop is closed using Q2_8MHz



MICH offset reduction

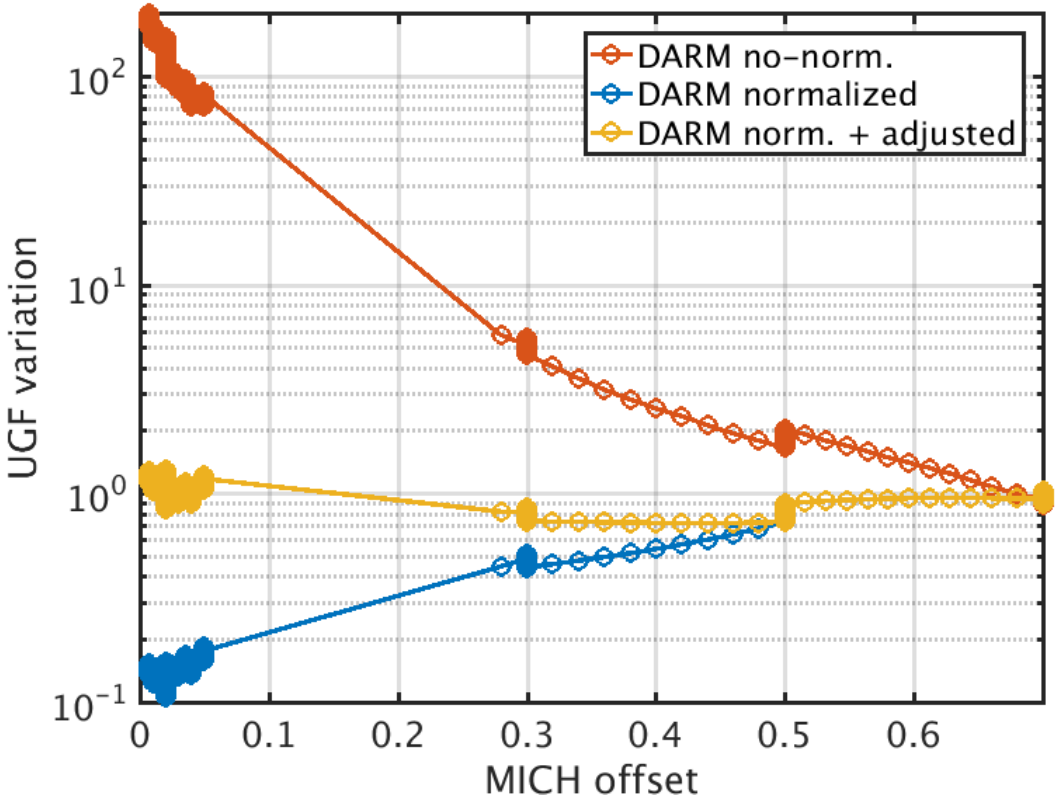
- Then we start **decreasing the offset** applied to the MICH error signal which is 0.5 @ half-fringe and is *0 @ Dark Fringe*

It can be seen that the ***powers*** in the ITF ***change a factor 10***



Error signals normalization

- These **power changes** affect the performance of the control loops because the *slope of the PDH is proportional to P_{in}* → we need to compensate for them: **normalization**

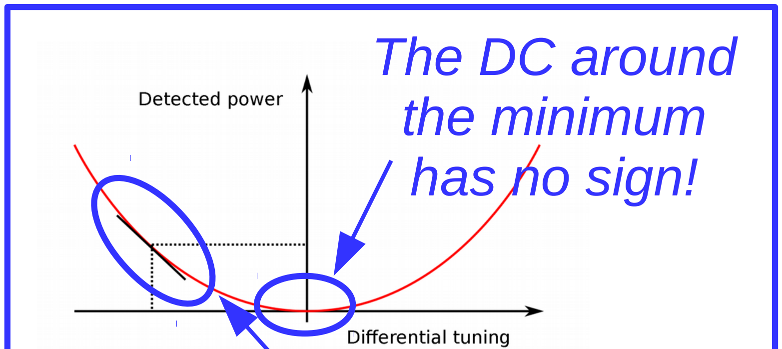


Normalization of the error signals by a DC power reduces this change by 2 orders of magnitude

	DARM	MICH	PRCL	CARM
Error signal	B7–B8 6MHz	B1 DC	B2 8MHz	B4 56MHz
DC power	**B7 / B8**	**B1+B4**	**B1+B4**	**B4**$^{(2/3)}$

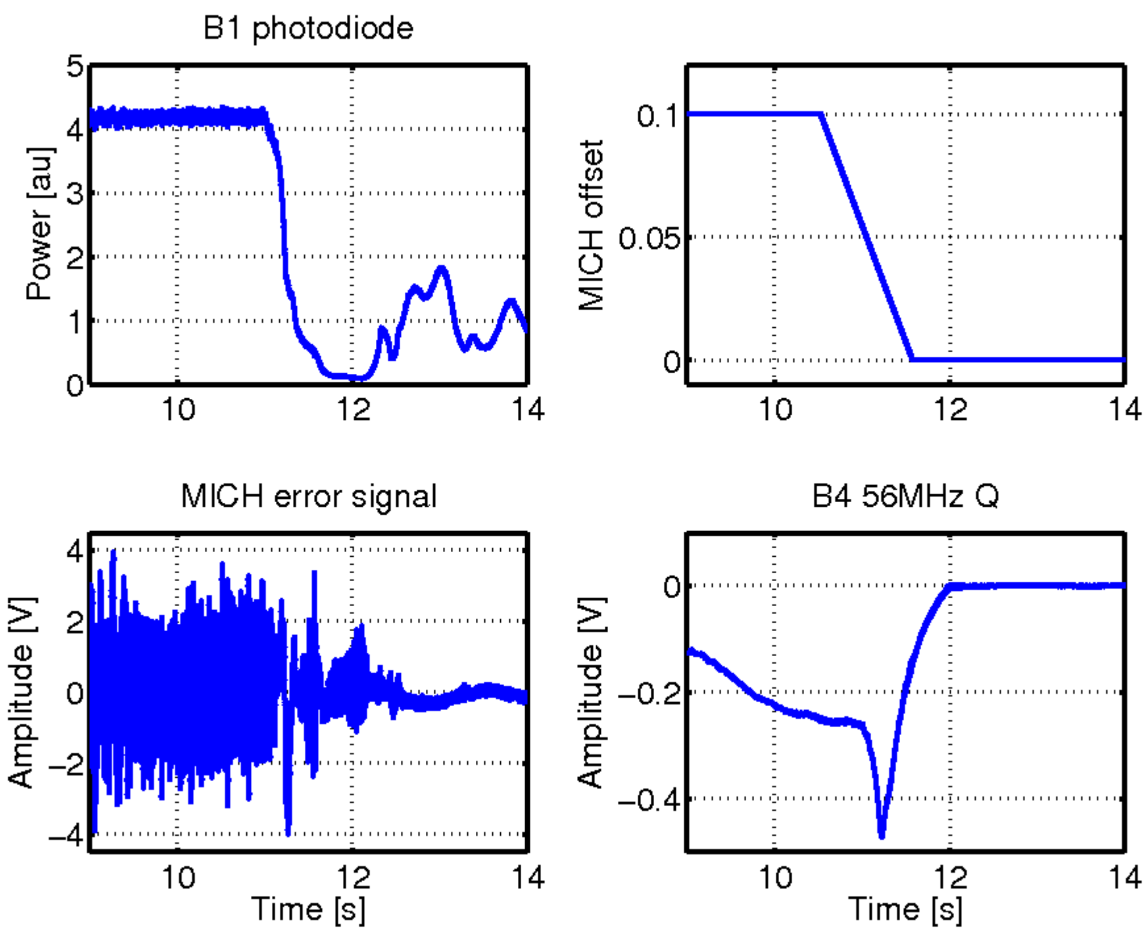
Dark Fringe

- We **“jump” to the Dark Fringe** from 0.1 of MICH offset and then **hand-off the MICH error signal** to an RF one (B4 56MHz Q) simultaneously



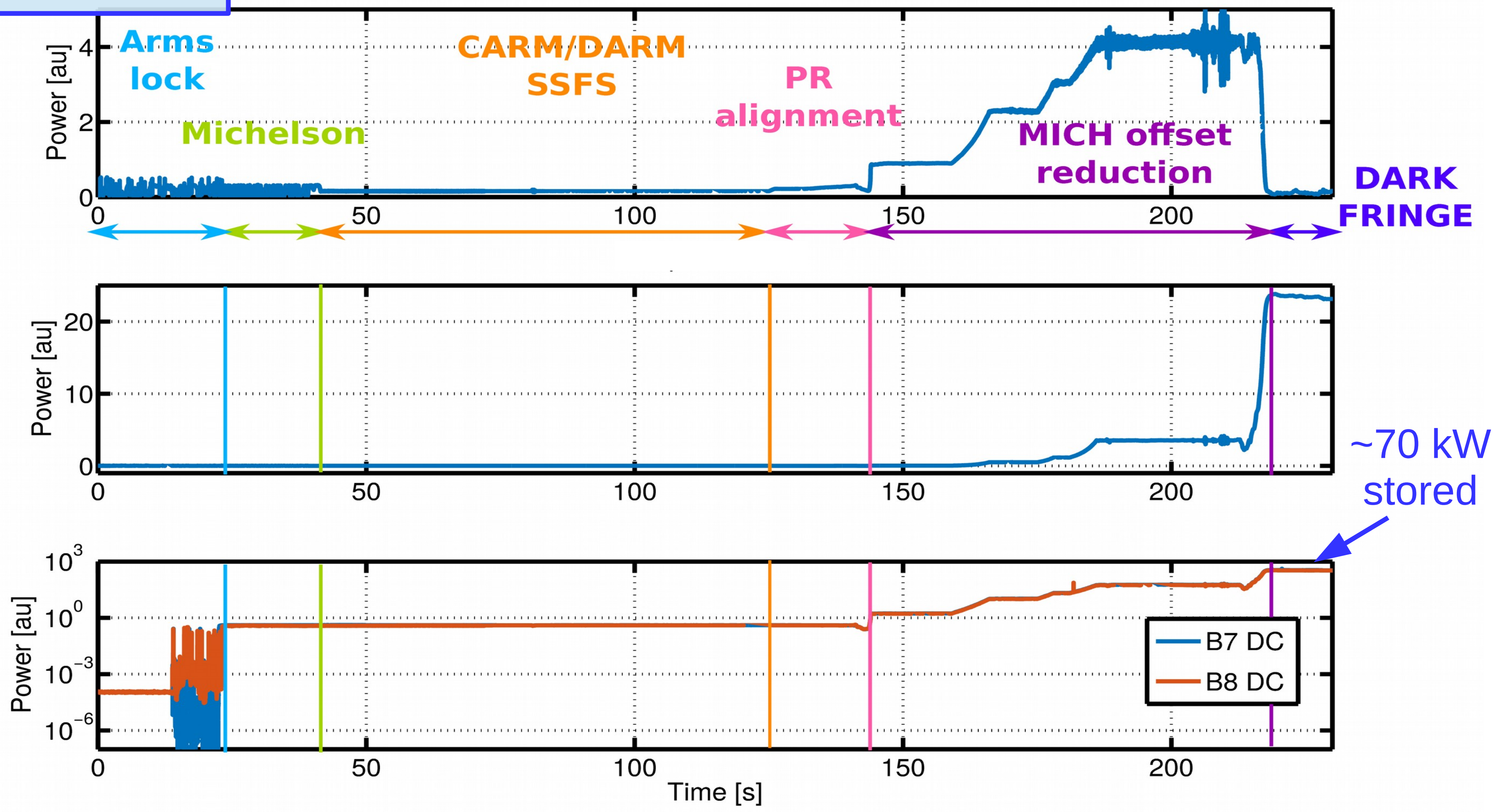
The DC around the minimum has no sign!

Close to DF the gain of the error signal (slope) starts to decrease!



Lock acquisition sequence

We reach Dark Fringe in ~ 5min



Automatic Alignment

- So far we had the PR tilt controlled using the Q2 8MHz quadrants and the arm cavities drift control (~20 mHz of UGF) using mechanical modulation
- In Dark Fringe we start using the quadrants, which allows us to close the loops in full bandwidth (~2 Hz of UGF):
  - **PR tilt** → Q5_I 56MHz in full bandwidth
  - **BS tilt** → Q5_Q 56MHz almost in full bandwidth
  - **PR translation** (input beam tilt) → Q2 8MHz in drift control
  - **COMM+** → Q5_DC in full bandwidth
  - **DIFF+** → Q1p 56MHz in full bandwidth
  - **COMM- / DIFF-** → are substituted by a *mechanical modulation on the end mirrors*, which is used to center the optical axis on them

Automatic Alignment

- Alignment improves the stability of the powers in the ITF
- Plays a key role to improve the CMRF