THE CLIC STABILITY STUDY ON THE FEASIBILITY OF COLLIDING HIGH ENERGY NANOBEAMS

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Abstract

The Compact LInear Collider (CLIC) study at CERN proposes a linear collider with nanometer-size colliding beams at an energy of 3 TeV c.m. ("colliding high energy nanobeams"). The transport, demagnification and collision of these nanobeams imposes magnet vibration tolerances that range from 0.2 nm to a few nanometers. This is well below the floor vibration usually observed. A test stand for magnet stability was set-up at CERN in the immediate neighborhood of roads, operating accelerators, workshops, and regular office space. It was equipped with modern stabilization equipment. The experimental setup and first preliminary results are presented.

1 INTRODUCTION

The Compact LInear Collider (CLIC) study at CERN [1] foresees 3 TeV collisions of electron on positron beams, where the beams have transverse spot sizes of 43 nm (horizontal) times 1 nm (vertical). The associated magnet vibration tolerances were reviewed for different linear collider projects in [2] and are summarized in Table 1. It is seen that CLIC tolerances [3] on the integrated uncorrelated rms motion of magnets above a so-called minimal frequency f_{min} range from 0.2 nm to 14 nm for different magnets and planes. The most challenging requirements are in the vertical plane with tolerances of 1.3 nm (linac) and 0.2 nm (FD). Below f_{min} effects of magnet vibrations are cured by beam-based feedbacks. The value of f_{min} depends on the repetition frequency, the layout, and the gain of the feedback. About 25 pulses are needed for correction [2] so that for CLIC f_{min} is about 100 Hz/25.

The CLIC stability study [5] aims at establishing the basic feasibility of the demanding CLIC parameters in terms of realistically achievable magnet stability. For this purpose prototypes of CLIC quadrupoles (as constructed and used for CTF-2) are investigated. A prototype quadrupole doublet is shown in Fig. 1. The study aims in particular at bringing state-of-the-art commercial stabilization technology to the accelerator field. In view of the available resources it was decided to buy existing industrial solutions instead of developing equipment directly adapted to the CLIC requirements. The full experimental set-up is shown in Fig. 2 and will be described later.

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Table 1: Summary of magnet stability requirements for a 2% loss in luminosity [3, 4].

Magnet	N_{magnet}	f_{min}	I_x	I_y
Linac	2600	4 Hz	14 nm	1.3 nm
Final Focus	2	4 Hz	4 nm	0.2 nm

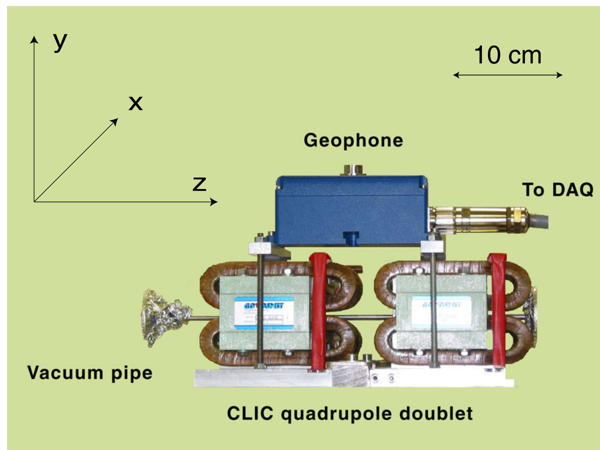

Figure 1: Picture of a CLIC prototype doublet of quadrupoles, as it has been constructed and used for CTF-2. It can be connected to electricity and cooling water and is being used in the stability study. For this purpose a geophone was installed on top of the doublet. The coordinate system is indicated.

2 BASIC NOTATION

For the study of magnet stability geophones are used for measuring magnet vibrations. The employed fast geophones have a frequency range of 4-315 Hz with a nominal resolution of 15.3 nm/s. The working principle of a geophone is illustrated in Figure 3. A coil of radius r_c with n_{coil} windings (reference mass) is suspended in a permanent magnetic field B. Then, a voltage U_{coil} is induced in the coil if the magnet moves with a velocity v with respect to the coil (for example due to vibration of the ground supporting the geophone):

$$U_{coil} = -n_{coil}\,(2\pi r_c B)\,v \qquad (1)$$

The installed fast geophones produce a voltage of 5 mV for a velocity of 1 μm/s.

The velocity $v(n)$ is measured at discrete times $n\Delta T$, where n is a positive integer and ΔT is the sampling time.

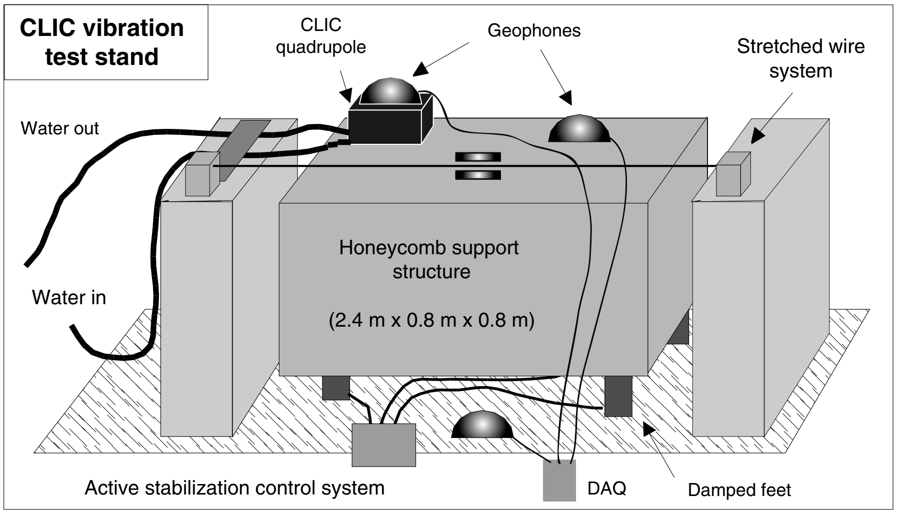

Figure 2: Schematic view of the experimental setup for the CLIC stability study. A honeycomb support structure sits on active vibration damping system with three feet. Quadrupoles are mounted on top and can be connected to a flow of cooling water. Motion is monitored with geophones and a stretched wire system.

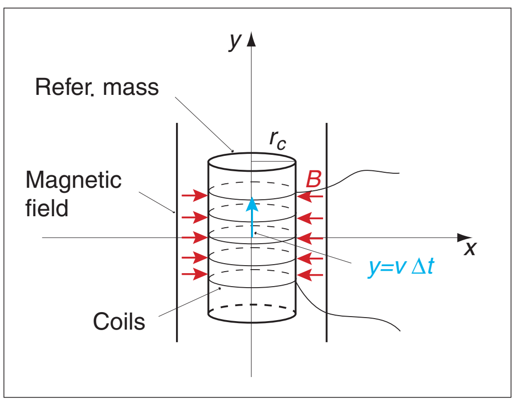

Figure 3: Working principle of geophones, as used for the CLIC stability study.

A sample of N velocity measurements is used to calculate the power spectral density $P_d(f_k)$ of vibrational displacements d:

$$P_d(f_k) = \frac{N\,(\Delta T)^3}{2\pi^2 k^2}\left[\sum_{n=1}^{N} v(n)\exp^{-2\pi ikn/N}\right]^2 \qquad (2)$$

Here $f_k = k/\left(N\Delta T\right)$ is the discretely sampled vibration frequency [3] with k being an integer. The integrated rms vibration I above a minimal frequency $f_{k_0} = f_{min}$ is obtained from:

$$I(f_{min}) = I(f_{k_0}) = \sqrt{\frac{1}{N\Delta T}\sum_{k=k_0}^{N/2} P_d(f_k)} \qquad (3)$$

As indicated in Figure 1, the vertical direction is denoted by y, the horizontal by x and the longitudinal by z. The longitudinal direction is collinear with the beam and for our set-up perpendicular to the wide side of the table.

3 EXPERIMENTAL SET-UP

A test stand for magnet vibration was set up on the CERN site in Meyrin, in the immediate neighborhood of roads, operating accelerators, workshops, and regular office space. Vibration properties were surveyed and found of appropriate level (not too low and not too high) [3]. The rms floor vibration above 4 Hz is about 6 nm and reflects the good geological conditions in the Geneva region. Though sub-nm stability is routinely observed in deep CERN accelerator tunnels [6], one cannot rely on this. Technical noise can easily enhance the vibration levels to the 5 nm level. The level of ground motion and technical noise at the CERN test stand is ideally suited to demonstrate that the critical CLIC vibration tolerances can be achieved in a realistic accelerator environment.

Advanced measurement and stabilization equipment was acquired or used from the CLIC alignment study [7]. The experimental set-up was mostly completed in March 2002. The overall set-up with all the different installed equipment is shown in Fig. 2. The main components are described:

1. Four geophones (see Fig. 1) were acquired for monitoring vibration amplitudes with sub-nm accuracy. This includes options for analog and digitized data acquisition.

2. Four actively stabilized feet (STACIS2000 system from TMC, see Fig. 4) were used as a "stiff" system for vibration damping. The STACIS2000 system relies on integrated geophones for measuring ground vibration, rubber pads for passive damping, and piezo-

electric movers for active damping of load vibrations induced from the ground.

3. A honeycomb support structure (table, see Fig. 4) with length 2.4 m, width 0.8 m, and height 0.8 m was used as a ”girder” for the quadrupoles. It is guaranteed by the manufacturer that the honeycomb table does not have a structural resonance below 230 Hz.

4. A pneumatic system (PEPS system from TMC, see Fig. 4) was used as ”soft” system for vibration damping. The system consists of four air piston supports for passive damping, distance sensors for micrometer alignment, and table top geophones for feedback on the air pressure (active damping).

5. Prototypes of CLIC quadrupole doublets (see Fig. 5) were used as objects to be stabilized. These quadrupoles can optionally be connected to an adjustable flow of cooling water. Another option is the use of the sophisticated CLIC alignment support between table and quadrupole.

6. A stretched wire system was mounted on top of the stabilized support structure for measuring changes in alignment with respect to the surrounding ground, as represented by two concrete blocks close by the table (see Fig. 2). Observation time is from seconds to days or weeks.

The sensors were carefully studied to establish the resolution and accuracy. The difference measurement between two near-by sensors is shown in Fig. 6. This gives an upper estimate on the resolution, assuming that both sensors measure the same vibration signal. In terms of rms vibration above a minimal frequency a resolution of better than 0.4 nm is obtained at 4 Hz and better than 0.2 nm at 10 Hz. The resolution improves for higher frequencies because velocity is measured.

The absolute scale of the used geophones should in principle have been calibrated by the manufacturer GeoSig. However, in the course of the CLIC stability study it was recently discovered that an error of a factor of two had been introduced by the manufacturer. This error had become only visible to us after installation of outlets for the analog source signals, allowing the usage of an external ADC and the comparison with a sensor from the Güralp company. The results in this paper have been corrected for this error. Differences of a factor of 2 with respect to previous publications are introduced. An error of 10% is assumed for the absolute scale. A future publication will analyze this error in detail.

Figure 4: Top: Picture of the honeycomb table supported by three feet that perform vibration damping. Bottom: The alternative pneumatic system for passive and active vibration damping and micron alignment. It can be mounted below the honeycomb table.

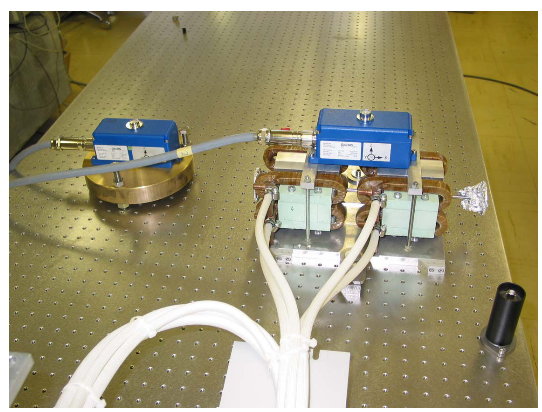

Figure 5: Picture of a doublet of CLIC linac magnets. The cooling water is provided from the white pipes. Geophones (blue) are located on the top of the doublet, on the table, and on the floor (not visible).

4 CLIC QUADRUPOLE STABILIZATION

The vibration of the considered quadrupole doublet depends on the floor vibration, the damping from the active feet, sources of technical noise like cooling water, and structural resonances in table, quadrupole, and support. Preliminary results are presented. These results differ from the first results presented at EPAC02 [8] due to the factor of 2 error in the manufacturer’s calibration of the GeoSig geophones.

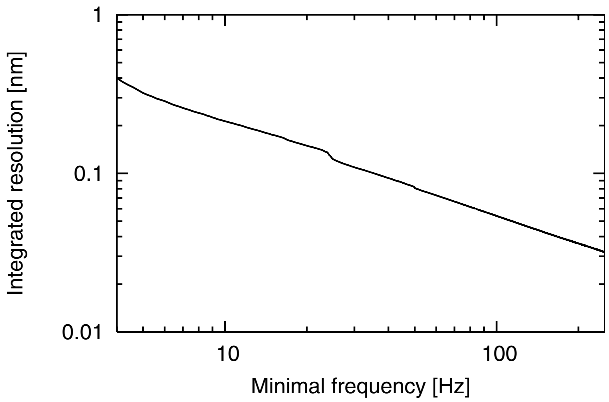

Figure 6: Estimate of measurement resolution versus frequency (difference of two sensors located side-by-side).

4.1 Stiff Piezo-Based System

The first system studied in detail was the STACIS2000 system, based on passive rubber damping and piezoelectric pushers. This is a stiff system that provides a solid support. The measured transfer function of vibration from the floor to the table top is shown in Fig. 7. A vibration damping of up to a factor of 20 is achieved. With this damping the table top was stabilized to (1.2±0.4) nm vertically (see Fig. 8), sufficient for the linac requirement and close to the requirement for the Final Focus magnet. The amplification above 200 Hz is a known problem [9] and is suspected to be due to electronic noise in the feedback circuit. It is not relevant for our application.

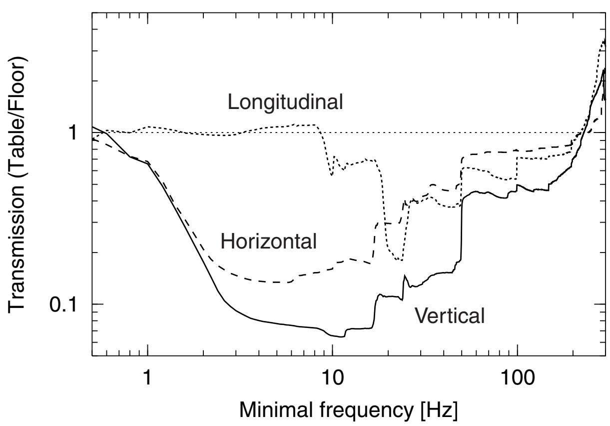

Figure 7: Transmission of horizontal, vertical, and longitudinal vibration amplitude from floor to table top.

The quadrupole doublet was either directly screwed onto the table top or placed on its alignment support (micrometer alignment movers) that then was screwed onto the table. The measured horizontal, vertical and longitudinal vibration data on floor, table, and quadrupole are shown in Fig. 8 for the direct connection to the table. At 4 Hz a vertical vibration amplitude of (1.8±0.2) nm is obtained on top of the quadrupole doublet. Vibration was reduced for all directions, with values of (0.8±0.2) nm and (6.4±0.8) nm for residual horizontal and longitudinal quadrupole vibrations above 4 Hz. The influence of cooling water on the vertical vibration level on top of the quadrupole is shown in Fig. 9. At 4 Hz and the nominal flow of cooling water (30 l/s) the vertical vibration is increased to (2.6±0.4) nm which is a factor of two above the tolerance for the CLIC linac quadrupoles. The studies on water induced vibrations are described in detail in [10]. Note that tap water was used for these studies, so that the effect of water pumps is not included (vibrations are generated from turbulent water flow only).

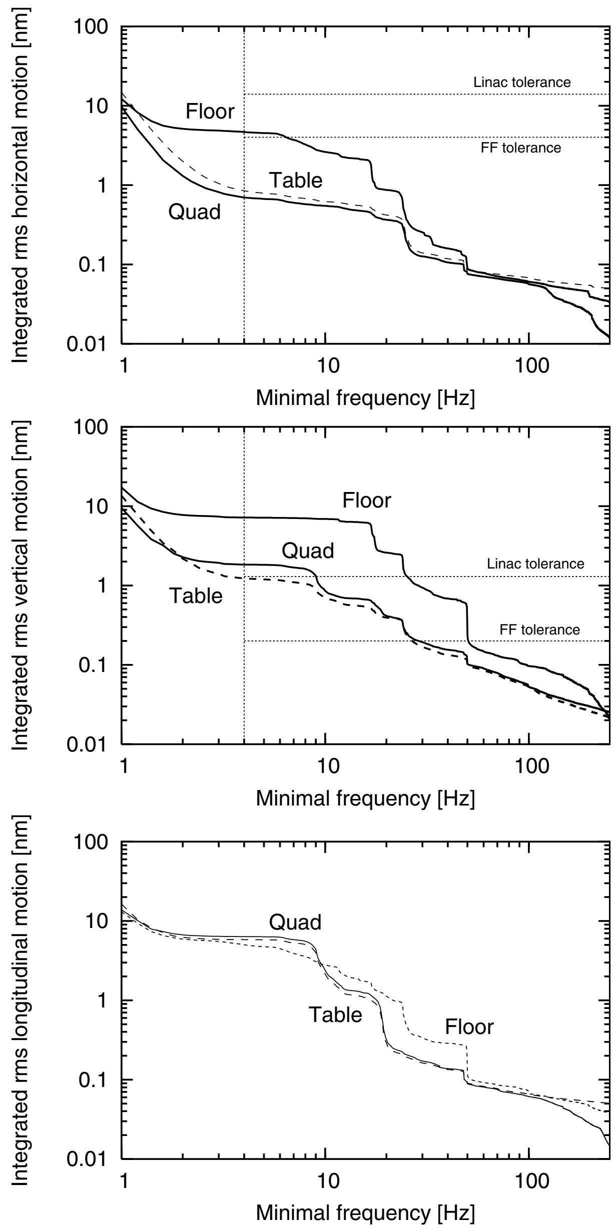

Figure 8: Horizontal (top), vertical (middle) and longitudinal (bottom) rms vibration versus frequency. Curves are given for simultaneous measurements on floor, table, and quadrupole. Were applicable the relevant CLIC tolerances are indicated.

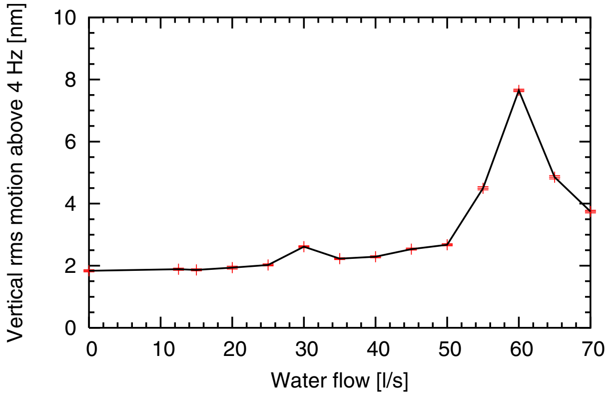

Figure 9: Vertical rms quadrupole vibration above 4 Hz versus flow of cooling water.

4.2 Soft Pneumatic System

After the successful study of the stiff system a soft system, based on air pressure was installed. This system decouples the magnet from the ground, the whole support is essentially floating on a cushion of air. The system can be operated as (1) a passive system with a slow micrometer alignment feedback on the air pressure or (2) as a mostly passive system with a slow micrometer alignment feedback on the air pressure and a faster active vibration feedback that just acts around a few Hertz (around the resonance of passive pneumatic damping). The transfer function of this soft support is shown in Fig. 10 (top). Vibration damping is not as good as with the STACIS2000 system but reaches still an impressive factor of 10 at various frequencies. It is also seen that the active feedback circuit works well and suppresses the passive resonance around 1-2 Hz efficiently. The absolute vertical vibration level is shown in Fig. 10 (bottom). Vertical rms vibration above 4 Hz is 1.8 nm on top of the table. This must be compared to the measurement of 1.2 nm at table top for the STACIS2000 system, as shown in Fig. 8. It is noted that the best measurements of the "stiff" STACIS2000 system show vertical rms vibrations as small as 0.6 nm above 4 Hz, three times smaller than the pneumatic "soft" system. These measurements are being analyzed and will be published in a future report. We can conclude that the "stiff" system has a better performance than the "soft" stabilization system, though both perform very well.

4.3 Transfer Function of CLIC Alignment Support

The transfer function of the CLIC quadrupole alignment support was studied with a speaker mounted onto the table. Acoustic waves were directed to the table to induce vibrations with a controllable frequency and amplitude. If the generated vibrations coincide with a structural resonance of the quadrupole support, a strong amplification in vibration amplitude from table to quadrupole is expected. Structural resonances were identified indeed. Inducing vibrations at

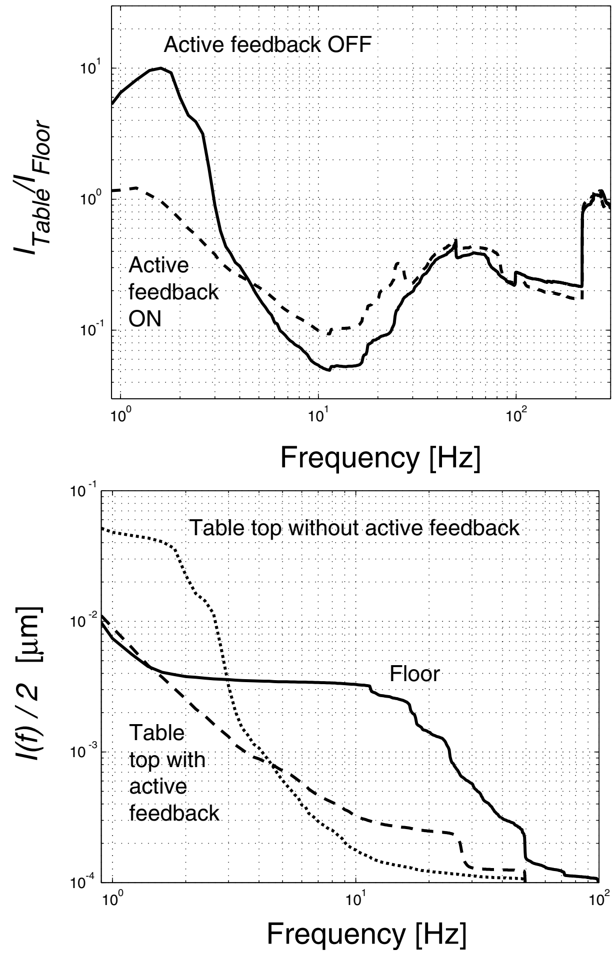

Figure 10: Top: Vertical transfer function of vibration from floor to top of support structure versus frequency, with and without active feedback circuit. Bottom: Half vertical rms quadrupole vibration on the floor and on top of the support structure above a given minimal frequency. Again, the table top vibration is given without and with an active feedback.

37 Hz an amplification of a factor of 10 in amplitude or 100 in power was measured between the quadrupole and table. The data is shown in Fig. 11 in the form of the power spectral densities with and without induced vibrations.

5 CONCLUSION AND OUTLOOK

A test stand for magnet vibration has been set up on the CERN main site and was equipped with advanced stabilization equipment. First measurements with the stiff active vibration damping system STACIS2000 showed suppression of floor vibration by up to a factor of 20. CLIC prototype quadrupoles have been stabilized vertically to an rms motion of (1.8±0.2) nm above 4 Hz, or (2.6±0.4) nm with a nominal flow of cooling water. For the horizontal and longitudinal directions a CLIC quadrupole was stabilized to (0.8±0.2) nm and (6.4±0.8) nm without cooling water. A soft pneumatic system performed well but not as good as the stiff system. The measured vibration on the top of the

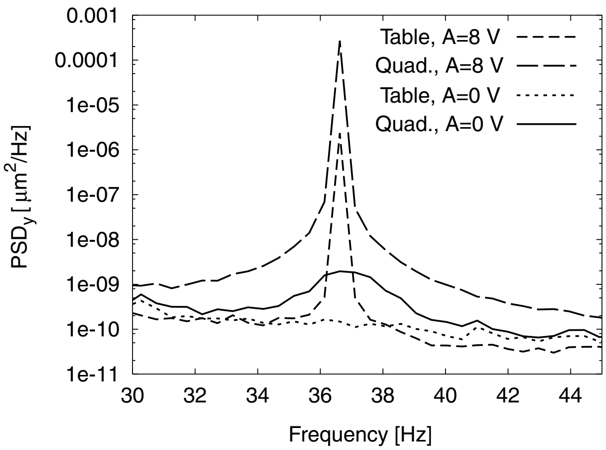

Figure 11: Power spectra for top of quadrupole and table around 37 Hz with and without induced noise at 37 Hz. The noise was excited on the table at the resonance of the CLIC alignment support.

support structure was at least 50% higher.

The measured vibration levels almost meet the requirements for the 2600 CLIC linac quadrupoles. A CLIC specific engineering solution could be based on or include the tested technology. Structural resonances were identified and can be minimized in future magnet designs. Further studies will aim at studying alignment stability and environmental effects (e.g. magnetic fields) and using the measurements for predictions of the CLIC luminosity stability. Vibration must be suppressed by a further factor of 4-10 to meet the tolerance for the Final Focus quadrupole. Further studies will also be required to address the question, how stable the magnetic center of a motionless quadrupole is at the nanometer level.

6 ACKNOWLEDGEMENTS

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