Characterization of Wide-Angle-Baffle's damping system in KAGRA

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(June 2019)

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1. Introduction

The Wide-Angle-Baffles (WAB) are located each directly in front of the test-masses facing the arm cavities (4 test-masses → 4 WABs) inside the, so called, C-chambers (see Figure 1). They are supposed to work under ultra-high vacuum and cryogenic (14 ~ 20 K) conditions. As for convention, "WAB" shall be used here to denominate the baffle plus its suspension.

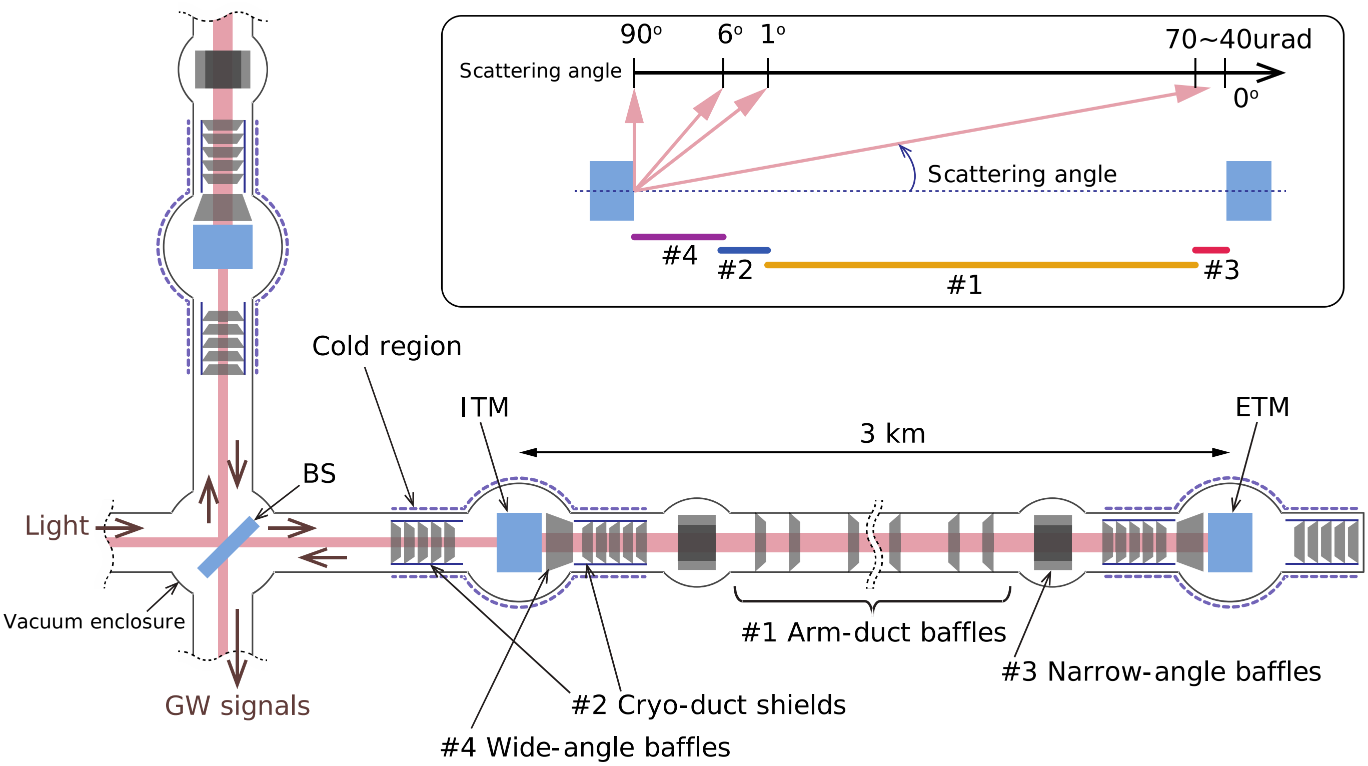

Figure 1: Sketch of the basic position for each type of baffle within the main interferometer. Basically shown is only the, so called, X-arm. The configuration in Y-direction is the same.

The WAB sits on an optical table directly in front of the test-mass (see Figure 2). The basic structure of a fully assembled WAB as it is installed inside each chamber can be seen from Figure 3.

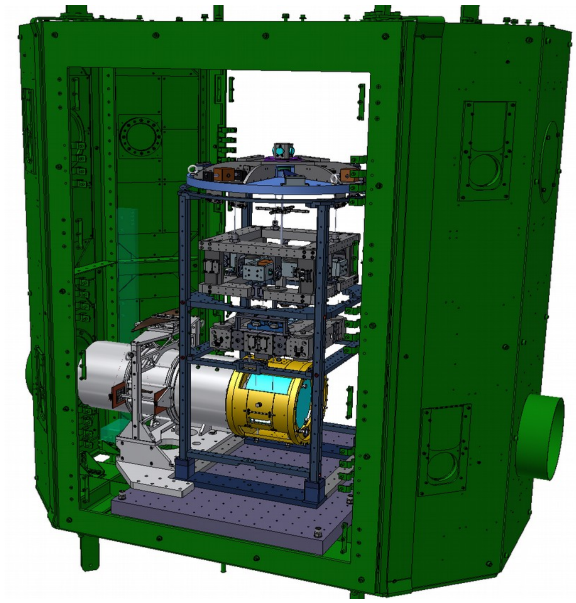

Figure 2: View inside the chamber with installed payload for the test-mass and the WAB.

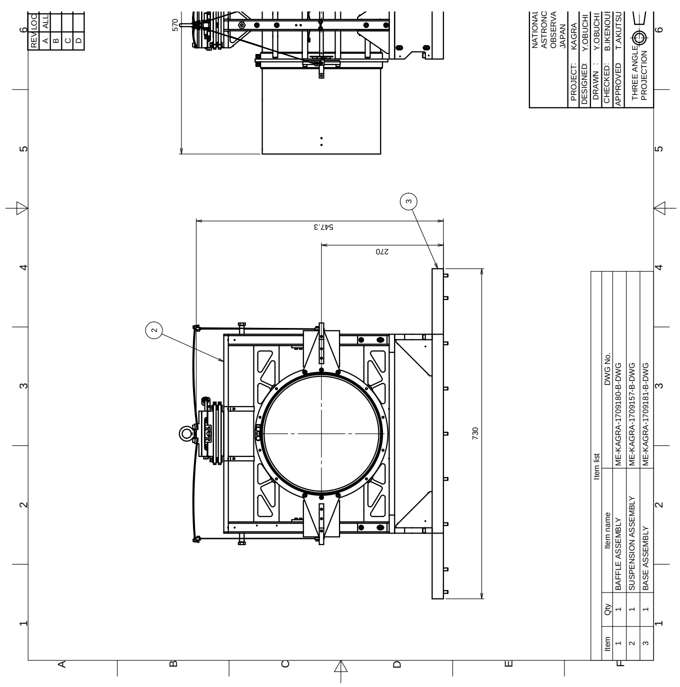

Figure 3: Drawing of the WAB structure fully assembled.

Note: Each WAB has a dedicated direction!
The side-view in Figure 3 makes it obvious. On the right-hand is the side that shows toward the cavity and on the left-hand is the side that faces the test-mass.

The baffle itself is covered with black NiPW plating (“Solblack”) and will directly be cooled down to ~14 K (~20 K when the laser is switched on). In the shown figures, the baffle is painted gray for a better visualization. In fact, once the WAB is installed, it is very hard to distinguish any details from its surface due to the black coating.

2. Suspension

2.1. General Notes

The baffle is suspended at 4 points along its horizontal plane-of-gravity. Each point has a distance of ~10 cm from the baffle’s point-of-gravity. As the baffle itself is merely a cylindrical structure, the basic symmetries are relatively simple.

The spring-blades which we are using are made of Phosphor-Bronze (JIS C5191; Young’s modulus between 110 and 125 GPa @ T = 300 K and 10 K, respectively) and have a thickness of ~ 4mm and a length of 221mm, while the wires for the pendulum are made of stainless-steel with a thickness of ~1mm. As mentioned already in the assembly documentation, the wires are very soft and easy to bend or kinked. Therefore, care must be taken at all time when dealing with the WAB!

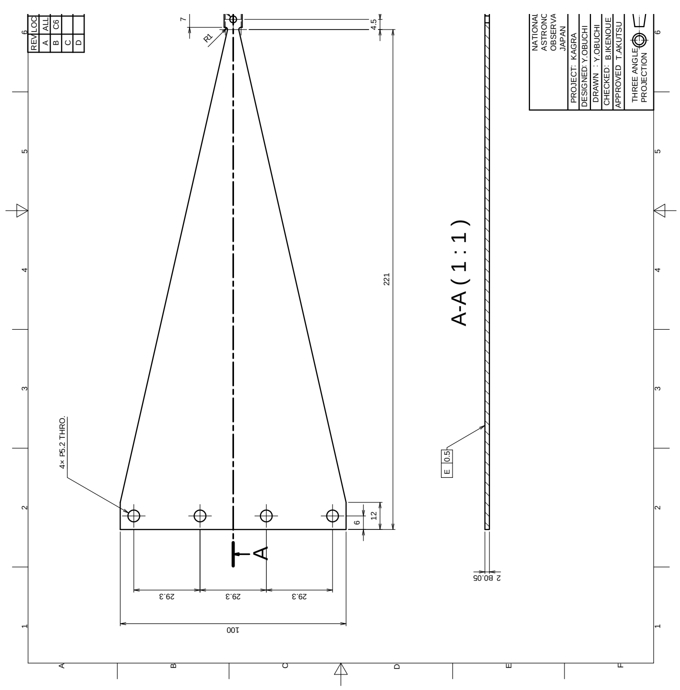

Figure 4: Design-drawing of the spring-blades for the WAB.

A special feature of the WAB-suspension is the fact that we are using two spring-blades (spring-constant = 1583 N/m) with four wires (and mount-points on the baffle-side), rigidly fixed on both ends. This means basically that we are suppressing degrees of freedom (DoF) down to the eigenmodes of the wires itself where the DoF would otherwise change the position of each pair of wire-mounting-point on the baffle contrarily. In particular, these DoFs are the yaw and the pitch modes. Since the wireeigenmodes (e.g., violin-mode) are at such high frequencies that the amplitudes keep small, we do not treat the yaw and pitch in this document as a particular measurement of those modes was impossible to realize in time.

According to a SUMCON-analysis, the eigenfrequencies of the WAB oscillations are as follows:

- Swing along the baffle's cylinder axis (longitudinal) – 0.81 Hz
- Swing perpendicular to the longitudinal mode (transverse) – 1.03 Hz
- Vertical – 3.5 Hz
- Roll – 6.28 Hz

Note, that the modes were calculated without any damping or additional influences like air-pressure.

Basically, there is also a yaw- and a pitch-mode which appear in the analysis (as mentioned above). However, the frequencies of these modes were calculated to be 26.4 Hz (yaw) and 32.7 Hz (pitch).

2.2. Damping

The baffle is passively damped as to avoid an endless swinging within the chambers. This is realized by "Eddy-current" damping via SmCo-magnets facing Al (6061) plates attached to the baffle in a distance of ~2mm (there may be some variation of ±1mm in the actual distance from case to case). Obviously, the margin for the baffle to move is quite limited but we do not expect strong impacts on the position of the baffle anyhow. Another point is that the proximity of the test-masses requires closely sit earthquake-stopper (they provide ~3mm margin for the baffle), so that the small margin by the damper may be seen as an additional security in this regard.

The reason why we are using SmCo-magnets and plates made of an Al alloy are to be found in the required cooling of the WAB down to 14 K. Magnets made of SmCo do not experience a drastic decrease of magnetization below 150 K as Nd-based magnets do (see picture below; ARNOLD – magnetic technologies, TN 0302 2015). At the same time, also certain Al alloys show just a minor decrease in theirs electrical resistivity which is the most important parameter for Eddy-current induction due to changes of the magnetic-field gradient.

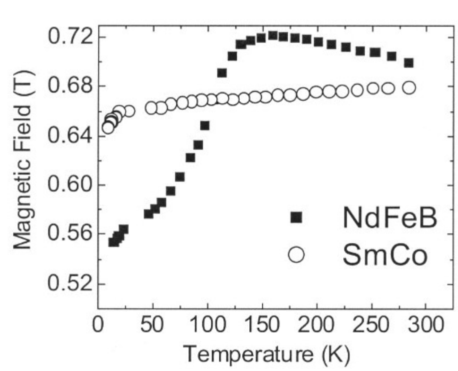

Figure 5: Magnetic-field vs. temperature of Nd-based and SmCo magnets.

A test in one of KAGRA’s cryostats in Spring 2018 demonstrated the necessity of a careful choice of materials to be used in cryogenic environments beforehand. At that time, the dampers were designed to use Cu-plates. But Cu, especially with a high purity, shows a strong decrease in its electrical resistivity (see Figure 6), which is reciprocate to the effective Eddy-current that can be induced.

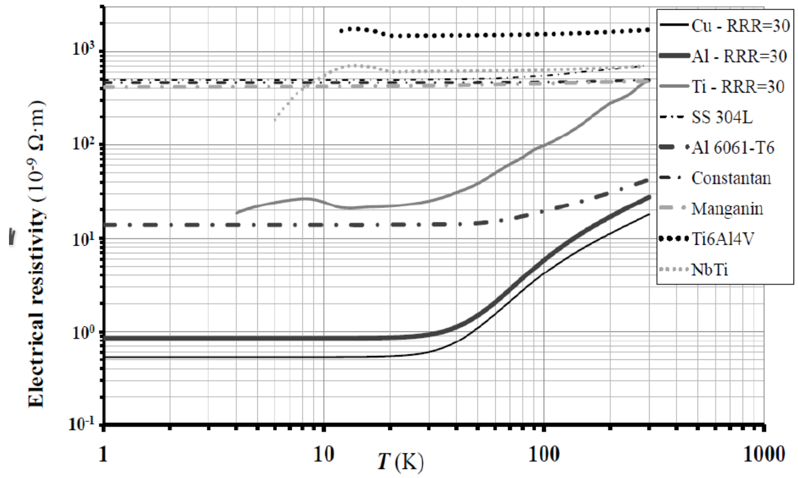

Figure 6: Development of the electrical resistivity with temperature for different metals and alloys.

In Figure 7 the signal of the OpLev which we used to track the motion of the WAB after a small remotely controlled impact to the baffle is shown at three different temperatures (298, 78.6, and 26 K). The signals of the two cooler states is increased by a factor of 100 each. Obviously, by reaching temperatures below 80 K, the damping became overwhelmingly effective and led to an overdamped baffle at ca. 30 K.

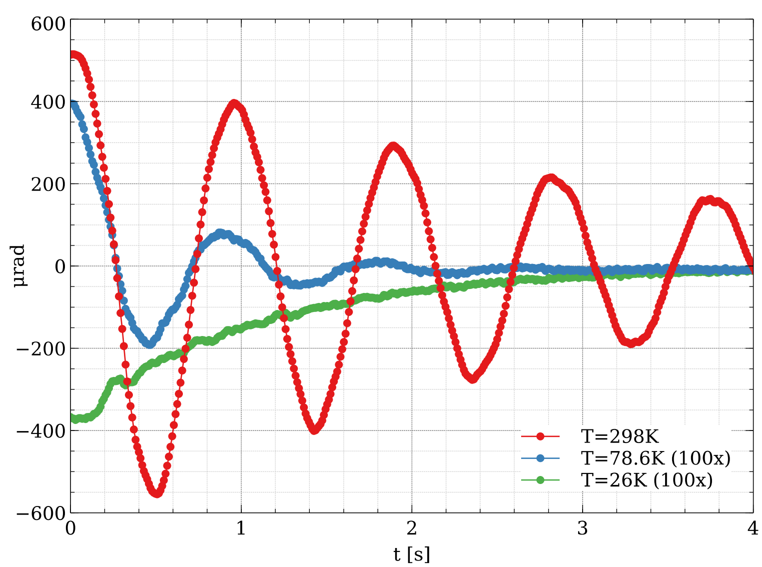

Figure 7: Signal of the swinging baffle with decreasing temperature. The data from the 78.6 and 26 K measurements are increased by a factor 100.

The data in Figure 6 are taken from the vertical signal-channel of the OpLev and corresponds to a pitch (hence, the ordinate is given in μrad). However, a similar behavior could be observed for all other channels during the cooling-test.

To solve this issue, several possibilities were weighted for the their pro and contra regarding costs and efforts. In particular, we thought about reducing the number of magnets and exchanging the Cu-plates with an alloy that shows a much weaker temperature dependence. Giving the amount of time we had to decide what to do, we couldn't expend many efforts on additional tests and measurements. Changing the number of magnets would have been risky without such a test as we were still unsure about the actual effect of decreasing the temperature. Therefore, we decided to exchange the Cu-plates with Al-6061 (its electrical resistivity can be read from Figure 6). That had the advantage that with some test-measurements at room-temperature, we will have already an estimate of the Eddy-current at 20 K since the electrical resistivity will decrease just by a factor of 3 ~ 4 (compare with Cu – RRR=30, where the decrease is almost two orders of magnitude).
At the same time, the actual difference to Cu-plates is relatively low so that we did not need to change the design.

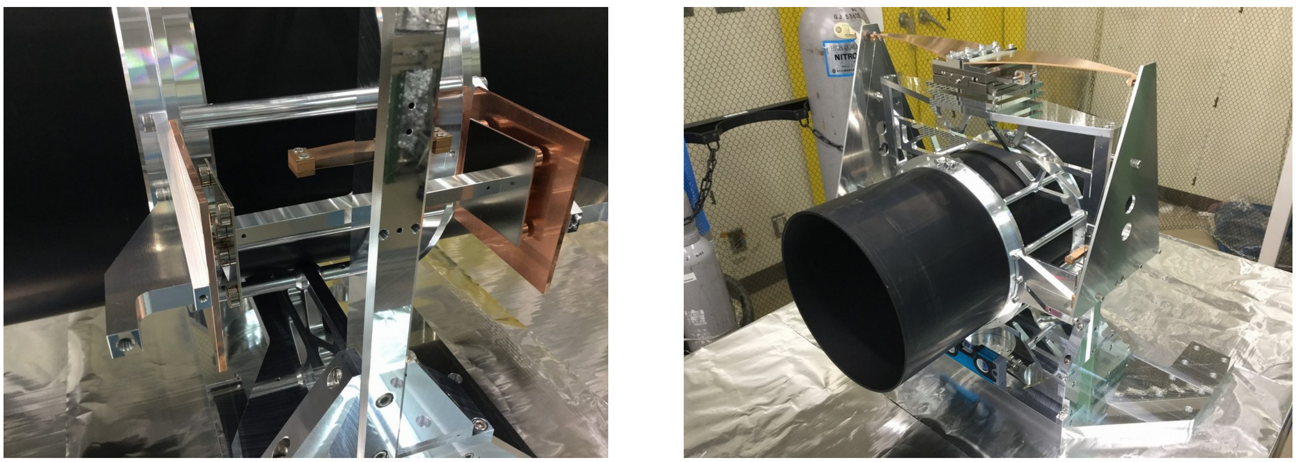

Figure 8: Photos of the WAB with Cu (left) and with Al (right) plates for the Eddy-current damping.

Theory

A damped oscillation may be described with the following formula:

$$y(t) = \Re\{A \cdot \exp(-2\pi f [d + i\sqrt{1-d^2}] \cdot t + i\phi)\}$$

Here, y is the elongation while A, f, d, and φ are the amplitude, frequency (undamped), damping-ratio, and the phase, respectively. This formula is used for all the fit-calculations to characterize the damping.

Alternatively, we can write:

$$y(t) = \Re\{A \cdot \exp(-\pi f [Q^{-1} + i\sqrt{4-Q^{-2}}] \cdot t + i\phi)\}$$

with Q being the quality factor of the oscillation. Although the fits have been made with the first formula, we will refer to the quality factor in the following characterizations.

3. KAGRA WABs

Below you can find a tabular overview of all modes and their most important parameters frequency (*f*) and quality factor (*Q*) as it was measured in the clean-room in Mitaka. In contrast to the NAB, we did not encounter issues with air-flow influencing the measurements, probably due to WAB's smaller size and the fact that we assembled and tested the WAB in the smaller clean-room where the air-flow is much lower.

As main measurement device, we used laser-displacement sensors from the ATC (→ Uragushi-san). We had 3 sensor-heads available.

Specification:

- "KEYENCE" - LK-H085 (sensor heads)
- "KEYENCE" - LK-G50000V (Controller)

	WAB@IXC		WAB 2@IYC		WAB@EXC		WAB@EYC	
	f	Q	f	Q	f	Q	f	Q
longitudinal	0.84	6.33	0.86	6.1	0.84	4.67	0.83	7.18
transverse	1	11.17	1	9.09	1	9.3	1	15.75
vertical	3.47	42.15	3.51	31.25	3.52	29.4	3.47	50
roll	5.79	37.6	5.89	31.25	5.91	26.3	5.76	45.45

Table 1: frequency and Q-factor from the fits to the measurements of each mode, done in the clean-room at Mitaka (before shipping).

It is obvious that the vertical-mode experiences the poorest damping but at the same time due to the high frequencies of both vertical and roll mode, all mode-vibrations will decay in more or less the same time.

For installing the WAB into the cryostats, we needed to have a close coordination with the CRY-group since the space inside the cryostat is actually too small to let two different installations taking place at the same time. The general procedure was therefore as follows:

1. **Alignment:** Place the WAB into the empty cryostat and align with respect to the center-line of the beam (that is ~270 mm above the optical-table inside the cryostat where the WAB is being placed). However, it is crucial to remember that the baffle will be cooled down and hence the height of the baffle is changing (+1 mm @ 20 K). Therefore, the initial alignment was to set the height of the baffle‘s center to 269 mm with respect to the optical table.

2. **"Saving-mode":** After aligning height and position (special care needs to be taken on the yaw-adjustment! The baffle has to be aligned straight towards the duct), the WAB is to be set into "saving-mode".
   The "saving-mode" means that the WAB is moved toward the duct-opening (in direction of the cavity) so far that it leaves the optical table and is partly inserted into the duct.
   For this procedure, two things are necessary:

   - A transportation device which is easy to install and deinstall and that can carry the WAB in the precise direction where we want it. This devise is called "Traverser".

It is set on some T-beams inside the cryostat at half-height and needs to installed from two-sides.

- Four Al-blocks (“WAB-feet”) with adjustable height so that the WAB may sit on them while in “saving-mode” (as the optical-table cannot be used in this situation). These blocks are placed on the T-beams on the ground of the cryostat (each one has a height of ca. 100 mm).

After the re-positioning of the WAB, the Traverser needs to be removed!

3. **HL-Tower:** Installation of the heat-link-towers (done by CRY-group)
4. **Payload:** Insertion of the payload (done by CRY-group)
5. **Nominal Position:** Setting the WAB back to its nominal position which is right in front of the test-mass (10 ~ 15 mm space in between the baffle and the edge of the recoil-mass). For this step, the Traverser is to be reinstalled into the cryostat again and hence the cryostat is already crowded with devices, special care during the installation needs to be taken (don’t hit the payload!).
After the WAB is in the position in front of the test-mass, fix it tightly (as per default, use the screw-holes on the base-plate). After fixing is done, the Traverser and the “WAB-feet” may be removed. As an additional measure, we put two “WAB-feet” which have been cut into halves below the base-plate-part that stands over the optical-table (the cutting was necessary as otherwise the block couldn’t have been inserted).
6. **Finalization:** This includes:
    - Attaching the heat-links to the baffle and the cooler-head
    - Attaching temperature sensors (one on the baffle-flange, one on the WAB-structure)
    - Attaching a small single heat-link between the X-Y-translator and the WAB-structure so that the spring-blades get a proper cooling (may be reduced due to the Z-translator with the Jack-screws)

3.1. IXC

This was the first WAB to be assembled and installed. The installation took place mainly in June 2018.

There were no issues during the installation. The only interesting point we observed was that the space-margin between the baffle and the duct-edge on both upper and lower side is a little bit (~2 mm) more than on the sides which indicated a rather elliptical duct-opening.

Below, you can find links to the installation and test reports on-site:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5343

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5366

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5387

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5410

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5432

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5517

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5530

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5871

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5889

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6127

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6142

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6497

In Figure 9, a summary of the data taken with laser-displacement sensors for different actuation of the baffle are shown.

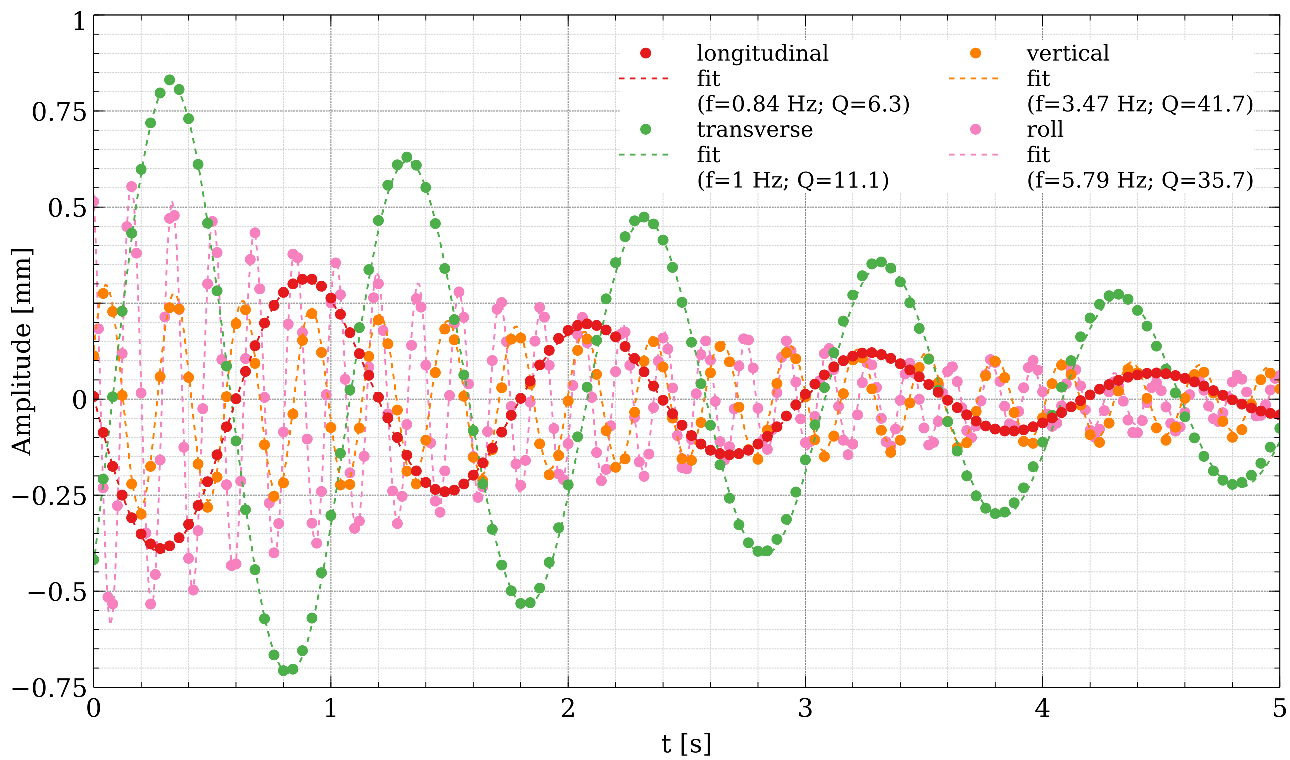

Figure 9: Comparison of the damping in all relevant modes for the WAB in IXC.

3.2. EYC

This was the second WAB to be assembled and installed. The installation took mainly place in September 2018.

We found an issue with one of the cooling-bars installed by the CRY-group prior to the WAB. When we tried to bring the WAB into the "saving-mode", we noticed that the bar blocks the way toward the duct-opening by a few mm even though it has a notch because it was installed obliqued. Thus, we removed the bar (on the advice of the CRY-group) so that the notch for the duct-opening could be widened.

Below, you can find links to the installation and test reports on-site:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5755

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5984

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6011

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6022

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6038

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6039

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8205

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8214

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8223

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8325

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8503

In Figure 10, the measurements taken on the WAB after the assembly in Mitaka are shown (from Aug. 1st 2018). We had some difficulties this time to get a stronger actuation of the roll-mode (note, that by actuating that mode, the vertical-mode is strongly coupling).

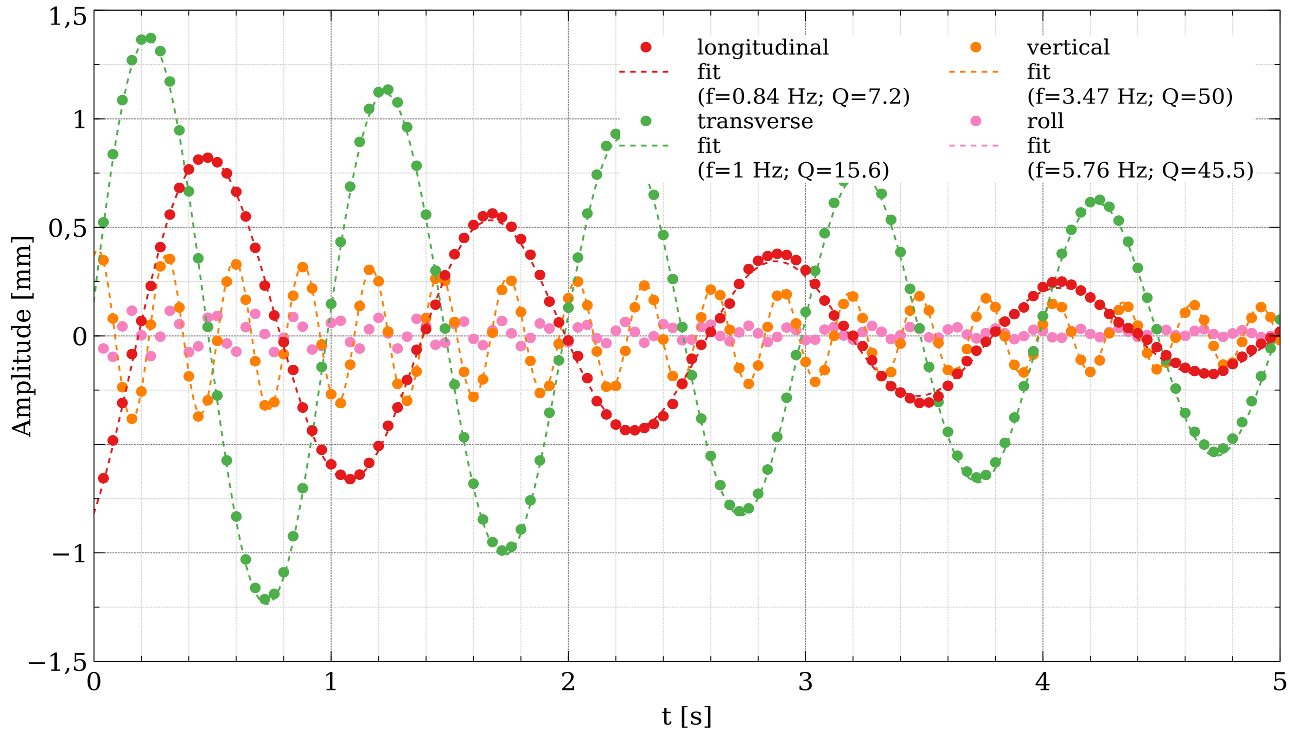

Figure 10: Comparison of the damping in all relevant modes for the WAB in EYC.

3.3. IYC

This was the third WAB to be assembled and installed.

There were no issues being reported during the installation into the cryostat.

Below, you can find links to the installation and test reports on-site:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6656

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6680

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6703

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6826

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7329

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7590

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7736

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8089

A summary of the damping measurements for this baffle can be seen in Figure 11. The longitudinal-mode couldn’t be very well fitted for some reasons. It looks as there is another highly damped oscillation at a higher frequency that causes this misalignment with just one oscillator (spectrum reveals indeed some higher frequencies >4 Hz and a fit with two oscillators suggests another mode at

~2 Hz). It might be that the dampers were a little bit misaligned during that test and we hit one damper when we actuated the longitudinal-mode. However, since χ^2~1.85 (and hence the regression error ~0.04), we can say the fit is not so bad.

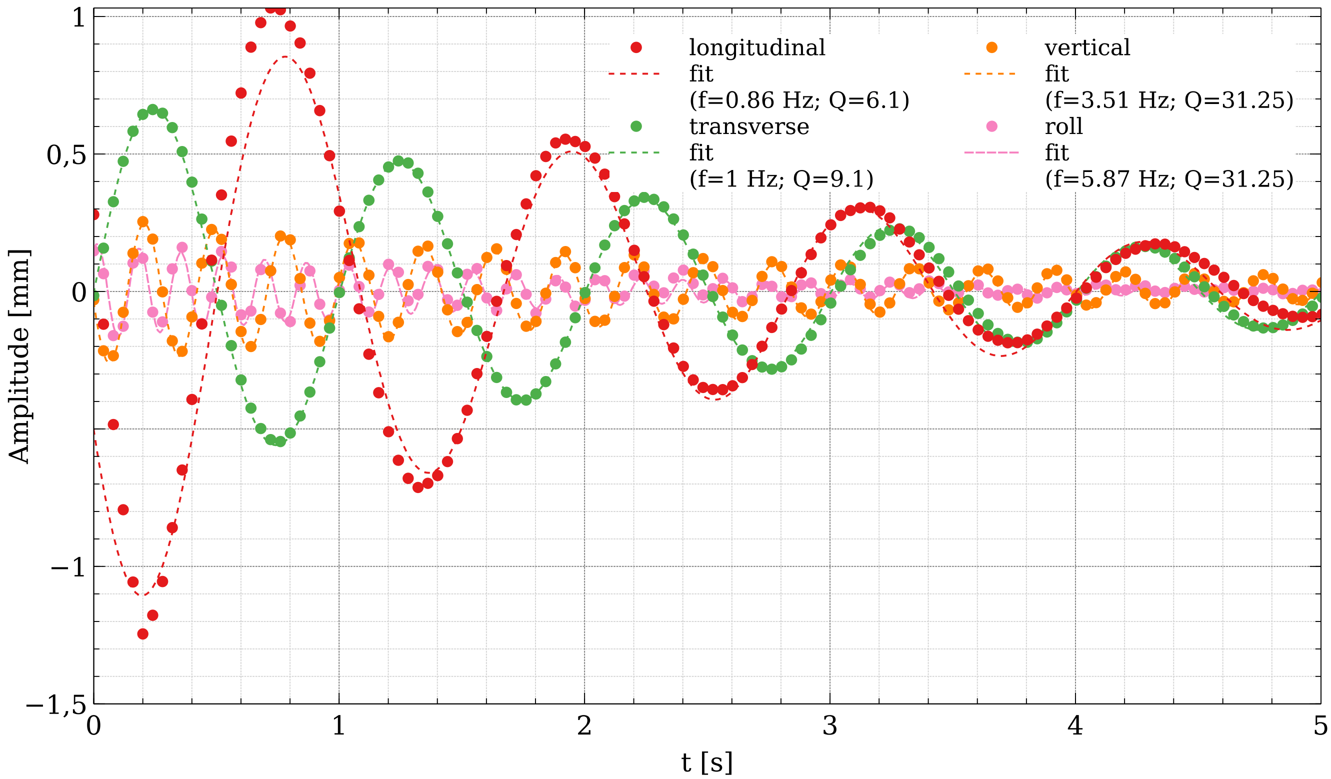

Figure 11: Comparison of the damping in all relevant modes for the WAB in IYC.

3.4. EXC

This was the last WAB to be assembled and installed.

There were no issues reported. The actual installation went very smoothly.

Below, you can find links to the installation and test reports on-site:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7661

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7678

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7683

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7894

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8318

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8412

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8477

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8511

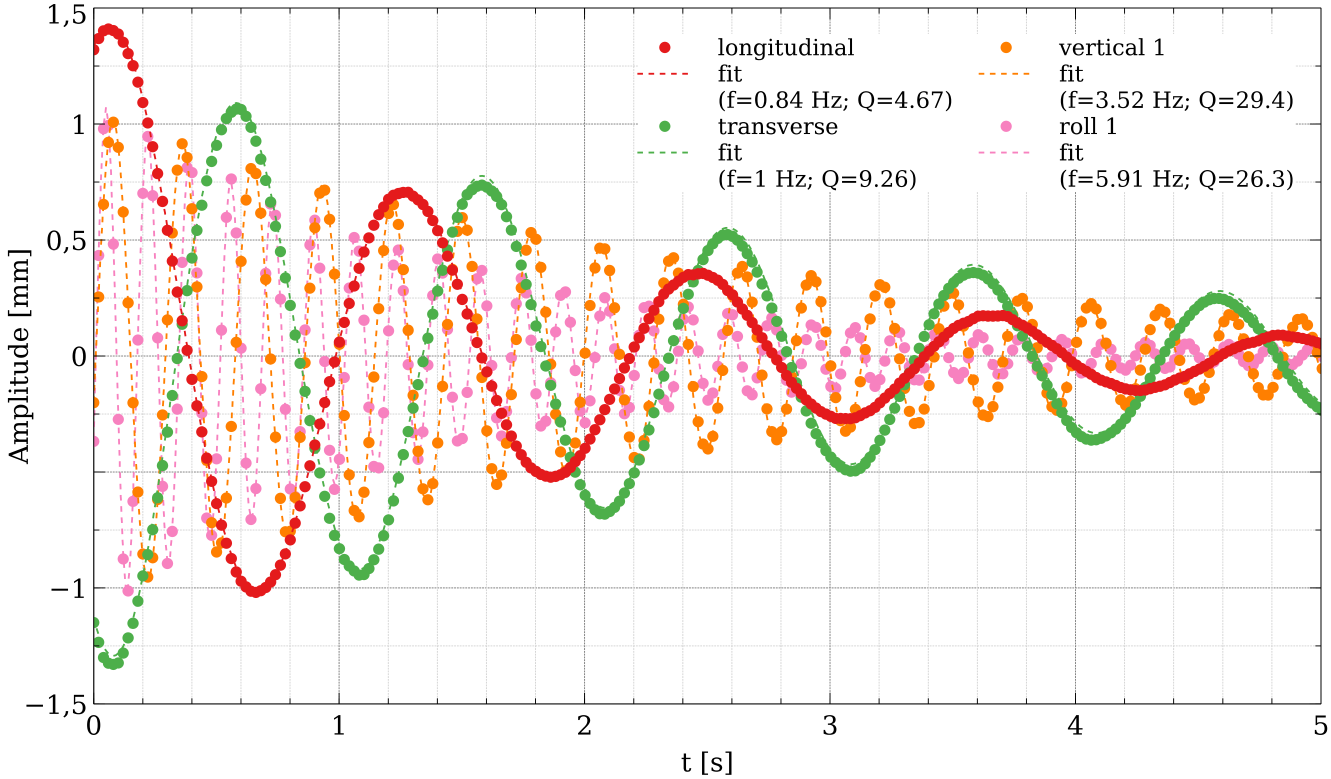

Figure 12: Comparison of the damping in all relevant modes for the WAB in EXC.

In Figure 12, the oscillator measurements on all eigenmodes are summarized. We got quite good fits to all modes which is probably due to the fact that the assembly itself went also very well and smoothly. The fourth WAB is therefore the one most closest to the design in terms of structure and characterization.