Newtonian Calibrator for Virgo (NCal)

Principle, first results, plans for O4,…

ILANCE workshop

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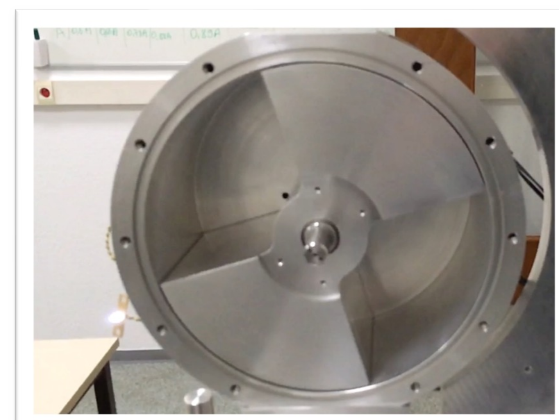
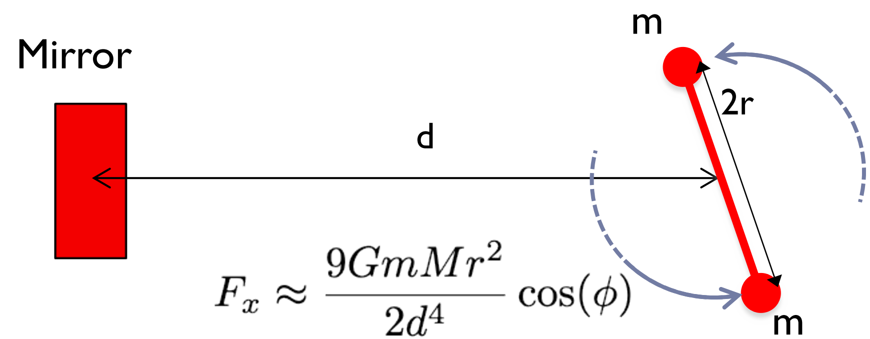
IPHC-Strasbourg



Newtonian calibrator for Virgo

Calibration: move a mirror by a known amount to calibrate the interferometer output

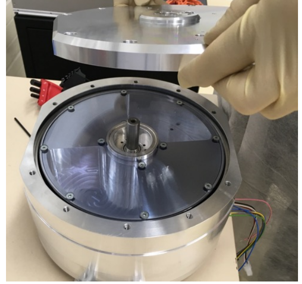
NCal basic principle

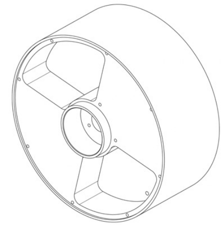


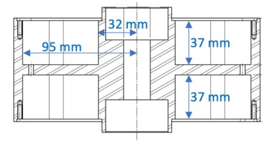
$$F_x \approx \frac{9GmMr^2}{2d^4}\cos(\phi)$$

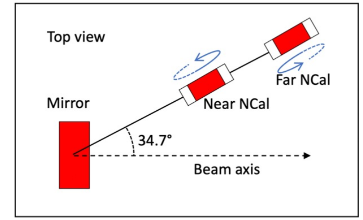
- Rotor made of two masses
  - Center of mass is not moving
  - The non linear Newtonian force creates the signal
  - Signal at twice the rotor frequency;
  - Signal proportional to $1/d^4$ effect → Mirror to NCal distance is critical
- Expected benefits
  - Signal depends mainly on the rotor geometry, mass and position
    - Mass of the mirror cancels out
    - Correction for a real mirror geometry compared to point particle: around 1%
  - No aging effect of the signal
  - Simple interface with the detector
    - Could be moved from one mirror or ITF to another
- An old principle, tested during O2:
  - "First test of a Newtonian calibrator on an interferometric gravitational wave detector" CQG. 35, 235009, 2018

O3 setup

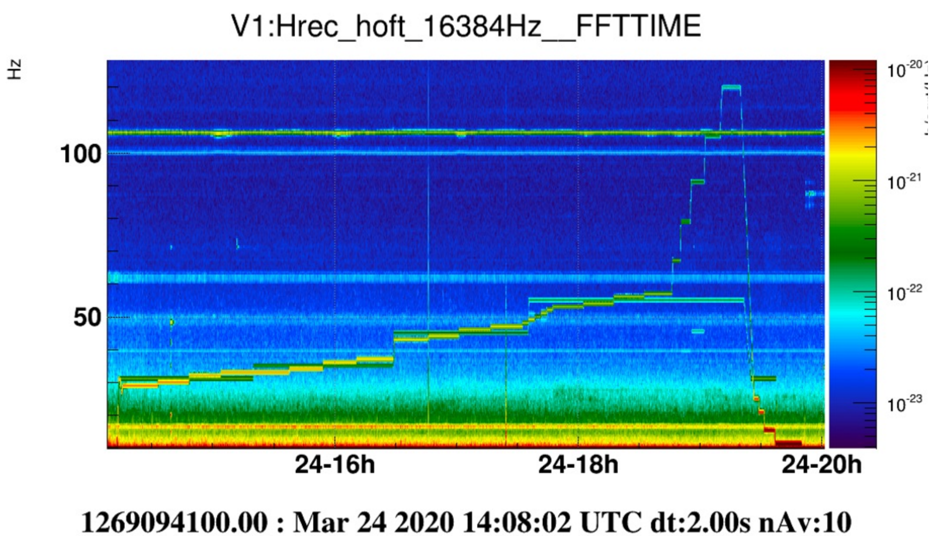


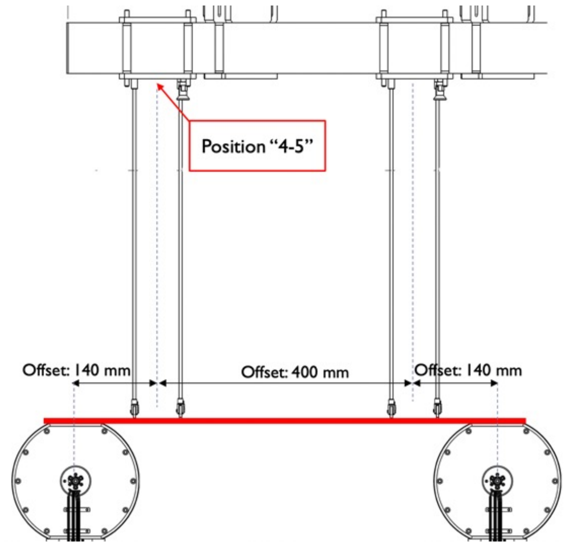






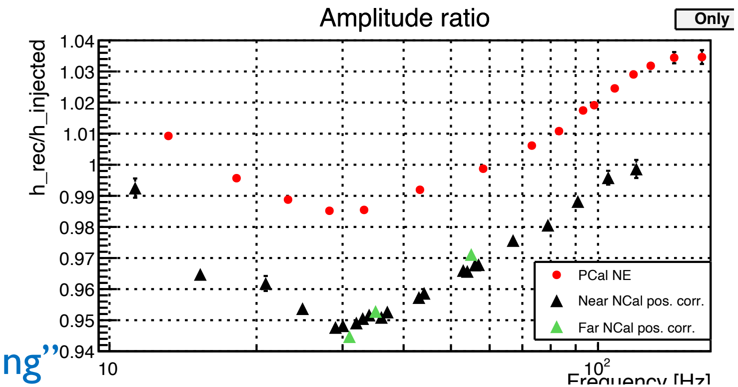
- Two NCals tested during O3 (build at LAPP)
  - At 1.27 and 1.95 m from the mirror → measure the NCal-mirror distance
- Most useful data set:
  - 6 hours on March 24, 2020

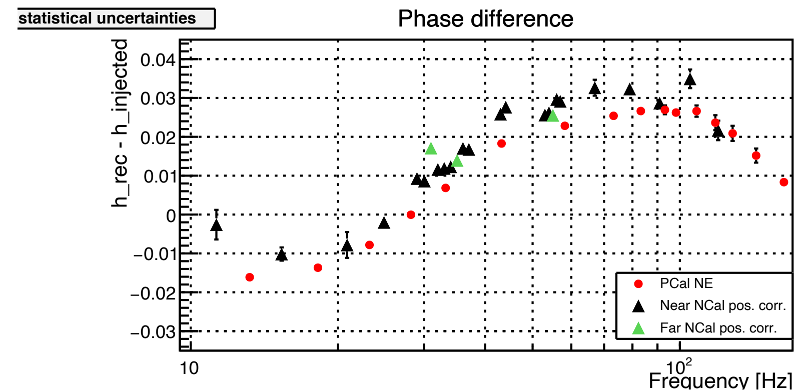




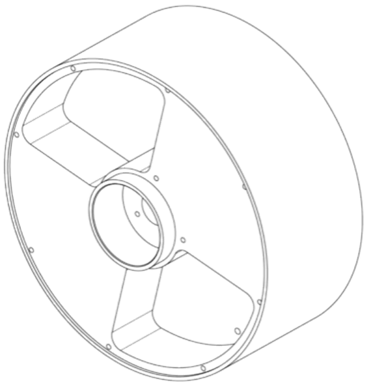
O3 results

- Accurate FEM simulation
- Results published: CQG **38**, 075012
  - "Newtonian calibrator tests during the Virgo O3 data taking"
- Probing h(t) up to 120 Hz (rotor @ 60 Hz)
- Same shape as PCal
- 3% amplitude offset between PCal and NCal
- Systematic uncertainties
  - At the level of the PCal uncertainties
  - Dominated by NCal-mirror distance

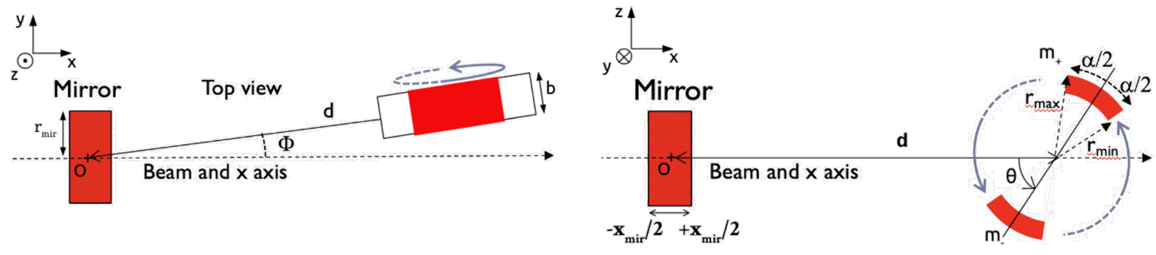




Parameter	uncertainty	formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
NCal to mirror distance d	6.4 mm	$4\delta d/d$	2.02	1.31
NCal to mirror angle Φ	5.0/3.3 mrad	$\delta\Phi \sin\Phi$	0.28	0.19
NCal vertical position z	1.3 mm	$5/2(z/d)^2$	0.03	0.01
Rotor geometry	see table 1		0.53	0.53
Modeling method	see end of section 4		0.018	0.017
Mirror torque from NCal	see end of section 4		0.05	0.03
Total	quadratic sum		2.1	1.4



Why this two 90° sector shape?



(a) Top view (b) Side view

$$a(f_{2rot}) = \frac{9G\rho_{rot}\ b\ \sin(\alpha)(r_{max}^4 - r_{min}^4)}{32\pi^2 f_{2rot}^2 d^4}\cos(\phi)\Big[1 + \frac{25}{54d^2}\frac{(r_{max}^6 - r_{min}^6)}{(r_{max}^4 - r_{min}^4)} + \left(\frac{45}{8}\sin^2(\phi) - \frac{5}{2}\right)\left(\frac{r_{mir}}{d}\right)^2 + \left(\frac{15}{8}\cos^2(\phi) - \frac{25}{24}\right)\left(\frac{x_{mir}}{d}\right)^2 - \frac{25}{72}\left(\frac{b}{d}\right)^2\Big] \quad (8)$$

- For 90° opening angle, the uncertainty goes to zero
- Rotor uncertainties are driven by:
  - Density
  - Thickness
  - Radius

O3 values

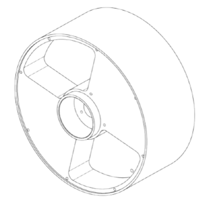
Rotor parameter			NCal signal uncertainty	
name	value	uncertainty	formula	value (%)
Density ρ (kg/m^3)	2805	5	$\delta\rho/\rho$	0.18
Thickness b (mm)	74	0.2	$\delta b/b$	0.27
$r_{\max}$ (mm)	95	0.1	$4\delta r_{\max}/r_{\max}$	0.42
Total uncertainty from the rotor (quadratic sum)				0.53

NCal for O4

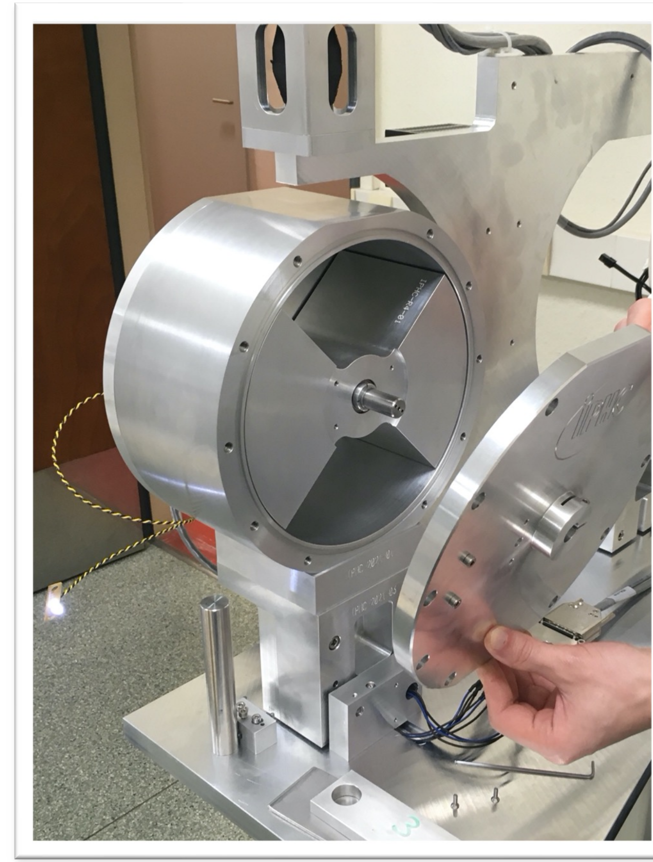
- O4 goals
  - Validate h(t) within 1% in the 10-200 Hz frequency range
  - Add a permanent NCal monitoring line
- Issues/challenges
  - Accurate knowledge of the NCal geometry/material
    - → Metrology
    - → Be able to swap NCals to easily compare/crosscheck them
  - Accurate knowledge of the mirror/NCal distance
    - Extract from measurements at several distances with known relative positions
    - → Several NCals,
    - → Know/survey of the relative NCal position
  - Do not introduce vibrations that may shortcut the signal or spoiled the sensitivity
    - → Suspend the NCals
    - → Reduce the mechanical vibration induce by the rotors
  - Reliability for long term operations

Improving the NCal rotor for O4

- Simpler geometry
  - Remove: the O3 external ring and central disk
- Make it thicker

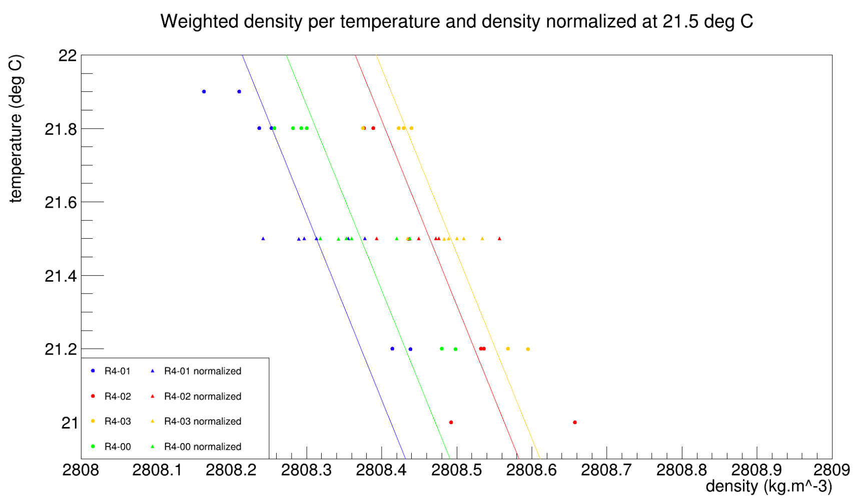


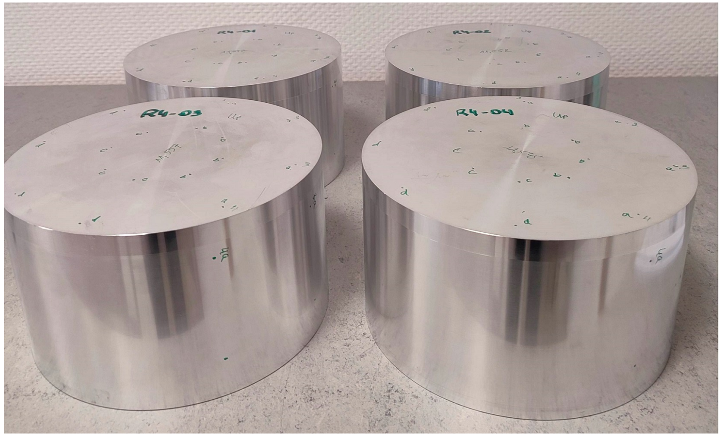
- Benefit
  - Force x 2 compared to O3
  - Simplify the metrology and prediction
- Challenge: air motion → friction
  - Go to 70 W motor
- Current test: 80 Hz rotor speed achieved
  - Will are building a three sectors rotor to probe h(t) up to 200 Hz

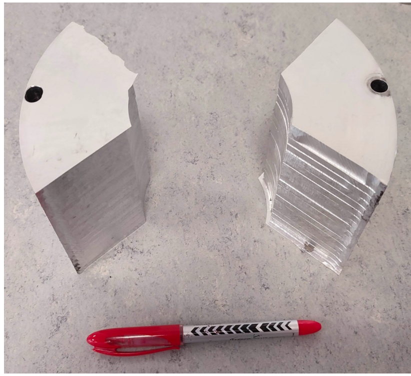


Improving the knowledge of the rotor: density

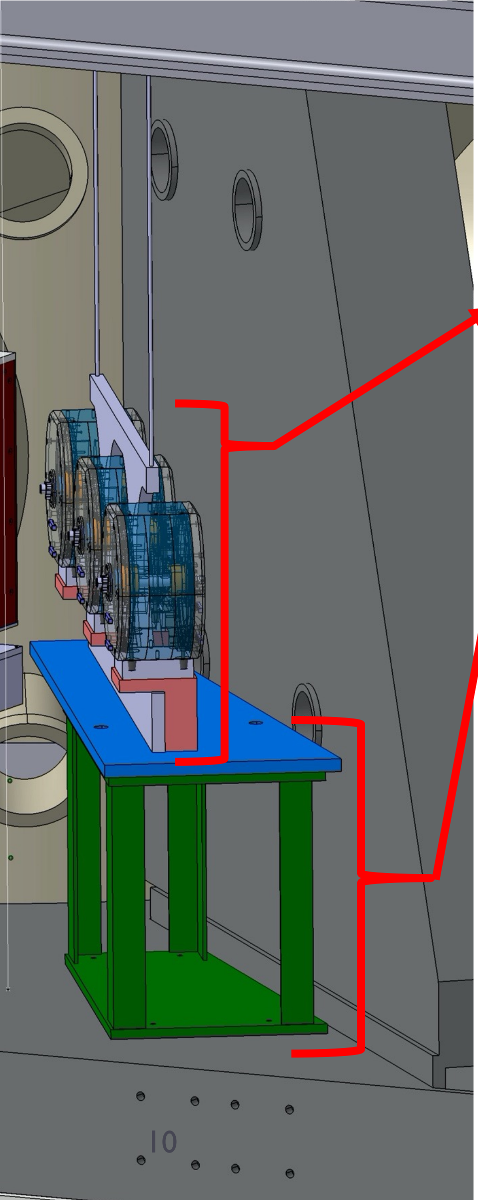
- Careful measurement of the material density
- Machine multiple blocs
- Mean density of 2808.41 ± 0.2 kg.m^{-3}
  - for aluminum 7075 at 21.5 °C
- Relative uncertainty: 0.007% (0.18 % for O3)
- Value is batch specific: could change by 10^{-3}
- Homogeneity check to better than 10^{-4}



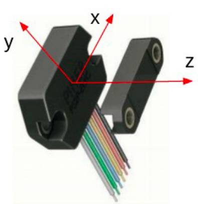


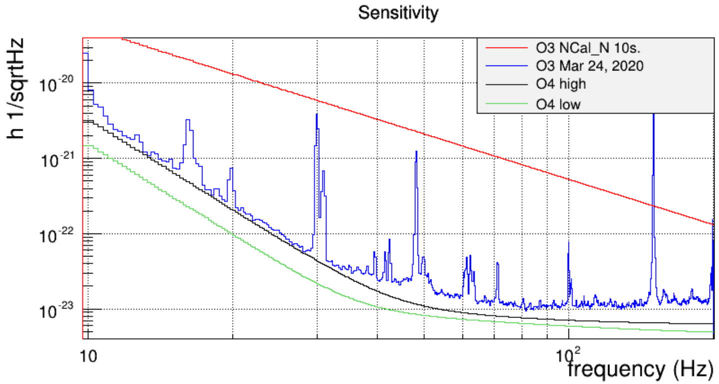


New NCal supports



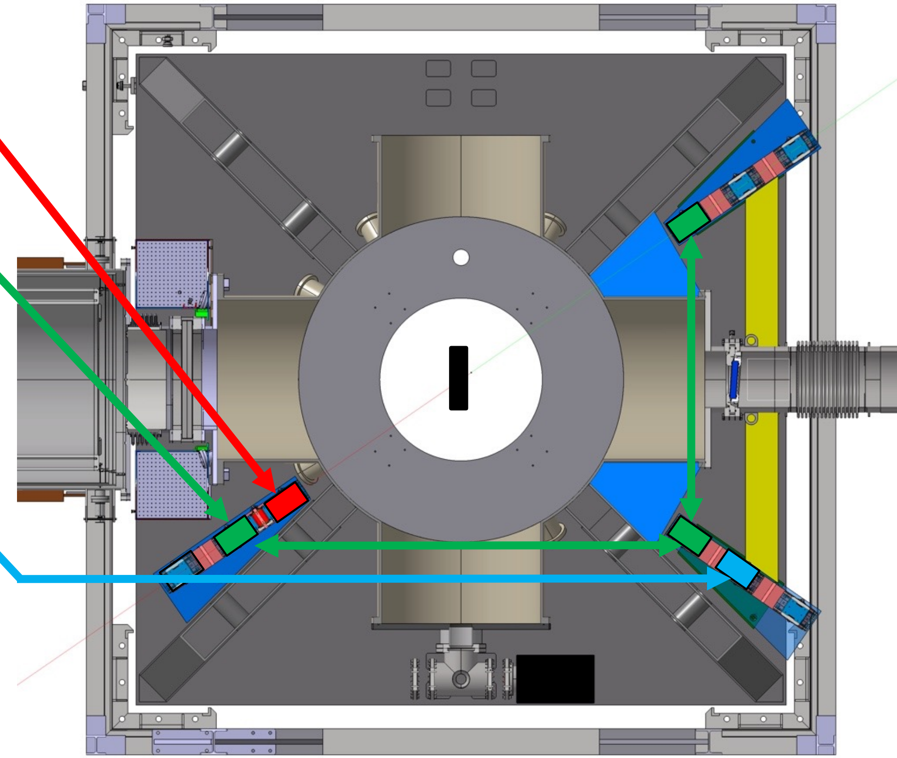
- Suspended NCal blocs
  - Three slots, only one or two slots used
    - Accurate relative positioning
  - Simple suspension:
    - rough filtering of NCal vibrations
- Bottom reference
  - Fixed to the tower base
- Relative position measurement
  - Using linear sensors:
    - PS2PLIN-CE-M002-1-A0-L0000-ELS120-05.
  - Preliminary test results:
    - ± 6 mm range along x
    - Could tolerate ± 3 to 4 mm offsets along y and z





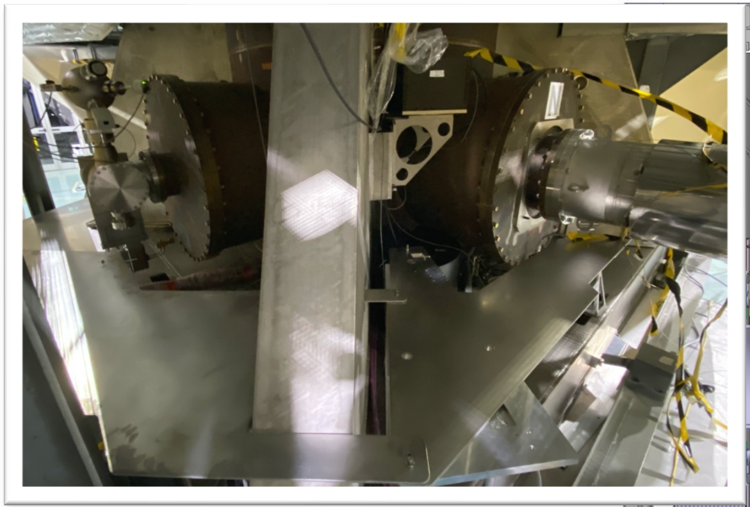
Layout for O4 at North End

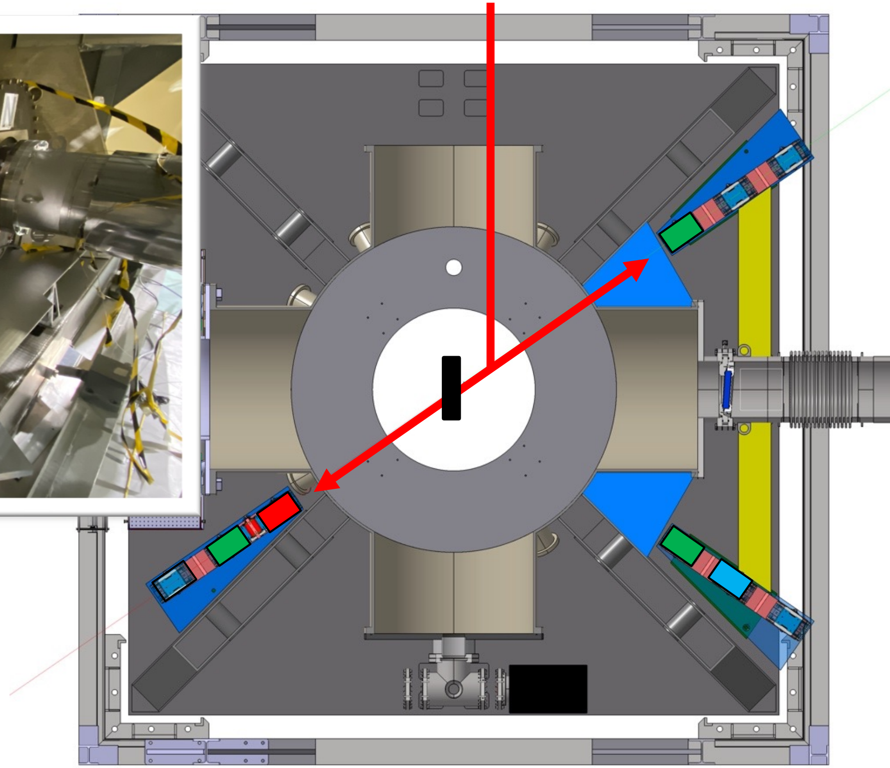
- 1 close NCal (red) for high frequency check
  - At 1.3 m from the mirror
    - Same distance as O3 NCal_N
- 3 NCals (green) for mirror position control
  - Same mirror distance to reduce model uncertainties
  - At 1.7 m from the mirror
    - Attenuation factor vs O3 NCal_N: 2.9
- 1 Far NCal (blue) for permanent line
  - At 2.1 or 2.5 m from the mirror
    - Attenuation factor vs O3 NCal_N: 6.8/13.7
  - Could be installed on any side;
  - Around 30 Hz (in h(t)) ?
- → Build 5+1 new NCals + positioning system



Knowing the NCal relative distance

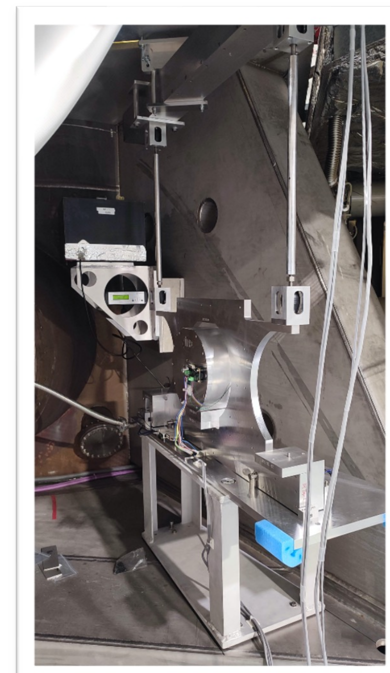
- Use a mechanical template for installing the NCal support
- Survey their positions





NCal foreseen operations during O4

- Dedicated commissioning shifts to:
  - Compare NCals strength by swapping NCals,
  - Extract mirror-NCal relative position by comparing NCal amplitudes
  - Check vertical position by moving the NCal along the vertical axis
  - Search for induced NCal noises, …
- Weekly, calibration period:
  - Frequency scan and check of the mirror-NCal position
  - Should not take too much time (less than half an hour)
- Permanent line(s) for h(t) monitoring
  - Strong enough to get a meaningful result
  - Not to strong to avoid sidebands



O5 NCal plans

- Improve the accuracy from less than 1 % (O4 goal) to less than 0.5 %.
  - Improve the knowledge (and stability) of the NCal position
- Install an NCal system on the West End tower,
  - To be able to inject accurate calibration signals on both arms.
- Extend the frequency band cover up to at least 250 Hz (in h(t)).
  - This corresponds roughly to the frequency where 95 % of the BNS SNR is accumulated.
    - → Work on new rotor
  - May need
    - To use denser material (could gain a factor 2.85 with stainless steel)
    - More powerful motor
    - Go to (partial vacuum)
    - Use magnetic bearing (also good to reduce the mechanical vibration
- Fix any issue that may be observed during O4

Summary

- We will have more and better NCals for O4
- The NCal systematic uncertainties might be smaller than for PCal

  … could be our absolute calibration reference for O4
- Will keep improving it for O5