Working with marginally-stable dual-recycling cavities:
Finesse simulations for commissioning Virgo in O4 and beyond

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Virgo for O4: dual-recycled; marginally stable

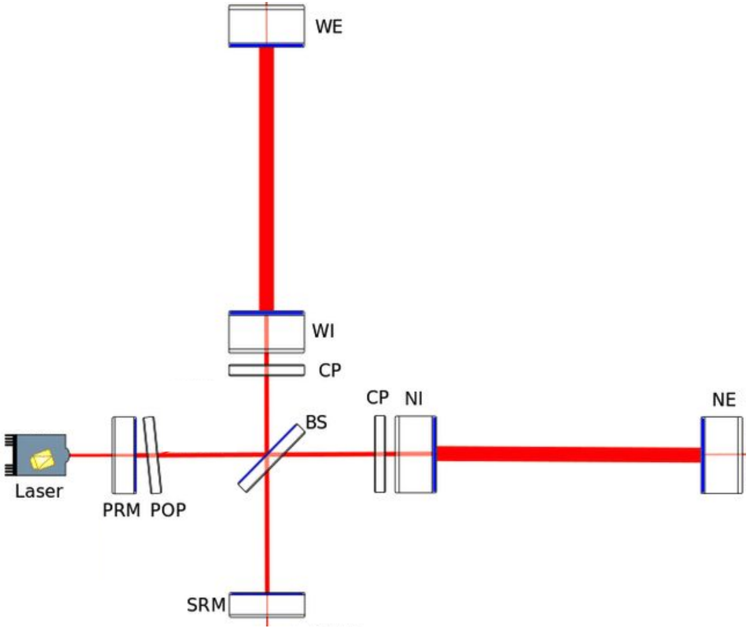
O4 Virgo adds signal recycling

- Both the SRC and PRC are marginally stable
- Long history, see e.g. LIGO-G2300588 (S. Hild LVK)

Huge commissioning effort required

- As seen in several talks this week
- New length, alignment, mode matching controls
- Tolerance to imperfections is especially low due to marginally stable recycling cavities

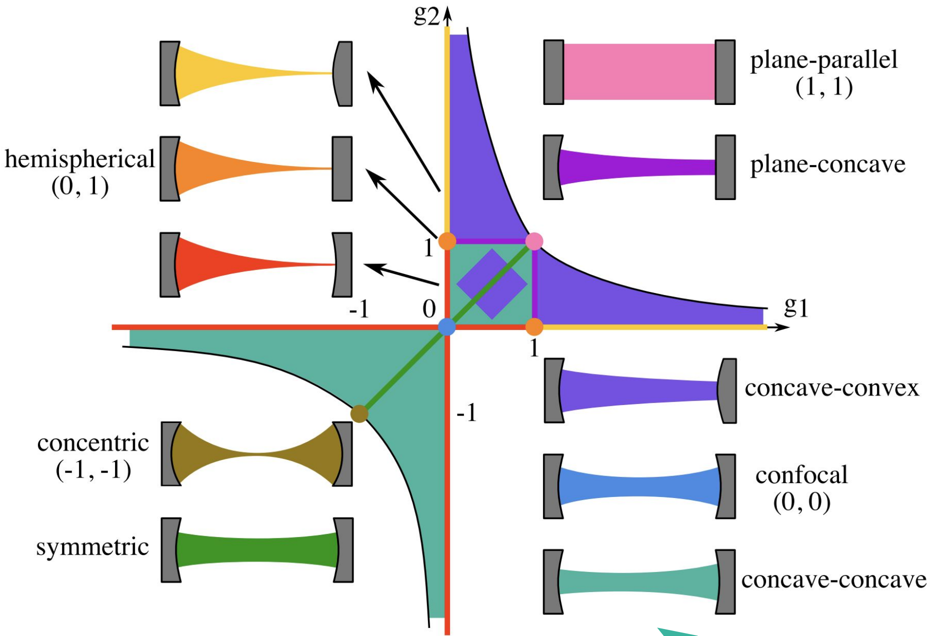
Behaviour is extremely challenging to predict/intuit – much more complex simulations required.



Cavity stability

Cavity stability is determined by geometry (lengths & mirror curvatures)

- Resonant condition - stable reproduction of the beam shape



Current GW detectors

PRD 2018/LIGO-P1700332

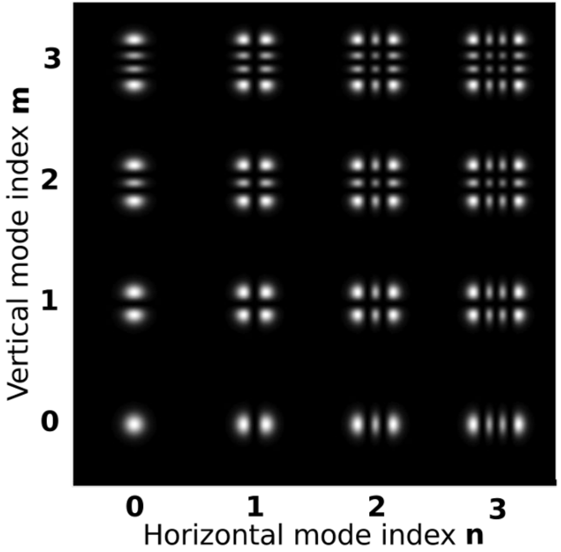
Describing the shape of the beam

We can represent the optical field as a series expansion of Gaussian modes (e.g. Hermite-Gauss, Laguerre Gauss)

$$E(t,x,y,z) \;=\; \sum_j \sum_{n,m} a_{jnm}\; u_{nm}(x,y,z)\;\; \exp\left(\mathrm{i}\left(\omega_j\, t - k_j z\right)\right)$$

This approach works well for paraxial beams dominantly described by a fundamental Gaussian beam, with higher order modes (HOMs) representing perturbations to the beam shape.

- Both mathematical description and physically observable in e.g. cavity scans



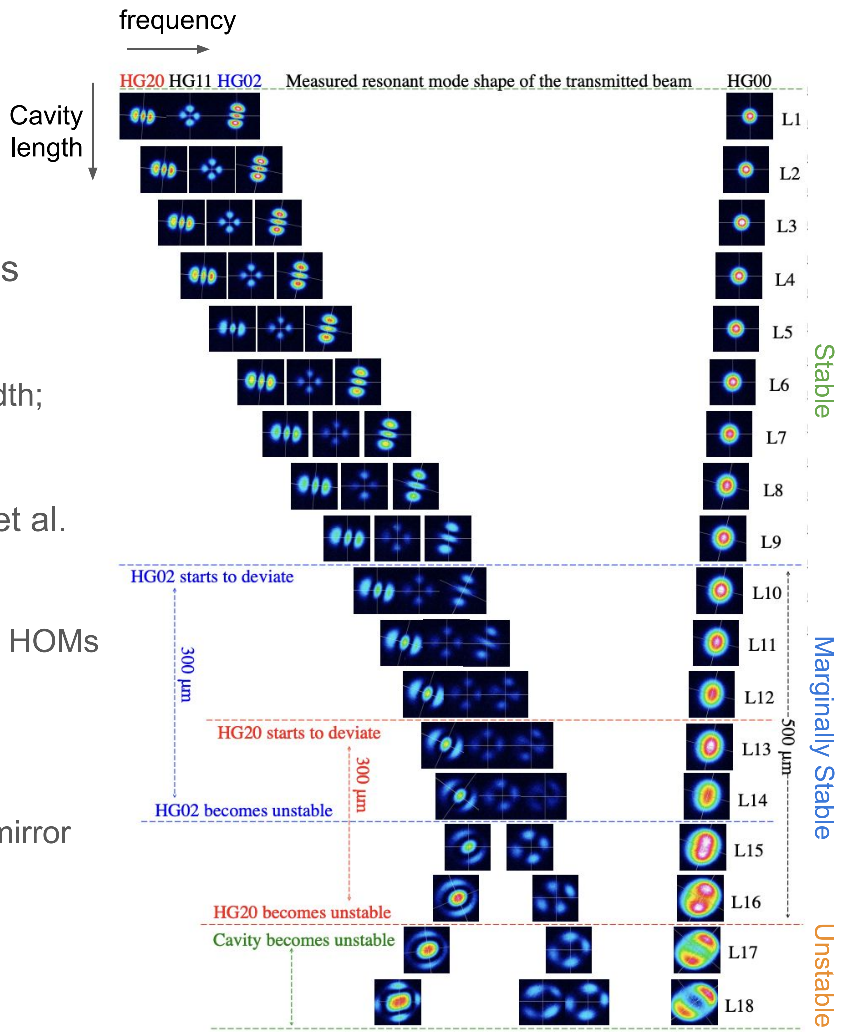
Cavities near instability

Near geometric instability, the beam shape in the cavity is easily distorted

- Gouy phase becomes so small that mode spacing < linewidth; HOMs can also resonate

Previous studies, and experimental results e.g. H. Wang et al. [PRD 2018](#)/[LIGO-P1700332](#) →

- Small imperfections e.g. surface quality create couplings to HOMs
- Couplings become larger, more chaotic, less predictable in near-unstable systems
- Usage in GW detectors needs very strict requirements on mirror surface quality + length and thermal controls
- Consistent with Virgo experience



Recent Finesse projects supporting Virgo commissioning

The developer team now use Finesse 3 (late-alpha) for all our work
& are winding down v2 support to focus on v3 full release

Other recent topics not covered today:

- **IMC baffle design**
  A. Bianchi, H. Yamamoto et al. - VIR-XXXX-23 (coming soon)
- **Mode mismatch impact on squeezing**
  A. C. Green et al. - VIR-0310A-23 (preliminary)
- **Tilt & Thermal actuation effects on DARM, contrast defect and common mode rejection**
  R. Maggiore, A. C. Green, E. Tournefier et al. - various, including: VIR-0801A-22, VIR-0282A-22, VIR-0470A-23,..

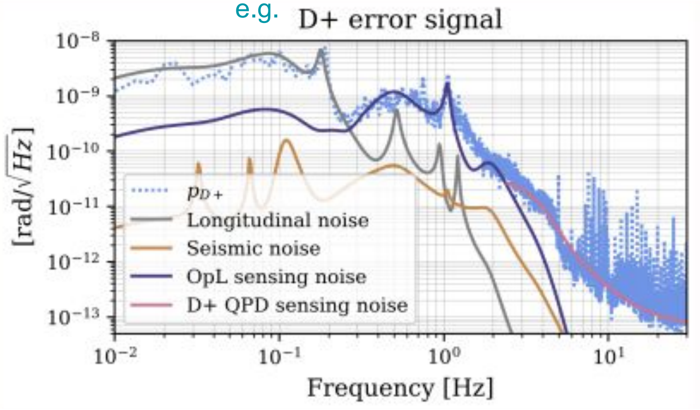
Example: Alignment sensing and controls

Angular controls characterisation
R. Maggiore et. al VIR-1193A-22 / paper coming soon

Goal: determine how much angular motion in the detection frequency band (f > 10Hz) is converted into DARM motion.

- Project noises through a full MIMO model of the ASC loops
  - With full opto-mechanical plant and ASC control scheme model; incorporating residual angular motion, beam miscentering on each mirror
- Excellent match to O3 noise data & DARM couplings
  - Now using similar techniques to make initial predictions for ET

e.g.



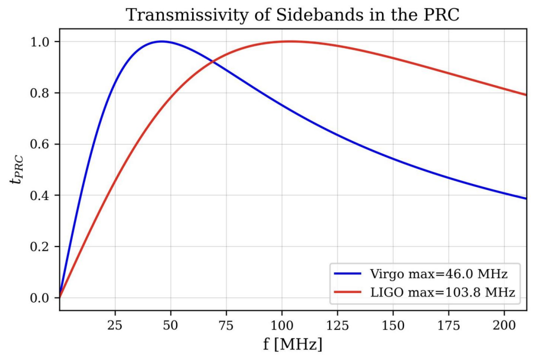
Examples: Alignment sensing and controls

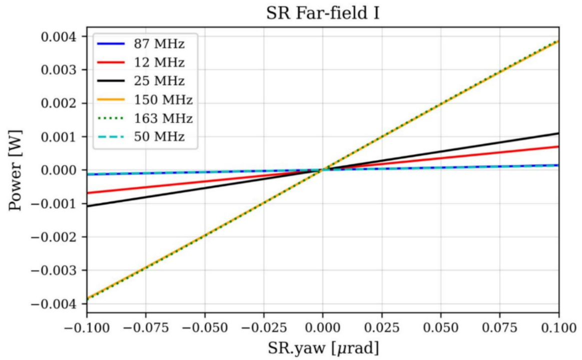
Automatic Alignment System for the SR Mirror
J. Perry, J. Casanueva et al VIR-0077A-23 / VIR-1107A-22

Goal: find a sideband-sideband QPD beat signal for globally controlling SR angle

- Swap from local dither signal (low SNR, lines); Target robustness to mode mismatch
- Cf similar work at LIGO

- Identified new modulation frequency @ 81MHz to beat with existing 56MHz sideband (demodulate at 25MHz)
  - Resonant in PRC
  - Best optical gain (higher freqs sensor-limited)
- New modulation implemented & tested, but low SRC Gouy phase found to make the signal unreliable.





Examples: Mode matching & thermal actuation

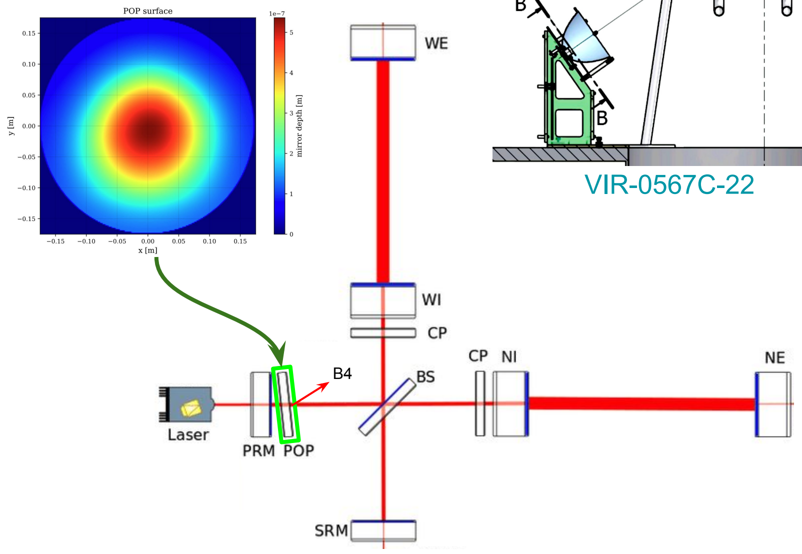
The **CHRoCC**
A. C. Green, A. Bianchi, D. Brown, J. Degallaix et. al.

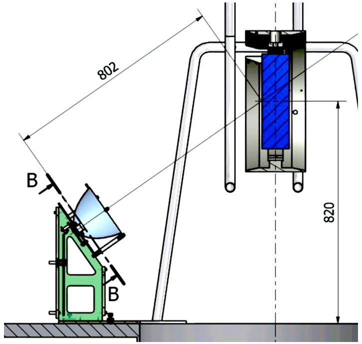
New thermal actuator targeting PRC beam shape:
“central heating radius of curvature correction”

Goal: assess if the CHRoCC actuator could be used without introducing significant new defects

Combined effort for different aspects & cross-checking:

- FFT (OSCAR) - good for distorted beams, especially higher-spatial-frequencies
- modal models (Finesse) - distorted beams, controls and transfer functions





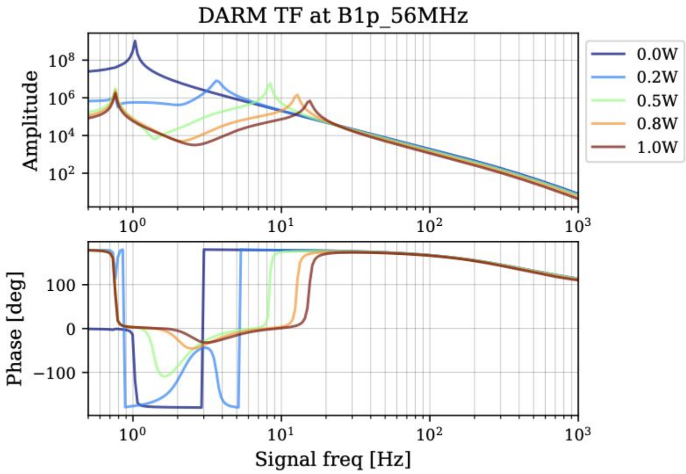
VIR-0567C-22

Examples: Mode matching & thermal actuation

The **CHRoCC**

A. C. Green, A. Bianchi, D. Brown et. al.

- *Residual* effect on powers, gains, DARM VIR-0738A-22
- Also when off-centre by up to 15mm VIR-0943A-22
  - Both show good agreement with OSCAR
- Convergence testing VIR-0944A-22 considered e.g. DARM spring frequency, error signal offsets, circulating power

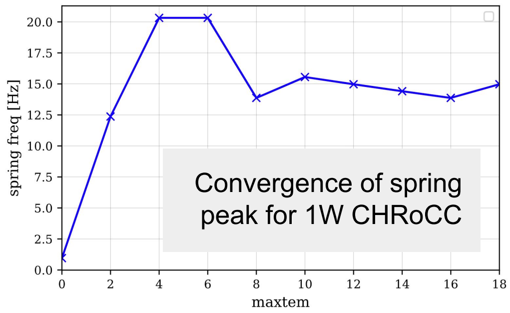


Outcome: minor effect on in-detection-band DARM. Now an active, successful part of Virgo O4 TCS.

Similar techniques are also used for assessing **performance of new optics with imperfect surface quality**

A. C. Green , J. Degallaix, S. Steinlechner, et al.

VIR-0909B-22 / VIR-1049A-22



Convergence of spring peak for 1W CHRoCC

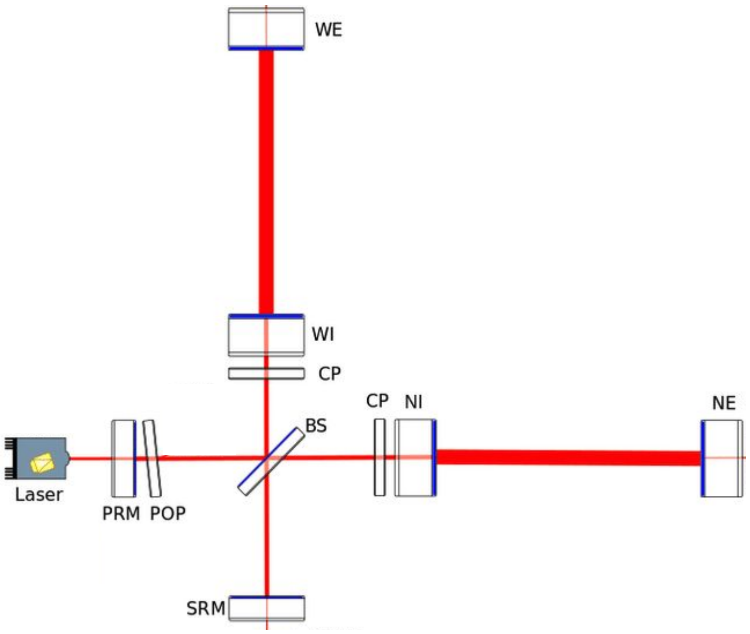
Key challenge: the Operating Point

To detect GWs the detector length degrees of freedom must be locked at its operating point

- Obvious, key part of commissioning
  - Resisting environmental effects, maintaining sensitivity
- *Also* an essential step in our simulations
  - Understanding how controls behave
  - But also, critically, the operating point depends on the detailed phase relations of HOMs in the interferometer

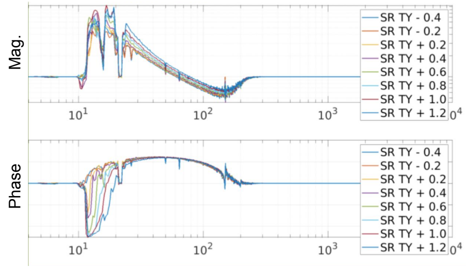
All interferometer behaviours change rapidly when **offsets** are introduced

- Imperfections, especially in marginally stable cavities, affect error signals - so offsets are often produced



Impact on DARM

Virgo data: DARM OLTF

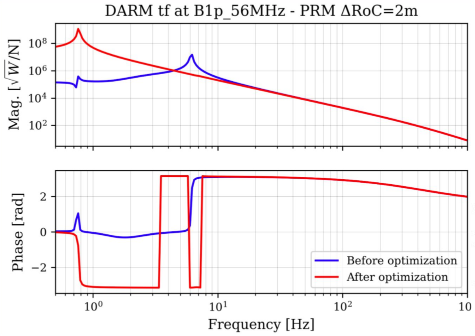


The DARM TF is often our most sensitive test case for detector performance

Common feature: Optical spring in DARM TF is distorted by defects - in experiment & simulations

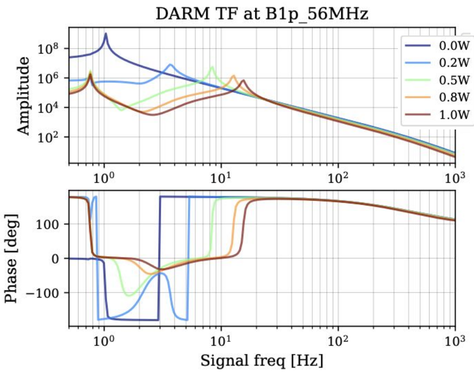
→ we want to understand exactly the mechanism, and confirm that DOF offsets are behind many of the issues we observe

Mode mismatch



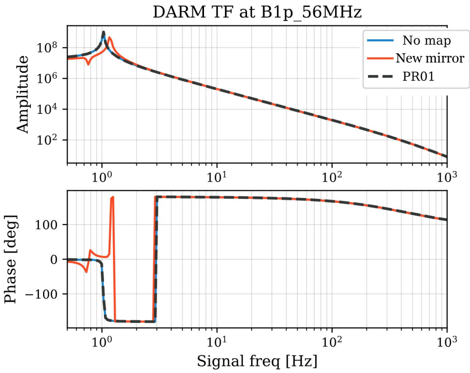
[VIR-0801A-22](VIR-0801A-22)

Thermal effects



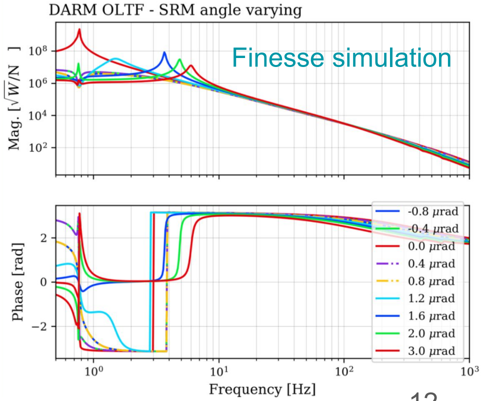
[VIR-0738A-22](VIR-0738A-22)

Surface microroughness



[VIR-0909B-22](VIR-0909B-22)

tilt



[VIR-0282A-22](VIR-0282A-22)

Impact on DARM

Optical spring: radiation pressure effect driven by microscopic cavity length detuning

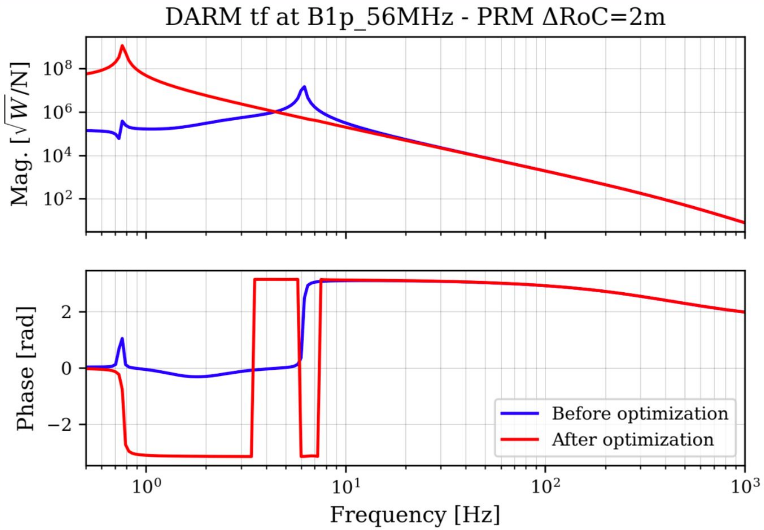
- *Shouldn't* be influenced by other degrees of freedom, but clearly is
- Clear flag: optical defects & resulting HOMs change the offsets of the length degrees of freedom, affecting the spring

E.g. 2m PR RoC mis-tuning

- Blue: DOF error signals zero (by 'lock dragging')
- Red: DOFs optimized to restore DARM TF

Offsets in DoF tunings (red-blue):

DoF	Offset [pm]
CARM	0.01
DARM	0.00
PRCL	18.0
MICH	15.4
SRCL	1015.8



VIR-0801A-22

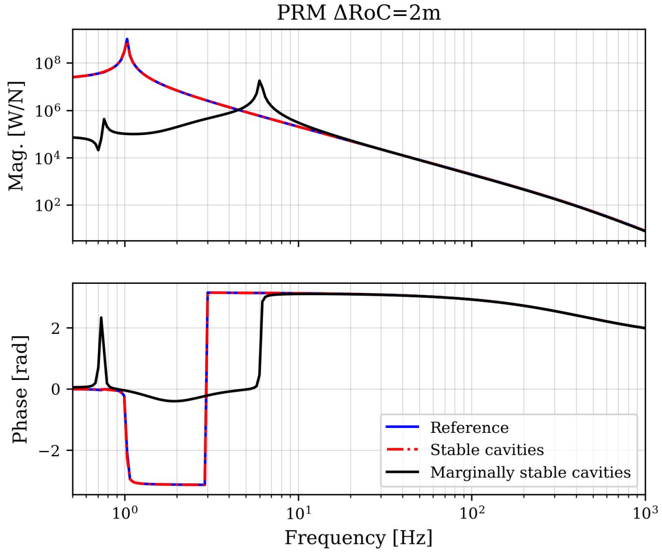
Current status

We've begun a **dedicated programme**:
Investigate how, fundamentally, HOMs cause offsets - & what this means for future detector design

Initial phase: simple test case of a single cavity
(Masters project, P. Hapke / R. Maggiore)

- Mismatch or tilt injected beam vs cavity eigenmode
- Even in this simple case, see an offset
- Origin appears to be phase shift in 00 mode of carrier when light couples into HOM(s)
- I.e. a fundamental behaviour for cavities with defects
- Severity depends on cavity stability - another reason to favour geometrically stable designs

Next: scaling up towards full detector configurations - watch this space…

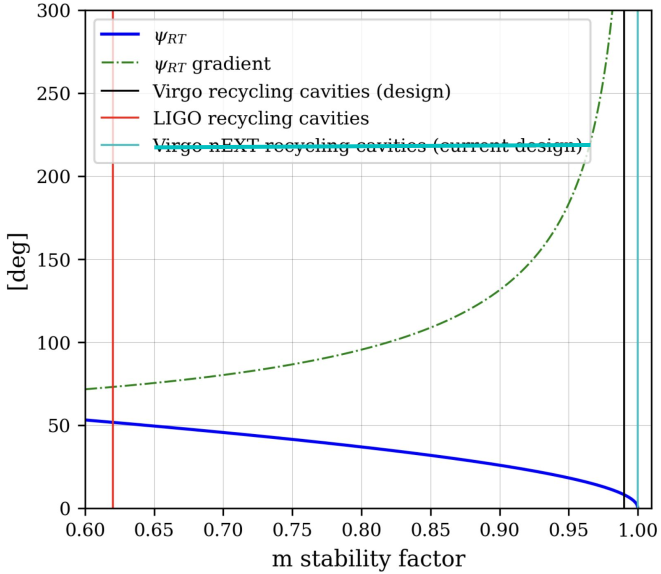


Looking ahead: Virgo's future

In line with our experiences, we contributed to "The Need for Stable Recycling Cavities in Virgo-nEXT" [VIR-0047A-23](VIR-0047A-23) (& talk LIGO-G2300588):

- current commissioning and simulation experience of marginally stable RCs
  - As you've heard this week
- Other likely positive consequences of moving to stable RCs
  e.g. meeting squeezing loss targets, simpler telescope designs, and efficient simulations

I.e. it would be extremely challenging to meet Virgo(_nEXT)'s goals without this change - news in this direction sounds very positive



Looking ahead: future simulation requirements

The problems we encounter in current and future detectors are increasingly complex (whether due to cavity stability, or other effects e.g. high thermal distortion) - so simulations become more essential.

Open question*:

**since we conveniently have an optical simulations workshop at Nikhef in <2 weeks time…*

what do we require of interferometer simulations to achieve our 3G detector goals?

Some opening thoughts:

- Efficiency, speed
- Cross-compatibility & cross-checking; integrations with e.g. FEM softwares, pyGWINC, …
- Person-power & accessibility; Open source, maintenance, documentation, …
- Missing physics e.g. polarisation/birefringence, …?

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