NCal uncertainties

NCal review for O4

VIR-0237A-24

March 8, 2024

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O4 NCal uncertainty budget

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi\sin(\phi)$	0.04	0.04
	NCal to mirror distance (d)	numerical	0.01	0.01
	NCal twist (ψ)	numerical	$\leq 10^{-3}$	$\leq 3 \times 10^{-3}$
	NCal vertical position (z)	$5/2(z/d)^2$	8×10^{-3}	5×10^{-3}
Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.19	0.24

NCal to NCal distance

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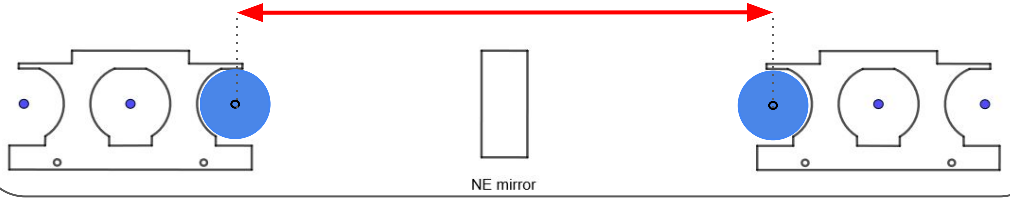
NCal to NCal distance



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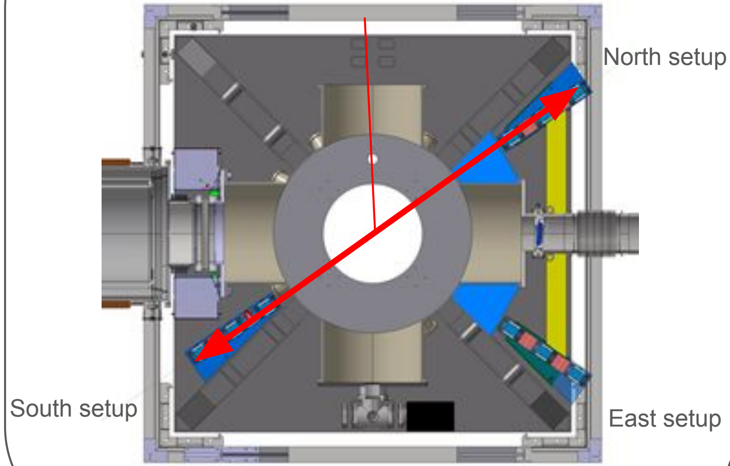
North to South Far reference hole distance



Top view of NE tower

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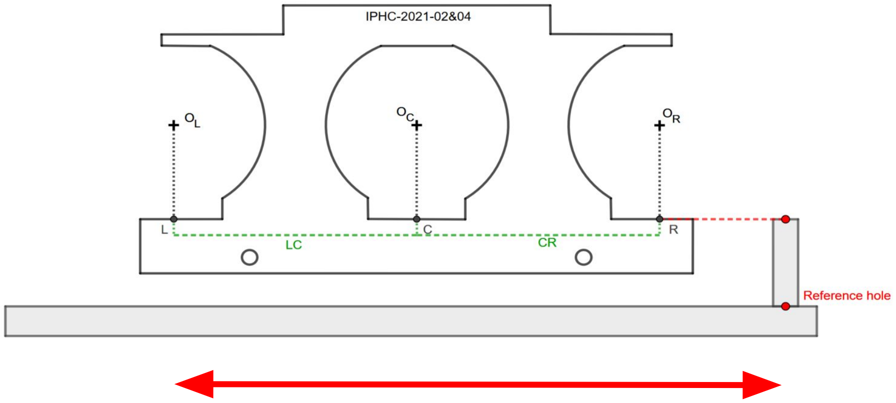

NCal to Far reference hole distance

NCal to NCal distance

North to South (N-S) Far reference hole distance

- Results from 2021 and 2023 geometrical surveys
  - Surveys provide several measurements per point
  - Compute all N-S distances possible
  - N-S Far reference hole distance = **4797.57 ± 0.23 mm**
  - Uncertainty is taken as the RMS of the measurements

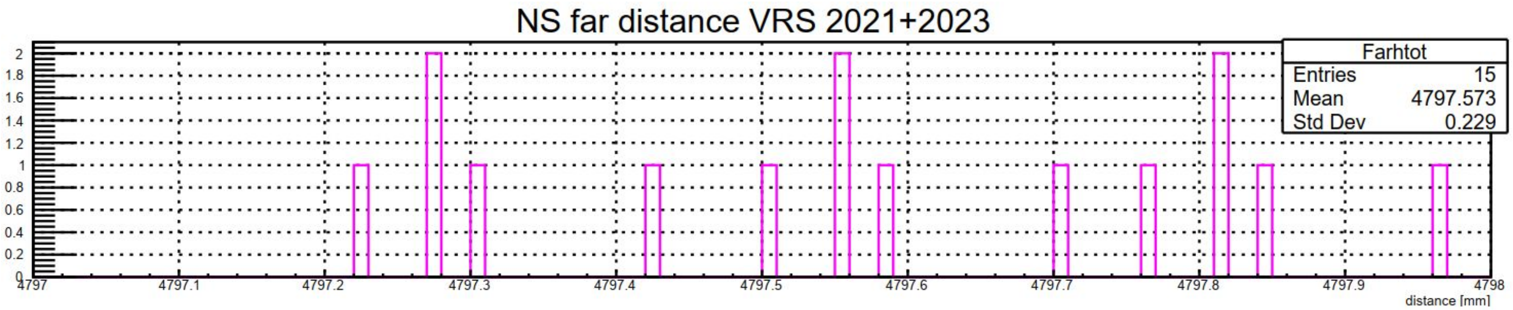

Figure 1 from VIR-0029A-24 in TDS

NCal to NCal distance

NCal to reference hole distance

In order to compute the distance between two NCals on the North to South axis we will use the distance between the North and South far reference holes of 4797.57 ± 0.23 mm from the last row of table 3. To this value we will subtract the distance between the considered NCals rods (slot of the NCal on the suspended plate) and their associated far reference hole.

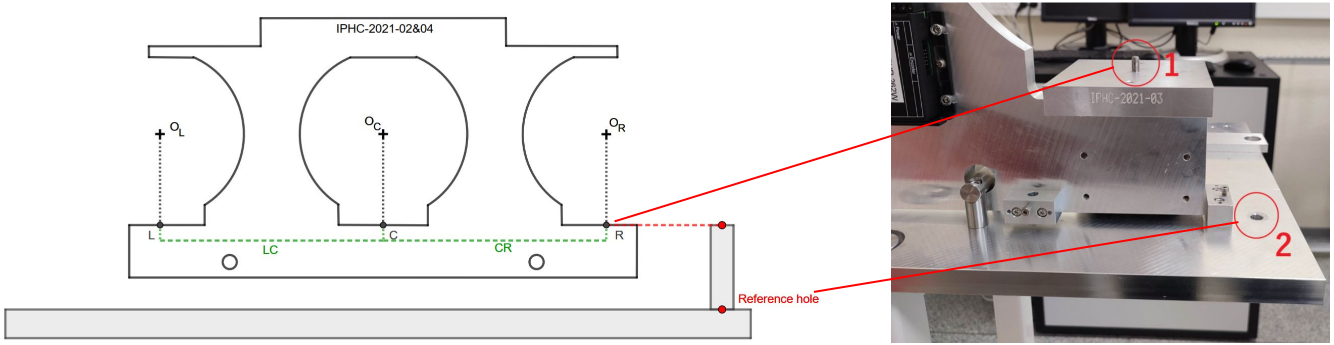

Plate	NCal	Distance to reference hole [mm]
NN	Near	900.24 ± 0.37
	Far	499.76 ± 0.37
NE	Near	899.96 ± 0.37
	Far	500.18 ± 0.37
NS	Near	499.94 ± 0.37
	Far	100.00 ± 0.37

Table 10: Distances between each NCal to the far reference hole of the associated setup.

➔ Uncertainty dominated by the setup motion uncertainty of 0.2 mm and the NCal axis offset uncertainty of 0.3 mm

Table 10 from VIR-0029A-24 in TDS

NCal to NCal distance

Using the results of table 10 we can compute the distance between two NCals on the North to South axis shown in table 12. The uncertainty on these distances is taken as the quadratic sum of the North to South far reference hole distance uncertainty (0.23 mm from last row of table 3), twice the table 10 uncertainty (0.37 mm) due to the two NCals, and the plane uncertainty of 0.067 mm (see section 3 of VIR-1009C-22 on a possible horizontal tilt defect) for a total uncertainty of 0.58 mm.

NCals	Distance [mm]
NNN-NSN	3397.39 ± 0.58
NNF-NSF	4197.81 ± 0.58
NNN-NSF	3797.33 ± 0.58
NNF-NSN	3797.87 ± 0.58

Table 12: Distances between two NCals on the North to South axis.

Table 12 from VIR-0029A-24 in TDS

- NCal to NCal distance uncertainty = 0.58 mm
  - Near NCals (1.7 m) = 0.14 %
  - Far NCals (2.1 m) = 0.11 %

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi \sin(\phi)$	0.04	0.04
	NCal to mirror distance (d)	numerical	0.01	0.01
	NCal twist (ψ)	numerical	$\leq 10^{-3}$	$\leq 3 \times 10^{-3}$
	NCal vertical position (z)	$5/2(z/d)^2$	8×10^{-3}	5×10^{-3}
Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.19	0.24

NCal to beam axis angle

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi\sin(\phi)$	0.04	0.04
	NCal to mirror distance (d)	numerical	0.01	0.01
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Table 4 from VIR-0029A-24 in TDS

Object	x [mm]	y [mm]
North near	-1315.15 ± 0.34	-908.40 ± 0.35
North far	-2137.68 ± 0.34	-1477.12 ± 0.36
East near	-1319.80 ± 0.45	903.20 ± 0.35
East far	-2145.33 ± 0.45	1467.03 ± 1.10
South near	987.70 ± 0.45	680.60 ± 0.98
South far	1810.70 ± 0.45	1248.13 ± 0.98

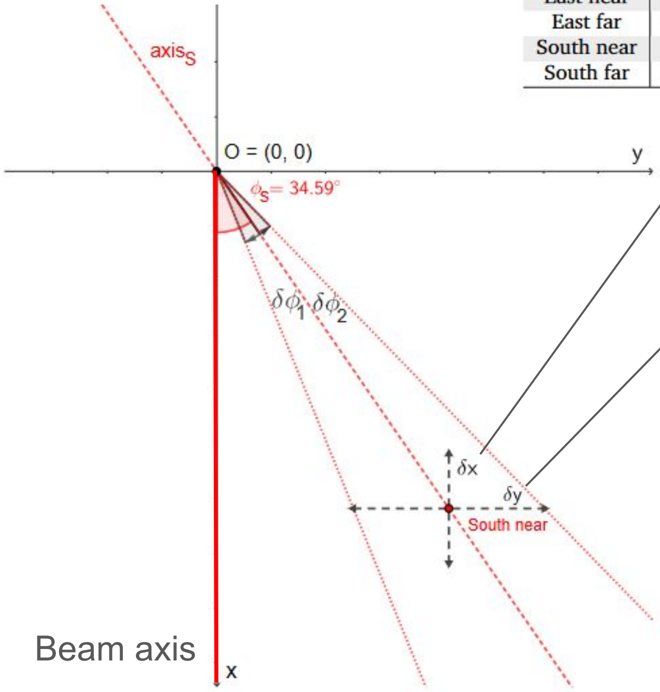
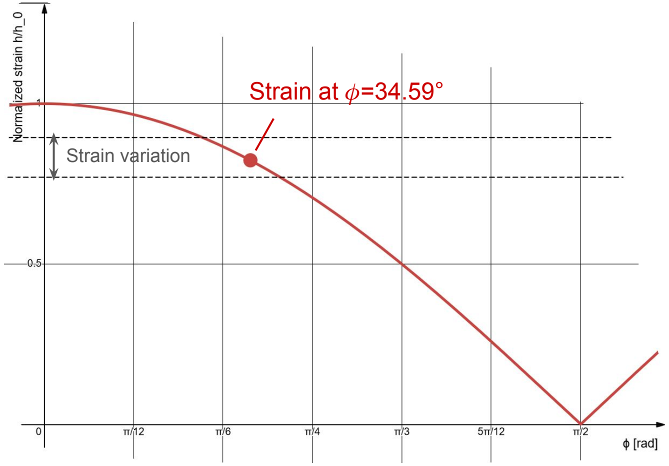


Figure 5 from VIR-0029A-24 in TDS



Worst case scenario with South Near reference hole position

➔ Uncertainty on ϕ = 0.06° (1.05 mrad) = 0.06 %/sqrt(2) for 2 NCals

NCal to mirror distance

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi \sin(\phi)$	0.04	0.04
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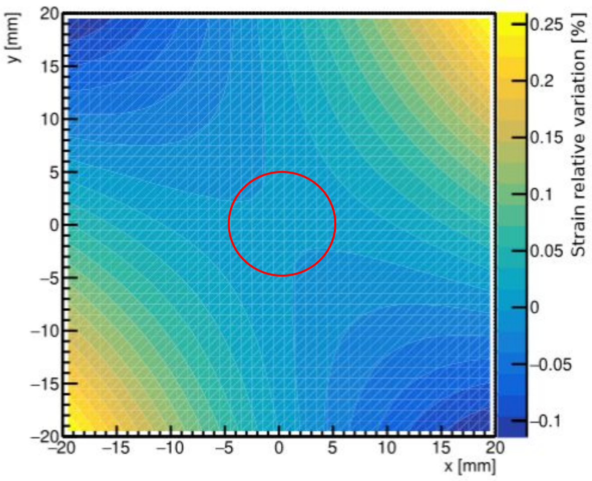
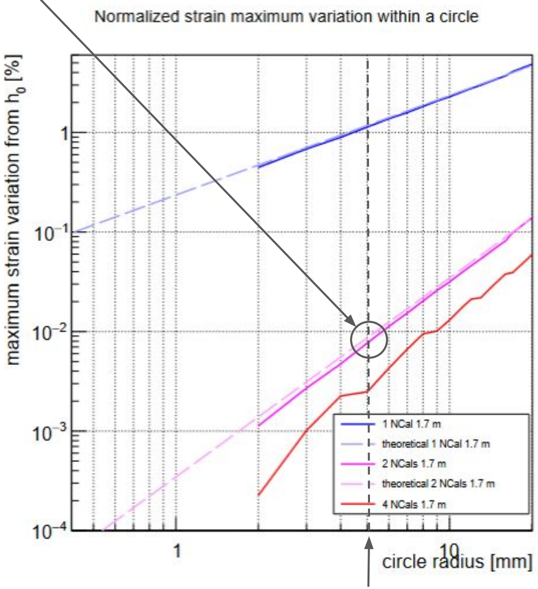
Mirror position constrained within 5 mm around the mechanical center of the tower

- Using 2 NCals, the strain relative variation is about 0.01 %



Strain relative variation of 2 NCals as seen by the mirror



5 mm

NCal twist

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi \sin(\phi)$	0.04	0.04
	NCal to mirror distance (d)	numerical	0.01	0.01
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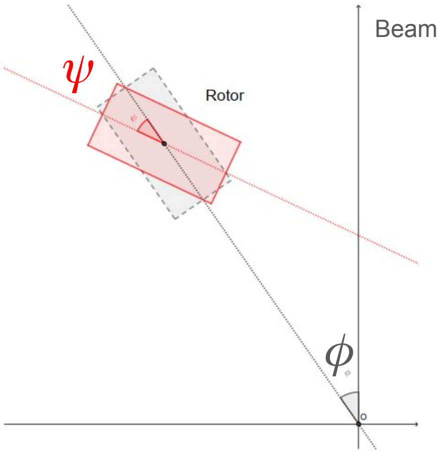

Figure 1: Top view of a rotor in the reference frame of the tower. In black is shown a rotor with no twist and in red is the same rotor with a positive twist ψ. The rotor is at an angle ϕ from the beam axis.

Figure 1 from VIR-0530A-23 in TDS

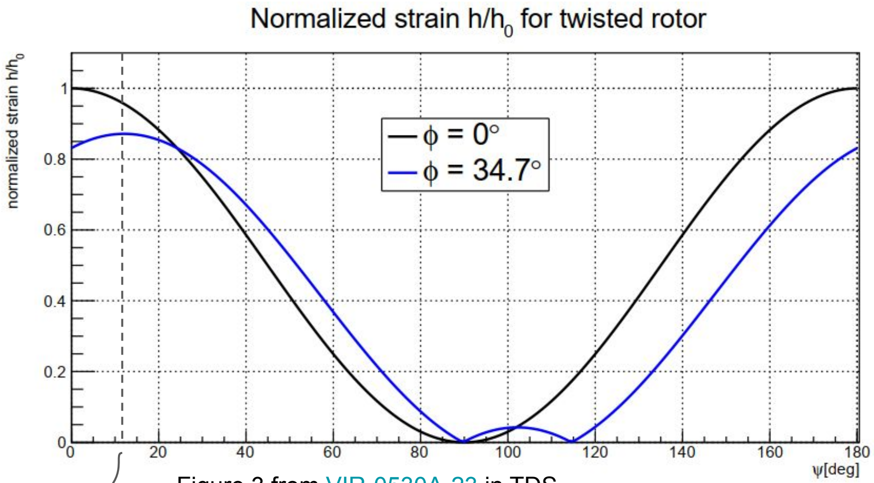

Figure 3 from VIR-0530A-23 in TDS

- **Optimal twist ψ for maximal signal ≈ 12°**
  - **Minimize the uncertainty**

➔ Twist uncertainty (mechanical) = 0.1°

Setup	ψ_{max} at 1.7 m	ψ_{max} at 2.1 m
North	12.03°	11.68°
East	11.45°	11.55°
South	12.05°	12.15°

Table 8: Twist ψ_{max} associated to the maximum signal for each setup distances.

Setup with $\psi = 12°$	Amplitude deviation [%] at 1.7 m	Amplitude deviation [%] 2.1 m
North	5.2×10^{-4}	2.4×10^{-3}
East	3.8×10^{-3}	3.2×10^{-3}
South	6.6×10^{-4}	1.3×10^{-3}

Table 9: Relative amplitude deviations for different NCal to mirror distances at a fixed $\psi = 12° \pm \delta\psi = 0.1°$.

Tables 8 and 9 from VIR-0029A-24 in TDS

NCal vertical position

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi\sin(\phi)$	0.04	0.04
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Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.19	0.24

Using the survey measurements of the elevation of the reference plates we transfer this value to the elevation of the NCals relative to the reference plates.

NCal	axis elevation [mm]
NNN (1.7 m)	-3.52 ± 0.64
NNF (2.1 m)	-3.40 ± 0.78
NEN (1.7 m)	-3.87 ± 0.12
NEF (2.1 m)	-3.35 ± 0.12
NSN (1.7 m)	-8.18 ± 0.90
NSF (2.1 m)	-8.57 ± 0.90

Table 7: Axis elevation of each NCal.

Table 7 from VIR-0029A-24 in TDS

In the worst case scenario (8.57 mm with a 0.90 mm error) the elevation offset for a NCal is below 10 mm. This offset translates to a signal variation of 9×10^{-3}% at 1.7 m and 6×10^{-3}% at 2.1 m, using the simple analytic formula. The results of a FROMAGE computation are similar: 8×10^{-3}% at 1.7 m and 5×10^{-3}% at 2.1 m.

Rotor induced strain

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
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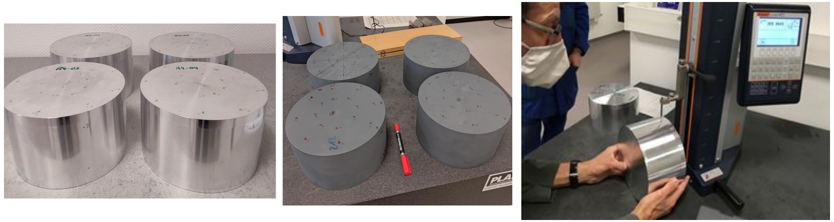
Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.19	0.24

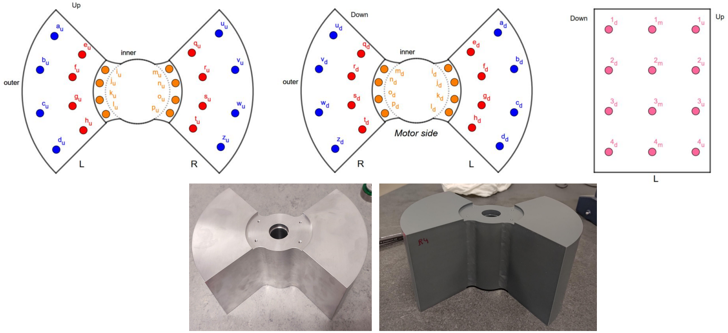
R4-10 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	1442.3	0.2	$\delta\rho/\rho$	0.014
Thickness b left sector (12 sub-sectors) (mm)	104.416	9×10^{-3}	$\delta b/b$	0.008
Thickness b right sector (12 sub-sectors) (mm)	104.415			
r_{max} left sector (12 ext sub-sectors) (mm)	103.840	5×10^{-3}	$4\delta r_{max}/r_{max}$	0.018
r_{max} right sector (12 ext sub-sectors) (mm)	103.838			
G (m^3.kg^{-1}.s^{-2})	$6.674\,30 \times 10^{-11}$	1.5×10^{-15}	$\delta G/G$	0.002
Temperature T (°C)	23	1.5	$\left\lvert\frac{\partial h}{\partial T}\right\rvert \frac{\Delta T}{h}$	0.024
Modelling Uncertainty				0.001
FROMAGE grid uncertainty				0.005
Opening angle and sector asymmetry uncertainty				0.002
Remaining geometry uncertainty				$<5 \times 10^{-4}$
Total uncertainty from the rotor (quadratic sum)				0.034

Table 10 from [VIR-0203A-24](VIR-0203A-24) in TDS

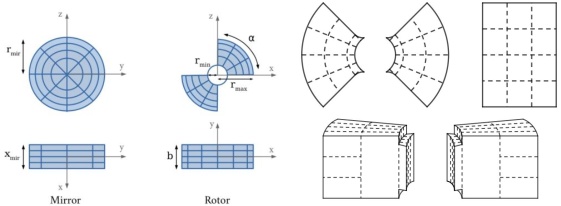
Density of the material



Metrology of machined rotors



FEM software for signal computing



Rotor induced strain

Density of the material

VIR-0160A-22 and VIR-0193A-24 on TDS

Figure 2 shows an outline of the faces and side of the cylinders with each measurement points shown as colored dots. There is a total of 40 points of measure on each cylinder to determine the volume. Points on one face are mirrored on the opposite face meaning for instance that "x_u" point on face up is associated to "x_d" on face down.

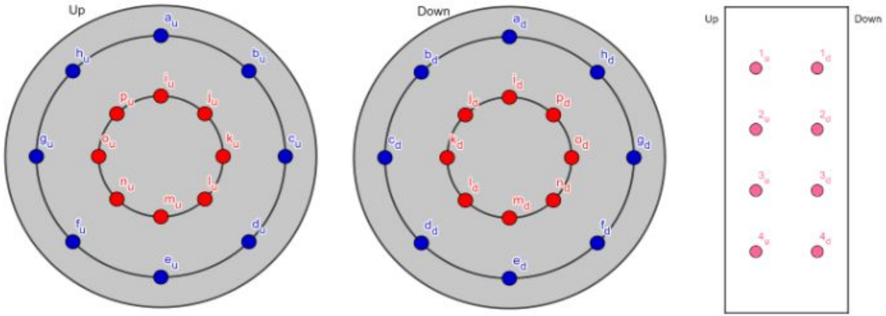


Figure 2: Outline of the faces and side of the cylinders, colored dots represent where the measures will be taken. From left to right, face up, face down, side.

In figure 2 we notice that the inner points (red colored points) are closer to each other than the outer points (blue colored points), the perimeter described by the outer points compared to the inner points is larger by a factor 2. To not bias the density we will then apply a weight of 0.5 on the interior points while computing the mean height.

- ➔ Density know up to 0.2 kg.m^-3
  - ◆ Aluminum density uncertainty = 0.007 %
  - ◆ PVC density uncertainty = 0.014 %

R4-10 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	1442.3	0.2	$\delta\rho/\rho$	0.014
Thickness b left sector (12 sub-sectors) (mm) Thickness b right sector (12 sub-sectors) (mm)	104.416 104.415	9×10^{-3}	$\delta b/b$	0.008
r_{max} left sector (12 ext sub-sectors) (mm) r_{max} right sector (12 ext sub-sectors) (mm)	103.840 103.838	5×10^{-3}	$4\delta r_{max}/r_{max}$	0.018
G (m^3.kg^{-1}.s^{-2})	$6.674\,30 \times 10^{-11}$	1.5×10^{-15}	$\delta G/G$	0.002
Temperature T (°C)	23	1.5	$\left\lvert\frac{\partial h}{\partial T}\right\rvert \frac{\Delta T}{h}$	0.024
Modelling Uncertainty				0.001
FROMAGE grid uncertainty				0.005
Opening angle and sector asymmetry uncertainty				0.002
Remaining geometry uncertainty				$<5 \times 10^{-4}$
Total uncertainty from the rotor (quadratic sum)				0.034

Computation method	R4-01	R4-02	R4-03	R4-04
Weighted density [kg.m^{-3}]	2808.0	2808.2	2808.2	2808.1
Density $\rho_{23°C}$ [kg.m^-3] =	2808.1			

Table 8 from VIR-0160A-22 in TDS

Measurements	Column 1 (21.2°C)	Column 2 (21.35°C)
Mean diameter D [mm]	210.028	210.023
Mean height h [mm]	109.864	109.865
Mass m [kg]	10.6998	
Density ρ (kg.m^{-3})	2811.0	2811.2
Density $\rho_{23°C}$ (kg.m^{-3})	2810.8	

Table 1 from VIR-0859A-22 in TDS

Average value		Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
D [mm]		211.040	211.047	211.029	211.034
h (weighted) [mm]		114.021	113.987	114.042	114.028
m_{rescaled} [kg]		5.7554	5.7535	5.7562	5.7554
ρ [kg.m^{-3}]	21°C	1443.0	1442.9	1443.1	1443.0
	23°C	1442.3	1442.2	1442.4	1442.3
Density $\rho_{23°C}$ [kg.m^-3] =		1442.3			

Table 4 from VIR-0193A-24 in TDS

Rotor induced strain

Metrology of machined rotors

VIR-0203A-24 and 9 others on TDS

R4-10 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	1442.3	0.2	$\delta\rho/\rho$	0.014
Thickness b left sector (12 sub-sectors) (mm) Thickness b right sector (12 sub-sectors) (mm)	104.416 104.415	9×10^{-3}	$\delta b/b$	0.008
r_{max} left sector (12 ext sub-sectors) (mm) r_{max} right sector (12 ext sub-sectors) (mm)	103.840 103.838	5×10^{-3}	$4\delta r_{max}/r_{max}$	0.018
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Modelling Uncertainty				0.001
FROMAGE grid uncertainty				0.005
Opening angle and sector asymmetry uncertainty				0.002
Remaining geometry uncertainty				$<5 \times 10^{-4}$
Total uncertainty from the rotor (quadratic sum)				0.034

To determine the geometry of the rotor we will use the same method as for R4-01 (see VIR-0591C-22). The thickness was measured using 16*2 = 32 points for the sectors and 8*2 = 16 points for the inner part. In addition we measured the outer diameter using four more points than the previous rotors for a total of 4*3 = 12 points. The measurement points are shown in fig. 1. We will use the drawing values for the inner diameter.

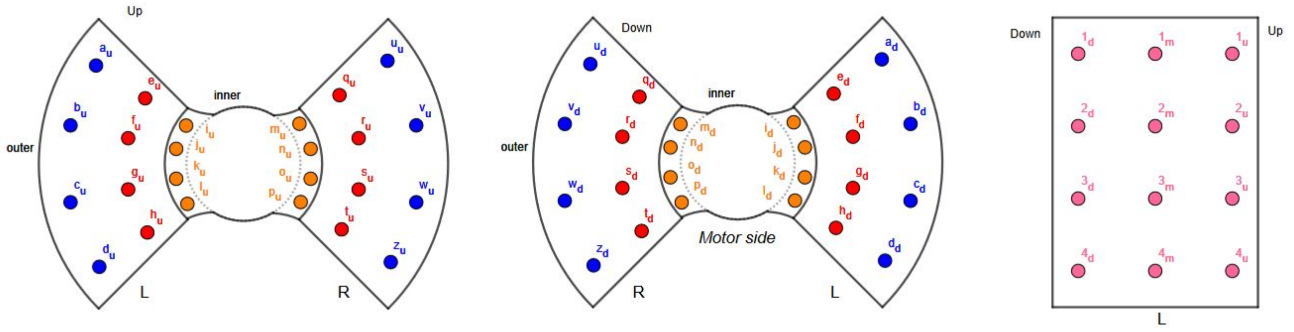

Figure 1: Outline of the faces of the rotor with the measurement points. Left is face up, center is face down and right is the side view of the left sector. Sectors have been labelled L for left sector and R for right sector.

➔ Rotor dependant

Rotor induced strain : Temperature

VIR-0203A-24 and 9 others on TDS

R4-10 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	1442.3	0.2	$\delta\rho/\rho$	0.014
Thickness b left sector (12 sub-sectors) (mm) Thickness b right sector (12 sub-sectors) (mm)	104.416 104.415	9×10^{-3}	$\delta b/b$	0.008
r_{max} left sector (12 ext sub-sectors) (mm) r_{max} right sector (12 ext sub-sectors) (mm)	103.840 103.838	5×10^{-3}	$4\delta r_{max}/r_{max}$	0.018
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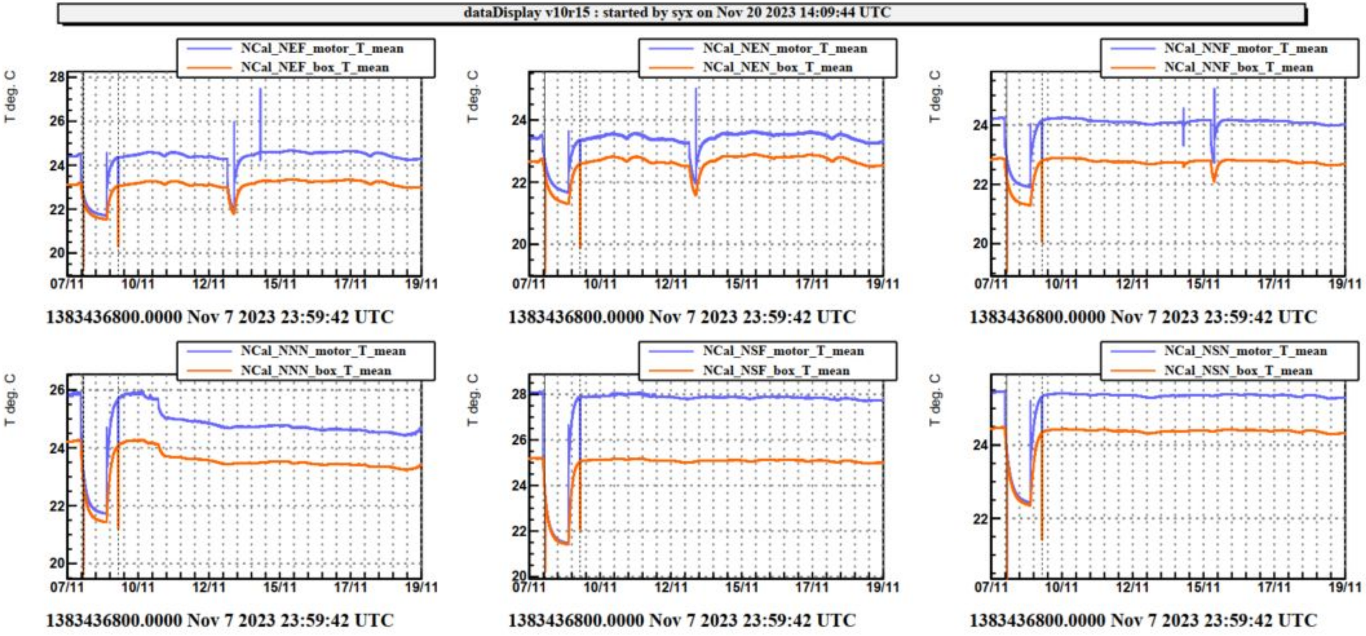
FROMAGE grid uncertainty				0.005
Opening angle and sector asymmetry uncertainty				0.002
Remaining geometry uncertainty				$<5 \times 10^{-4}$
Total uncertainty from the rotor (quadratic sum)				0.034

Operating temperatures at f = 21 Hz in the NE building : T = 23 ± 1.5 °C

- Signal uncertainty due to temperature uncertainty
  - Aluminum rotors = 0.007 %
  - PVC rotors = 0.024 %



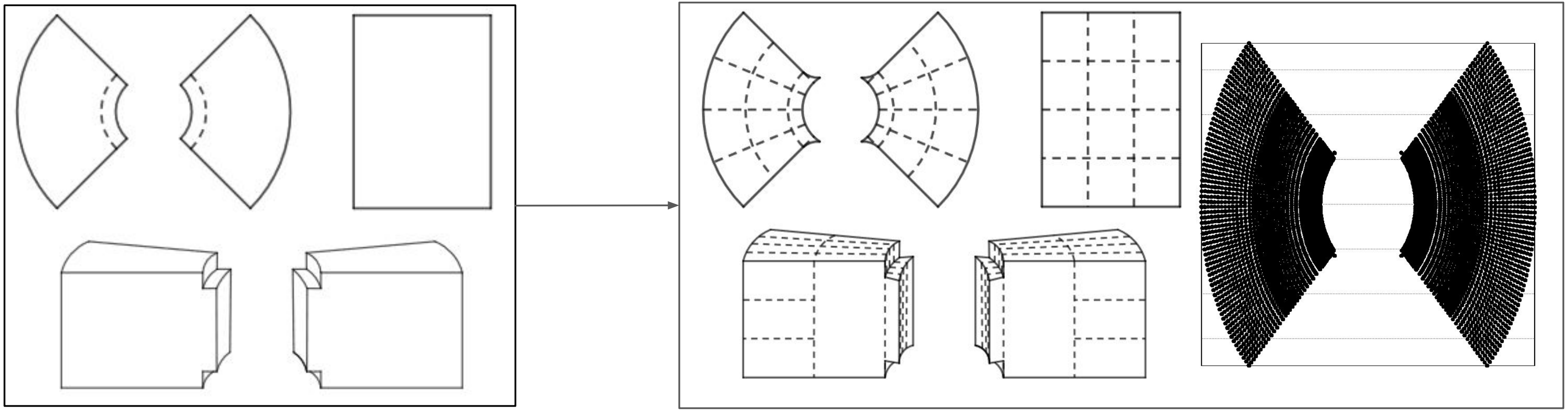
Rotor induced strain : Modelling

VIR-0203A-24 and 9 others on TDS

R4-10 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	1442.3	0.2	$\delta\rho/\rho$	0.014
Thickness b left sector (12 sub-sectors) (mm) Thickness b right sector (12 sub-sectors) (mm)	104.416 104.415	9×10^{-3}	$\delta b/b$	0.008
r_{max} left sector (12 ext sub-sectors) (mm) r_{max} right sector (12 ext sub-sectors) (mm)	103.840 103.838	5×10^{-3}	$4\delta r_{max}/r_{max}$	0.018
G (m^3.kg^{-1}.s^{-2})	6.67430×10^{-11}	1.5×10^{-15}	$\delta G/G$	0.002
Temperature T (°C)	23	1.5	$\left\lvert\frac{\partial h}{\partial T}\right\rvert \frac{\Delta T}{h}$	0.024
Modelling Uncertainty				0.001
FROMAGE grid uncertainty				0.005
Opening angle and sector asymmetry uncertainty				0.002
Remaining geometry uncertainty				$<5 \times 10^{-4}$
Total uncertainty from the rotor (quadratic sum)				0.034

Rotor modelling uncertainty = difference between a simple and a more refined geometry in FROMAGE*

➔ Rotor dependant



Simple rotor geometry, averaged values for sectors

Advanced rotor geometry, sub-sectors with different thickness and radius, opening angles…

- Each block is made of 8x17x14 sub blocks (grid size) for both cases

Figures 2 and 5 from VIR-0203A-24 in TDS

*FROMAGE is a simulation tool developed for gravitational effects induced by rotating masses using a Finite Element Analysis (FEA) and written in C/C++ (see VIR-0759B-20 in TDS)

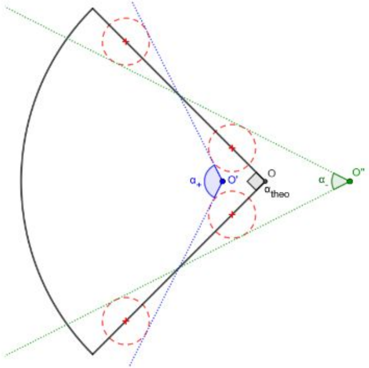
Rotor induced strain : Opening angles

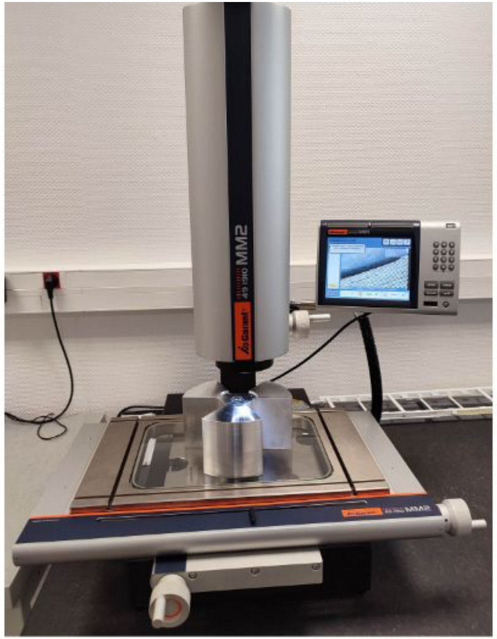
VIR-0203A-24 and 9 others on TDS

R4-10 rotor parameter advanced model (23°C)			NCal 2f signal uncertainty	
name	mean value	uncertainty	formula	value (%)
Density ρ (kg.m^{-3})	1442.3	0.2	$\delta\rho/\rho$	0.014
Thickness b left sector (12 sub-sectors) (mm)	104.416	9×10^{-3}	$\delta b/b$	0.008
Thickness b right sector (12 sub-sectors) (mm)	104.415			
r_{max} left sector (12 ext sub-sectors) (mm)	103.840	5×10^{-3}	$4\delta r_{max}/r_{max}$	0.018
r_{max} right sector (12 ext sub-sectors) (mm)	103.838			
G (m^3.kg^{-1}.s^{-2})	$6.674\,30 \times 10^{-11}$	1.5×10^{-15}	$\delta G/G$	0.002
Temperature T (°C)	23	1.5	$\left\lvert \frac{\partial h}{\partial T} \right\rvert \frac{\Delta T}{h}$	0.024
Modelling Uncertainty				0.001
FROMAGE grid uncertainty				0.005
Opening angle and sector asymmetry uncertainty				0.002
Remaining geometry uncertainty				$<5 \times 10^{-4}$
Total uncertainty from the rotor (quadratic sum)				0.034

- Opening angles and asymmetry uncertainty (rotor dependant) □ 0.002 %

Figure 15: Method used to determine the uncertainty on the opening angles using the video microscope. In red are shown the points used to determine the two lines for the opening angle computation, the red dotted circles represent their uncertainty ($\pm$ 2 µm). The theoretical angle α_{theo} is equal to $\pi/2$, α_+ and α_- are the maximum and minimum values of the error on this angle. The proportions have been amplified for the visualization. This method combines the uncertainties in the most pessimistic way making them conservative.





Video Measuring microscope

- Remaining uncertainty geometry < 5e-4 %

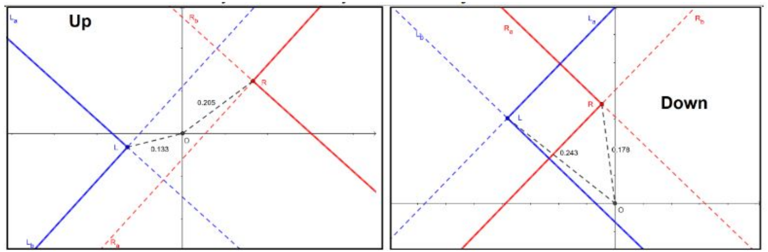


Figure 19: Offset of the centers of the centers to the axis center in mm. Left is face up, right is face down. L sector is shown in blue and R sector in red.

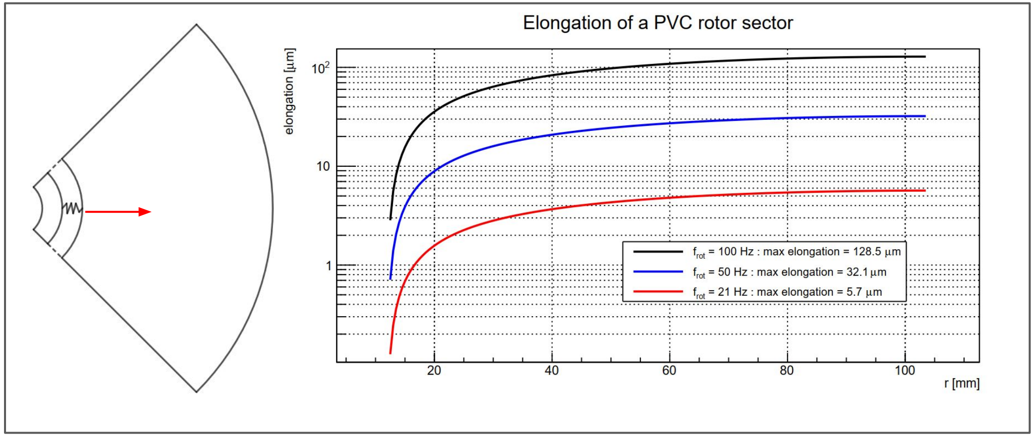
Figures 15 and 19 from VIR-0591C-22 in TDS

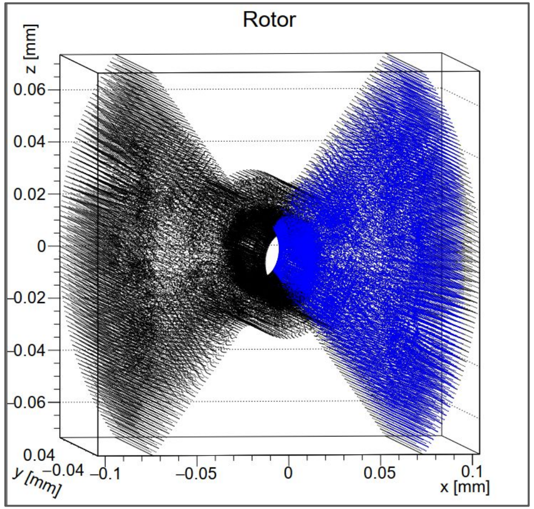
Rotor deformation at 21 Hz

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi \sin(\phi)$	0.04	0.04
	NCal to mirror distance (d)	numerical	0.01	0.01
	NCal twist (ψ)	numerical	$\leq 10^{-3}$	$\leq 3 \times 10^{-3}$
	NCal vertical position (z)	$5/2(z/d)^2$	8×10^{-3}	5×10^{-3}
Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.19	0.24

PVC is expected to undergo more deformation than aluminum

- Compute the rotor elongation
  - Using simple analytical model (spring and mass)
  - Using FEM of rotor geometry to confirm
- Impact on signal for a 21 Hz rotation
  - Aluminum rotor = < 1e-2 %
  - PVC rotor = 0.03 %

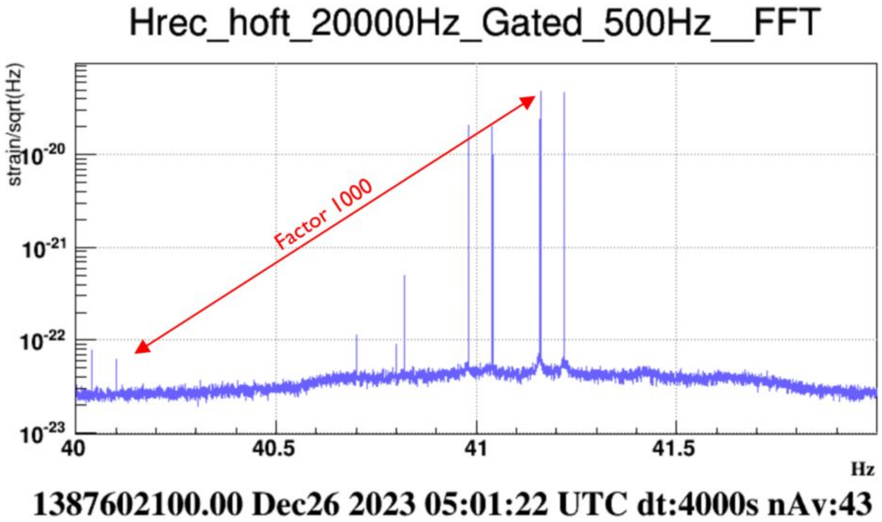


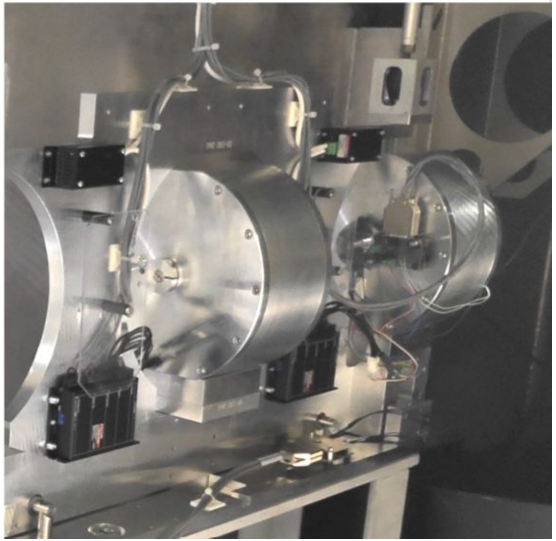


Residual coupling

Parameter		Formula	h_{rec}/h_{inj} near [%]	h_{rec}/h_{inj} far [%]
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi\sin(\phi)$	0.04	0.04
	NCal to mirror distance (d)	numerical	0.01	0.01
	NCal twist (ψ)	numerical	$\leq 10^{-3}$	$\leq 3 \times 10^{-3}$
	NCal vertical position (z)	$5/2(z/d)^2$	8×10^{-3}	5×10^{-3}
Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.19	0.24

- Rotate the rotor about 90°
  - Actually 89.7° due to rotor/mirror size
- Expect cancelation of NCal signal
- Measured residual signal : 0.1 %
  - Aluminum rotor
  - Part is due to alignment/twist uncertainty
  - Other part from parasitic coupling : residual magnetic field





O4 NCal uncertainty budget

Parameter		Formula	h_{rec}/h_{inj} near [%] (PVC rotors)	h_{rec}/h_{inj} far [%] (Aluminum rotors)
Positioning	NCal to NCal distance	$4\delta d/d$	0.14	0.11
	NCal to beam axis angle (ϕ)	$\delta\phi\sin(\phi)$	0.04	0.04
	NCal to mirror distance (d)	numerical	0.01	0.01
	NCal twist (ψ)	numerical	$\leq 10^{-3}$	$\leq 3 \times 10^{-3}$
	NCal vertical position (z)	$5/2(z/d)^2$	8×10^{-3}	5×10^{-3}
Rotor induced strain		see end of section 4	0.057	0.061
Rotor deformation at 21 Hz		numerical	0.03	$\leq 10^{-2}$
Residual coupling (including magnetic)		see section 5	≤ 0.1	0.2
Total		quadratic sum	0.19	0.24