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Study of supports for the final doublets of ATF2

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STUDY OF SUPPORTS FOR THE FINAL DOUBLETS OF ATF2*

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Abstract

We investigated supports for the final doublets of ATF2 with vertical relative motion to the floor of final doublets below 10nm. Our calculations of relative motion were done by using data of ATF ground motion.

We studied the vibratory behaviour of a steel lightweight honeycomb table as a base for fixing magnets.

First, the table was fixed to the floor by four steel feet at its corners. Its first vertical resonance was at 41Hz, which induces a non negligible relative motion (5.7nm) compared to ATF2 tolerances.

Modal shape measurements show that the six first resonances of the table (below 150Hz) are rigid body modes in the six degrees of freedom.

The conclusion of these measurements is that the table is very rigid and well adapted for ATF2 project but the rigidity of the four steel feet is not sufficient compared to the rigidity of the table.

Consequently, the table was fixed to the floor on one entire face to break these six rigid body modes by three large steel plates. The first vertical resonance was then at higher frequencies (92Hz), which show that good boundary conditions were chosen for the table. The relative motion was then low (3.5nm above 0.1Hz) compared to ATF2 tolerances.

To finish, we studied the vibratory behaviour of one ATF2 FD sextupole and one ATF2 FD quadrupole with their intermediary supports made at LAPP and used to fix these magnets to the honeycomb table.

The measurements showed that the final doublets with their intermediary supports were well designed because the first resonance of sextupoles and quadrupoles was at high frequency (above 100 Hz and at 76Hz respectively), which induced a small relative motion of final doublets to the floor compared to ATF2 tolerances.

INTRODUCTION

The final focus system of ATF2 ends with the final doublets which have to reduce the size of the beam to its final size and with the Shintake Monitor which has to measure the size of the beam.

The first goal of ATF2 is to obtain a vertical beam size of 37nm [1] and the Shintake Monitor will check this size by measuring it.

In order to measure the size of the beam with only 5% error, vertical relative motion between Shintake Monitor and final doublets has to be less than 10nm [2] above 0.1Hz because beam-based-feedback is efficient only below 0.1Hz due to the beam repetition rate of 1Hz [3].

Because ground motion is coherent up to a distance of 4m [4] [5] which corresponds to the distance between the Shintake Monitor and the final doublets, the ATF2 collaboration chose to make the Shintake Monitor and the final doublets move like the ground by fixing them to the ground with intermediate stiff supports [6] [7].

Because we want to have the same configuration than the one of ILC, the ATF2 collaboration has decided to use two separate supports, one for the Shintake Monitor and the other one for the final doublets.

Our work is to study and find stiff supports for final doublets of ATF2 in order that relative motion of final doublets to the floor is less than 10nm above 0.1Hz.

In this paper, some first vibratory studies done on a honeycomb table [8] used as a base for fixing magnets is shown for two boundary conditions of the table: the table fixed to the floor by four steel feet at its corners and the table fixed to the floor on one entire face by three large steel plates.

To finish, some vibratory studies done on the ATF2 final doublets with their intermediary supports made at LAPP and used to fix magnets to the honeycomb table are shown for one sextupole and one quadrupole.

BASE PUT ON FOUR RIGID FEET

A honeycomb table has been chosen as a base to fix final doublets because of its rigidity, its easy mounting surfaces, its cost, its light weight and its non-magnetic properties [9]. Some studies have been done in order to choose the best boundary conditions for stability.

In order to do a first easy and fast vibratory study of this table, the table was first put on four steel feet at its corners.

Experimental set-up

The experimental set-up for the table on four steel feet at its corners is shown in figure 1.

Figure 1: Honeycomb table fixed to four steel feet with adjustable height at its corners

Because the height of these feet can be adjusted, the same pressure was obtained on each foot by using a torque wrench. Also, the four feet were fixed to the floor and to the table with some beeswax, which allow obtaining good transmissions of vibrations [10] while avoiding any small gaps. This set-up was chosen to avoid

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table rocking on the feet in order to have good vibration transmissions between floor and table.

Because final doublets will have to be put on table and because they were not yet at LAPP for this first study, some masses of lead have been put on the table to simulate the weight of final doublets in order to see the evolution of the table resonances with weight on it.

In figure 2, the table with lead masses simulating the weight of final doublets (1188kg) is shown at left and with lead masses simulating the weight of final doublets divided by two (594kg) is shown at right:

Figure 2: Honeycomb table with lead masses representing final doublets weight (1188kg) and final doublets weight / 2 (594kg)

Some vibration measurements have been done simultaneously on the table and on the floor in the three configurations: no masses on table, weight of final doublets and weight of final doublets divided by two.

We have used two types of vibration sensors in order to measure vibrations from 0.1Hz to 100Hz [11] [12]: GURALP geophones were used to measure vibrations from 0.1Hz to 13Hz and ENDEVCO accelerometers to measure vibrations from 13Hz to 100Hz.

Signal to Noise Ratios and Coherences

Coherence between floor and table vibration measurements has been calculated for the three configurations and results are shown in figure 3.

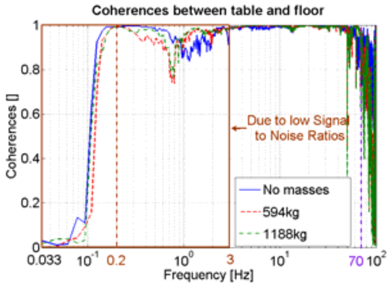

Figure 3: Coherence between the measurements of floor and honeycomb table vibrations for the three configurations

Coherence of measurements was very good from 0.2Hz up to 70Hz for the three configurations. Note that the fall of coherences below 0.2Hz, the slight fall of coherences between 0.2Hz and 3Hz and the slightly bigger fall of coherences above 70Hz were due to the fact that the measurement signals were contaminated by the instrumental noise [11] [12]. In figure 4, Signal to Noise Ratios have been plotted for the measurements of floor and table vibrations with no masses (a), with masses of 594kg (b) and with masses of 1188kg (c) on table.

To conclude, vibration coherences and consequently vibration transmissions between floor and table were very good up to at least 70Hz. Beeswax and adjustable feet were thus very efficient fixations.

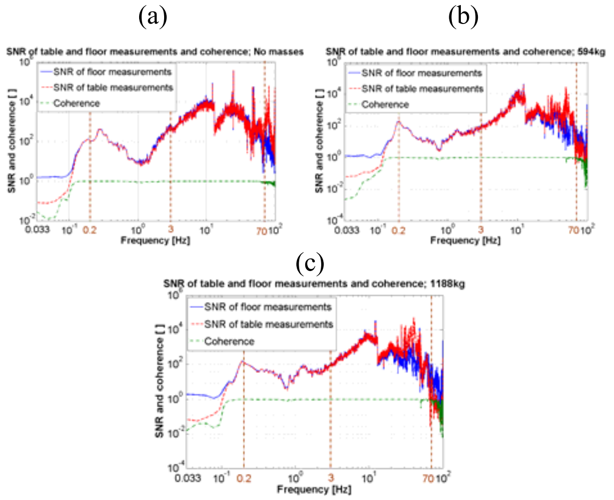

Figure 4: Signal to Noise Ratios and coherence of floor and table vibration measurements with no masses (a), with masses of 594kg (b) and with masses of 1188kg (c) on table

Transfer function of the table with its four feet

From measurements done on the floor and on the table, the transfer function of the table vibrations with its feet has been calculated. Its magnitude and phase are shown in figures 5 and 6 respectively for the three configurations.

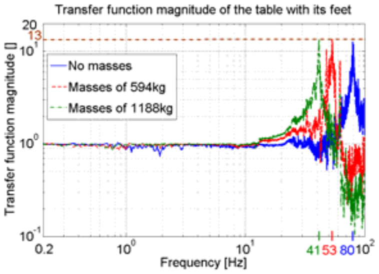

Figure 5: Transfer function magnitude of the honeycomb table with its four feet

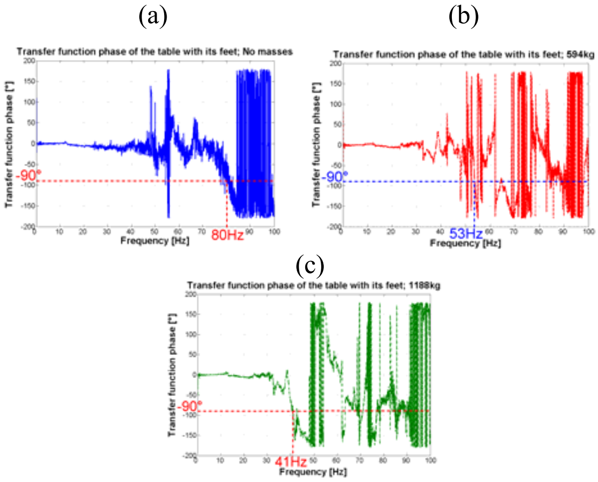

Figure 6: Transfer function phase of the honeycomb table with its four feet for the cases where no masses (a), where masses of 594kg (b) and where masses of 1188kg (c) were put on table

The transfer function magnitude shows one vibration peak which frequency decreases with weight on table and the transfer function phase shows that it corresponds to the first vertical resonance of the table because of the phase of 90°:

- No masses: 80Hz
- Masses of 594kg: 53Hz
- Masses of 1188kg: 41Hz

With the weight of the final doublets on table, the first vertical resonance of the table is low and can induce a non negligible vertical relative motion between table and floor compared to ATF2 tolerances because ground motion increases with the decrease of frequency.

Consequently, relative motion due to this resonance has to be calculated in order to know if it is needed to break this resonance with other boundary conditions.

Relative motion predicted on ATF2 floor

In order to have a value of relative motion in a given frequency range, the integrated Root Mean Square of relative motion between table and floor has to be calculated.

This calculation was predicted on the ATF2 site by integrating the vibratory behaviour of the table measured at LAPP, that is to say the transfer function of the table, and the PSD of ground motion at ATF available thanks to KEK data from a STS-2 seismometer [5] and a servo accelerometer [13]. In figure 7, the PSD of ATF ground motion is shown at left while the integrated RMS of ATF ground motion is shown at right.

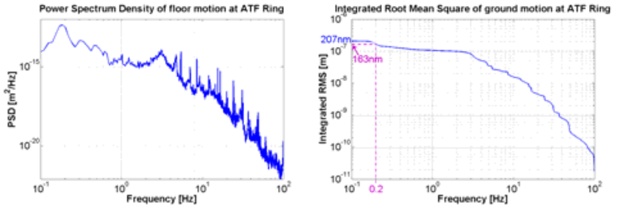

Figure 7: PSD of ground motion (left) and integrated RMS of ground motion (right) at ATF

Note that the new floor of ATF2 of same design as ATF floor should have the same vibratory behavior than the one of ATF and that amplitudes of motion should be the same for the two floors. Consequently, data of ATF floor vibrations could be used to predict relative motion between table and floor at ATF2.

To obtain the formula of integrated RMS of relative motion between table y(t) and floor x(t) with the table transfer function and the PSD of ATF floor motion, let's start with the definition of the Discrete Fourier Transform (DFT) $S_{y\text{-}x}(k)$ of the signal y(t) subtracted to the signal x(t) and the one of the discrete table transfer function H(k):

$$\begin{aligned} S_{y\text{-}x}(k) &= S_y(k) - S_x(k) = H(k)S_x(k) - S_x(k) \\ &= [H(k) - 1]S_x(k) \end{aligned}$$

In fact, the DFT is a linear operation. From the DFT of relative motion, the Power Spectrum of relative motion $G_{y\text{-}x}(k)$ can be defined with $H^*(k)$ the conjugate of H(k):

$$\begin{aligned} G_{y\text{-}x}(k) &= \left|[H(k)-1]S_x(k)\right|^2 = \left|H(k)-1\right|^2\left|S_x(k)\right|^2 \\ &= [H(k)-1][H^*(k)-1]G_{xx}(k) \end{aligned}$$

By normalizing in each side of the equation the Power Spectrum by the frequency resolution and by the power bandwidth of window, we obtain the PSD of relative motion $PSD_{y\text{-}x}(k)$:

$$PSD_{y\text{-}x}(k) = [H(k)-1][H^*(k)-1]PSD_x(k)$$

From this calculation, the integrated RMS of relative motion can be calculated with k_1 and k_2 the lower and upper boundaries of integration and with Δf the frequency resolution:

$$RMS_{int[y\text{-}x]}(k) = \sqrt{\sum_{k_1}^{k_2}[H(k)-1][H^*(k)-1]PSD_x(k)\Delta f}$$

Relative motion at ATF2 due to resonances

In order to see the impact of the table resonance on relative motion between table and floor, the RMS of relative motion at ATF2 has been integrated in the bandwidth of the resonance, that is to say between 10Hz and 100Hz, for the three configurations. Results can bee seen in figure 8.

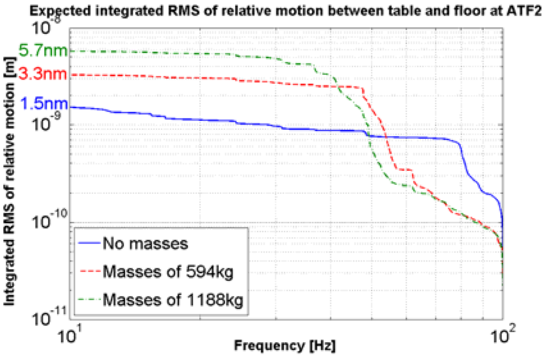

Figure 8: Integrated RMS of relative motion between the honeycomb table and the floor predicted at ATF2

The first resonance of the table induces a relative motion of 1.5nm with no weight on table, of 3.3nm with 594kg on table and of 5.7nm with 1188kg on table.

Consequently, relative motion between table and floor increases with the decrease of resonant frequency, which is completely logical because ground motion increases with the decrease of frequency.

With the weight of final doublets on the table, relative motion due to the first resonance is not negligible compared to ATF2 tolerances and modal shape of this resonance has consequently to be found in order to choose optimal boundary conditions for the table to break this resonance.

Modal shape measurements

Consequently, measurements of table modal shape have been done thanks to the collaboration CERN-LAPP. A report of them has been done [14] with among others the characteristics of the materials used.

To do these measurements, a meshing of the table was first done in PAK software. Then, some impacts were given with an impact hammer (equipped with a force transducer) on different points of the table corresponding to each mesh crossing point. Two tri-axis accelerometers, used for modal analysis in the three axis of space, were put on the top and below the table in order to have a representation of a volume for the table (see figure 9).

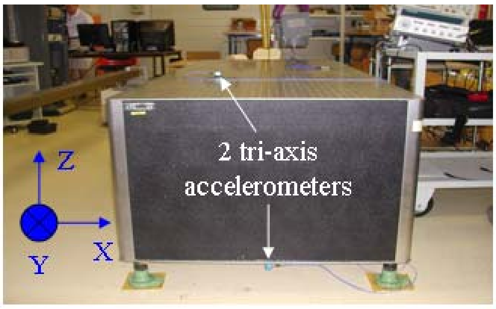

Figure 9: Experimental set-up done to measure modal shapes of the honeycomb table

The different transfer functions of the table (vibration measurements divided by input force measurements) were imported in the PAK software and modal shapes of the table could then be reconstructed for each resonance up to 150Hz (upper limit of the transducer force frequency range) and in the 3 axis of space. Some videos showing the motion of the meshed table are available [15].

The six first modal shapes of the table have been identified: they are rigid body modes in the 6 degrees of freedom as can be seen in table 1 (T means translation while R means rotation) and in figure 10. Particularly, the vertical resonance at 80Hz observed in the transfer function of the table measured with GURALP and ENDEVCO sensors is a vertical translation of the table.

Table 1: Six first modal shapes of the honeycomb table measured and identified as rigid body modes

Modal shape	**1) T-X**	**2) T-Y**	**3) R-Z**	**4) T-Y**	**5) R-Y**	**6) R-X**
Frequency (Hz)	34.8	41.8	60.6	80.6	103.9	136.0
Damping (%)	2.8	2.6	2.4	2.3	2.1	4.0

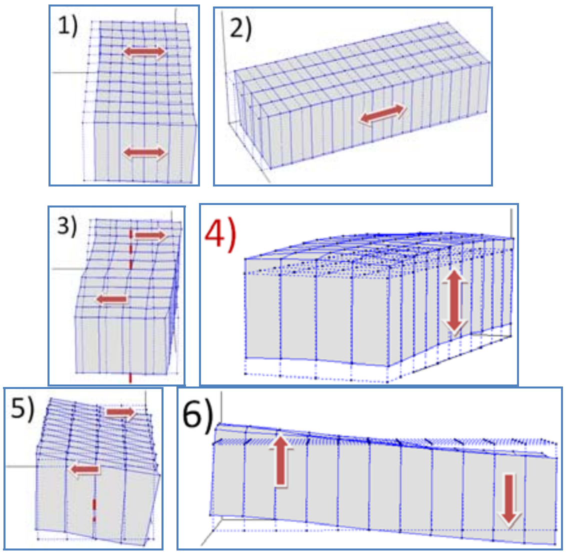

Figure 10: Rigid body modes of the honeycomb table measured

The first conclusion is that the table has no deformation in the 3 axis of space below 150Hz and is consequently very stiff and well adapted as a base for ATF2 final doublets.

The second conclusion is that the rigidity of the boundary conditions chosen for the table (the four feet) is not sufficient compared to the rigidity of the table. Consequently, the table has to be fixed on one entire face to the floor in order to break these resonances and particularly the vertical translation which induces a vertical relative motion non negligible compared to ATF2 tolerances with final doublets weight on the table (see figure 8).

BASE FIXED ON ONE ENTIRE FACE

Experimental set-up

The ATF2 collaboration asked that the set-up can be moved in the future. For that, the table was fixed on entire face to the floor by three steel plates with a thickness of 4cm as in figure 11. The table was fixed to these plates with some beeswax and the plates were bolted to the floor. In fact, beeswax can be unglued, bolts can be removed and there are some spaces between plates to move the table with slings.

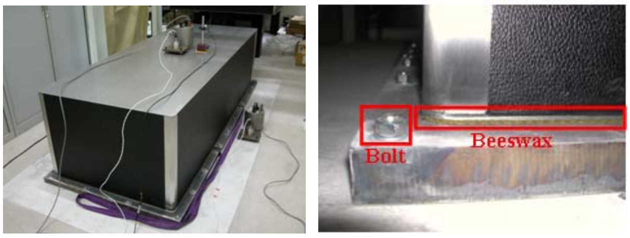

Figure 11: Honeycomb table fixed on one entire face to the floor by the intermediary of three steel plates

Moreover, bolts and beeswax should allow good transmissions of vibrations between floor and table.

To finish, beeswax is insensitive to radiations and is stable in time, which are essential properties because of high radiations due to the beam and because of the length of the project of over several years.

Some lead masses simulating final doublets weight have been put on the table as in figure 12 in order to see the evolution of table resonances when putting final doublets on it.

Figure 12: Honeycomb table with lead masses representing final doublets weight (1188kg)

Vibration measurements have been done from 0.1Hz to 100Hz with the same two types of vibration sensors than previously for the two configurations: table without any masses and table with masses simulating weight of final doublets.

Signal to Noise Ratios and Coherences

Coherence between measurements of floor and table vibrations has been calculated for the two configurations and results are shown in figure 13.

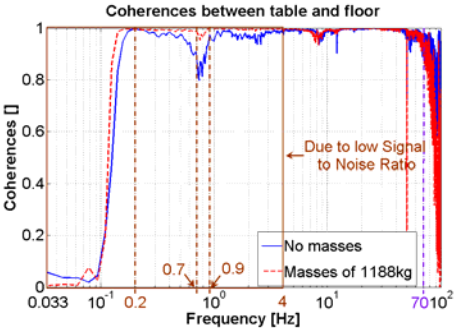

Figure 13: Coherence between the measurements of floor and honeycomb table vibrations for the two configurations

Coherence of measurements was very good from 0.2Hz up to 70Hz for the two configurations. Note that the fall of coherences below 0.2Hz for the two configurations, the slight fall of coherence between 0.2Hz and 4Hz for the measurements with no masses on table and the one between 0.7Hz and 0.9Hz for the measurements with 1188kg on table, and to finish the slightly bigger fall of coherences above 70Hz for the two configurations are due to the fact that the measurement signals were contaminated by the instrumental noise. In figure 14, Signal to Noise Ratio has been plotted at left for the measurements with no masses on table and at right for the measurements with masses of 1188kg on table.

As a conclusion, coherences between floor and table vibrations were very good up to at least 70Hz and so were the transmissions of vibrations. Beeswax and bolts were consequently very efficient fixations.

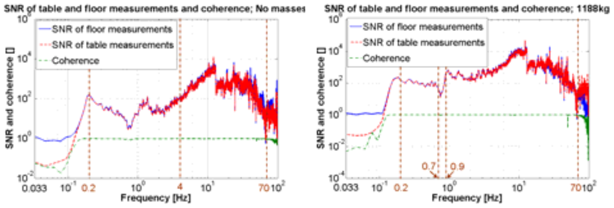

Figure 14: Signal to Noise Ratios and coherence of floor and table vibration measurements with no masses (left) and with masses of 1188kg (right) on table

Table transfer function with the three plates

From measurements done on the floor and on the table, the transfer function of the table with the three plates has been calculated. In figure 15, its magnitude is shown at left and its phase is shown at right for the two configurations.

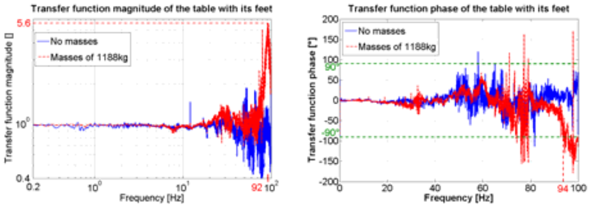

Figure 15: Magnitude (left) and phase (right) of the table transfer function with the three plates for the two configurations

The transfer function magnitude shows that with no masses on table (blue curve at left), there are no vibration peaks, and consequently no resonances, which is confirmed by the transfer function phase where there is no phase at 90° (blue curve at right).

The transfer function magnitude shows that with masses representing final doublets weight (red curve at left), a vibration peak appears at high frequency, that is to say 93Hz, and the transfer function phase shows that this peak is a resonance because of its phase of 90° (red curve at right). Resonant frequency thus falls with weight on table.

Consequently, very good boundary conditions were chosen for the table and even with the weight of final doublets on the table, relative motion between table and floor is expected to be very low compared to ATF2 tolerances.

Relative motion at ATF2 above 0.1Hz

The integrated RMS of relative motion at ATF2 between table and floor has been calculated for the two configurations between 0.2Hz and 100Hz. Results are shown in figure 16.

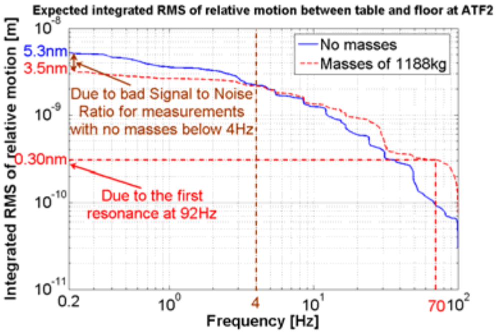

Figure 16: Integrated RMS of relative motion between the honeycomb table and the floor predicted at ATF2

Above 0.2Hz, relative motion between table and floor is higher with no masses on table than with masses on table representing final doublets weight. This difference is only due to Signal to Noise Ratios which were slighty low between 0.2Hz and 4Hz for the measurements with no masses on table.

Anyway, relative motion with weight of final doublets on table is the most important result and Signal to Noise Ratios of these measurements were good above 0.2Hz.

This relative motion is of 3.5nm above 0.2Hz, which is very good compared to ATF2 tolerances. Even more, relative motion obtained should be lower in reality. In fact, ATF ground motion is of 163nm above 0.2Hz (see figure 7 at right) and measurement errors of only 1% on the transfer function (for instance, calibration error on sensors or Signal to Noise Ratios equal to 100) induce consequently a relative motion overestimation of 1.6nm.

Note also that relative motion due to the first resonance (at 92Hz) has been calculated by integrating the RMS of relative motion in the bandwidth of this resonance ([70; 100] Hz). It is only of 0.30nm, which is really negligible.

SEXTUPOLE FIXED ON THE BASE

Experimental set-up

Figure 17 shows an ATF2 FD sextupole fixed to its intermediary supports which are fixed themselves to the honeycomb table.

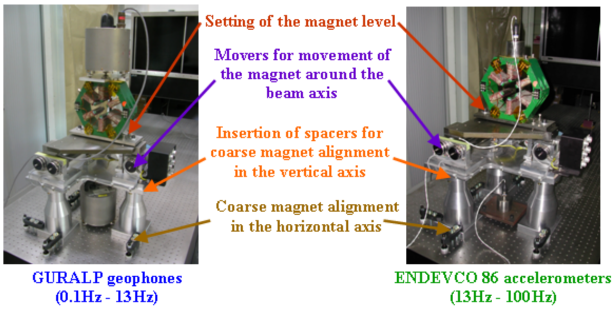

Figure 17: An ATF2 FD sextupole with its intermediary supports fixed to the honeycomb table

A system with screws has been made at LAPP for the setting of the magnet level. Also, the movers of ATF2 [16] can do a fine movement of the magnet around the beam axis. Some spacers with a thickness precision of 0.05mm have been made and can be inserted for coarse alignment of the magnet in the vertical axis. Finally, a system has been made at LAPP for coarse magnet alignment in the horizontal axis.

Vibration measurements have been done at LAPP with GURALP and ENDEVCO sensors as previously.

Because GURALP sensor was too big to be put directly on top of the magnet, it was put on a T-plate fixed with beeswax on the magnet as in figure 18. But the sensor may rock on the magnet.

Figure 18: GURALP sensor put on the ATF2 sextupole by the intermediary of a T-plate fixed with beeswax

Signal to Noise Ratios and Coherence

Coherence between the measurements of the table and the ATF2 sextupole vibrations as well as Signal to Noise Ratios of these measurements have been calculated. Results are shown in figure 19.

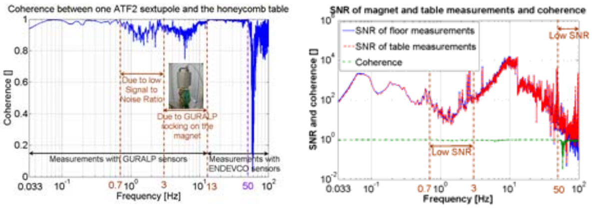

Figure 19: Coherence between the measurements of the table and the sextupole vibrations (left) and Signal to Noise Ratios of these measurements (right)

Coherence was very good up to at least 100Hz, which means that there were very good transmissions of vibrations between table and sextupole up to at least 100Hz, and consequently fixations of the sextupole to the table are efficient. Note that the slight fall of coherence obtained between 3Hz and 13Hz was certainly due to the GURALP sensor rocking a little bit on the magnet.

Sextupole transfer function with its supports

From measurements done on the floor and on the table, transfer function of the sextupole vibrations with its intermediary supports has been calculated. In figure 20, its magnitude is shown at left and its phase at right.

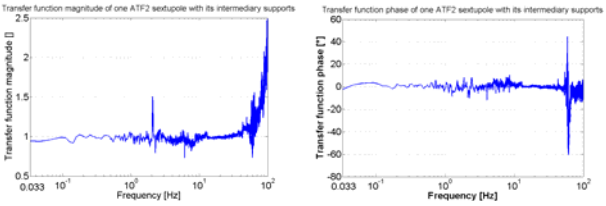

Figure 20: Magnitude (left) and phase (right) of the sextupole transfer function with its intermediary supports

The phase shows that there are no resonances below 100Hz and both phase and magnitude show that the transfer function is very good up to at least 100Hz.

Sextupoles and intermediary supports were consequently well designed and their relative motion to the floor should be very low compared to tolerances.

Relative motion at ATF2 above 0.1Hz

The integrated RMS of relative motion at ATF2 between the sextupole and the table has been calculated from 0.1Hz to 100Hz. Results are shown in figure 21.

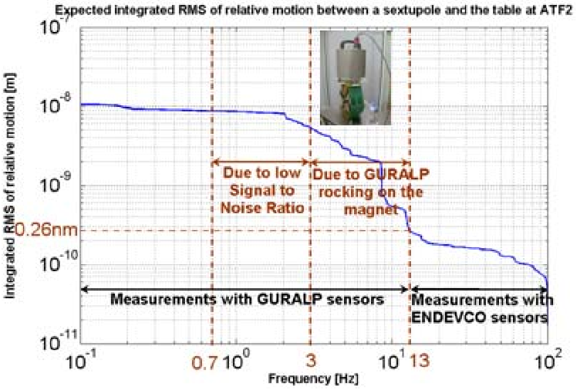

Figure 21: Integrated RMS of relative motion between the sextupole and the honeycomb table predicted at ATF2

Values of relative motion are overestimated between 0.1Hz and 13Hz because of the slightly inaccurate measurements (see figure 19) due to the slightly low Signal to Noise Ratio (between 0.7Hz and 3Hz) and certainly due to the GURALP sensor rocking a little bit on the magnet (between 3Hz and 13Hz).

However, measurements are very accurate above 13Hz and show a relative motion of only 0.26nm, which is very good compared to ATF2 tolerances (10nm).

QUADRUPOLE FIXED ON THE BASE

Experimental set-up

In figure 22, an ATF2 FD quadrupole is shown fixed to its intermediary supports which are fixed themselves to the honeycomb table.

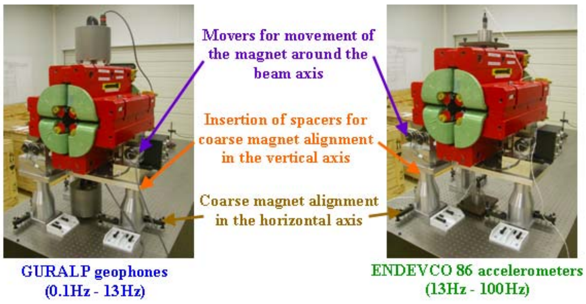

Figure 22: An ATF2 FD quadrupole with its intermediary supports fixed to the honeycomb table

As for the intermediary supports of the ATF2 FD sextupole (see figure 17), ATF2 movers are still used for fine movement of the magnet around the beam axis, it is still possible to insert our spacers for coarse alignment of the magnet in the vertical axis, and we have still used our home-made system for coarse magnet alignment in the horizontal axis.

However, because the quadrupole is directly put on the mover, it was not possible to use our system with screws for the setting of the magnet level.

As previously, we have done some vibration measurements between 0.1Hz and 100Hz with the same types of sensors.

Signal to Noise Ratios and Coherence

Coherence between the measurements of the table and the quadrupole vibrations as well as Signal to Noise Ratios of these measurements have been calculated. Results are shown in figure 23.

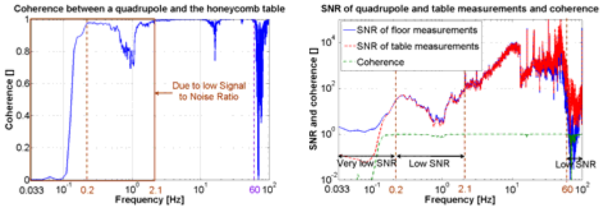

Figure 23: Coherence between the measurements of the table and the quadrupole vibrations (left) and Signal to Noise Ratios of these measurements (right)

Coherence of measurements was good from 0.2Hz up to at least 100Hz. The fall of coherence below 0.2Hz, the slight fall of coherence from 0.2Hz to 2.1Hz and the slightly bigger fall of coherence around 70Hz were due to the measurement signals which were contaminated by the instrumental noise (see the Signal to Noise Ratios). Consequently, transmissions of vibrations between the table and the quadrupole were good up to at least 100Hz, and fixations of the quadupole to the table are thus good.

Quadrupole transfer function with its supports

From measurements done on the table and on the quadrupole, the transfer function of the quadrupole with its intermediary supports has been calculated. In figure 24, its magnitude is shown at left and its phase at right.

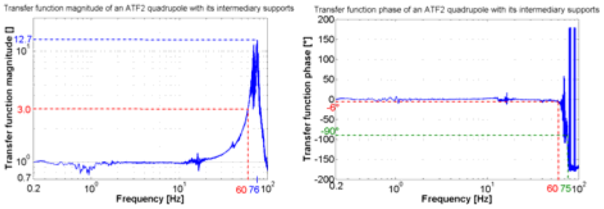

Figure 24: Magnitude (left) and phase (right) of the quadrupole transfer function with its intermediary supports

The magnitude shows a vibration peak at 76Hz, and the phase shows that it is a resonance (phase of 90°).

This resonance is high enough in frequency to allow a very good transfer function up to around 60Hz.

As a conclusion, quadrupoles and intermediary supports were well designed and their relative motion to the floor should be very low compared to tolerances.

Relative motion at ATF2 above 0.1Hz

The integrated RMS of relative motion at ATF2 between the quadrupole and the table has been calculated from 0.2Hz to 100Hz. Results are shown in figure 25.

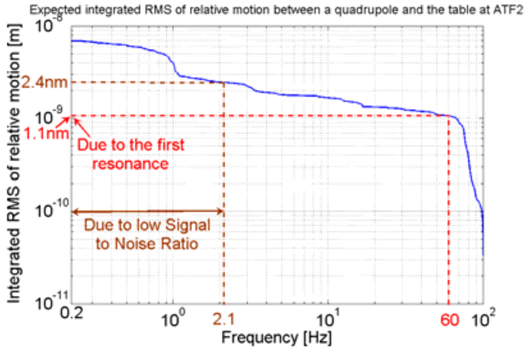

Figure 25: Integrated RMS of relative motion between the quadrupole and the honeycomb table predicted at ATF2

Because below 2.1Hz, the Signal to Noise Ratios are low, values of relative motion are overestimated.

However, measurements were accurate above 2.1Hz and show a relative motion of only 2.4nm, which is very good compared to ATF2 tolerances.

Note that relative motion due to the first resonance has been calculated by integrating the RMS of relative motion in the bandwidth of this resonance ([60; 100] Hz). It is only of 1.1nm, which is quite negligible.

CONCLUSION

Boundary conditions of the honeycomb table have been optimized. With final doublets weight on it, its first resonance is high in frequency (92Hz) and consequently allows a relative motion of the table to ATF floor (calculated by integrating data of ATF ground motion and measured transfer function at LAPP) of only 3.5nm above 0.2Hz. Moreover, this value is probably overestimated because measurement errors of only 1% on the transfer function induce a relative motion overestimation of 1.6nm because ATF ground motion is of 163nm above 0.2Hz.

Intermediary supports to fix ATF2 FD sextupoles and ATF2 FD quadrupoles to the table have been made at LAPP. For a sextupole with its intermediary supports, there are no resonances from 0.1Hz to 100Hz and relative motion is only of 0.26nm above 13Hz. For a quadrupole with its intermediary supports, there are no resonances from 0.1Hz to 76Hz and relative motion is only of 2.4nm above 2Hz.

For frequencies below 13Hz and below 2Hz, vibration measurements done respectively on one sextupole and one quadrupole were slightly inaccurate (slightly low Signal to Noise Ratios and Guralp sensor certainly rocking a little bit on the sextupole) and relative motion was consequently overestimated because of the high amplitude of ATF ground motion at these frequencies. However, relative motion of these magnets to the table should be very low compared to ATF2 tolerances because there are no resonances and motions are slow (thus coherent) in these frequency ranges.

As a conclusion, relative motions of sextupoles and quadrupoles to the floor above 0.1Hz should be very good compared to ATF2 tolerances. More accurate measurements will be done at ATF2 because ground motion is higher than the one of LAPP and consequently, the Signal to Noise Ratios will be higher since the sensor noise will be unchanged.

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