CLIC MAGNET STABILIZATION STUDIES

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Abstract

One of the main challenges for future linear colliders is producing and colliding high energy e^+e^- beams with a transverse spot size at the collision point in the nanometre range ("nanobeams"). The Compact LInear Collider (CLIC), presently under investigation at CERN, aims at colliding e^+e^- beams with a vertical spot size of 0.7 nm, at a centre-of-mass energy of 3 TeV. This requires a vertical stability to the 1.3 nm level for the 2600 linac quadrupoles and to the 0.2 nm level for the two final doublets at either side of the interaction point. In the framework of the CLIC Stability Study, it has been demonstrated for the first time that CLIC prototype quadrupoles can be stabilized to the 0.5 nm level in a normal working area on the CERN site.

INTRODUCTION

The Compact LInear Collider (CLIC) study [1] at CERN is investigating the feasibility of building an e^+e^- linear collider with centre-of-mass energies up to 5 TeV, at a luminosity of 10^{35} cm^{-2}s^{-1}. High luminosities will be achieved by colliding opposing e^+e^- beams with transverse spot sizes of $\approx 60 \times 0.7$ nm^2 (horizontal×vertical), which imposes tight tolerances on the stability of the focusing quadrupoles. The CLIC tolerances for a 2 % luminosity reduction for uncorrelated RMS displacements above 4 Hz are summarized in Table 1 for the 2×1300 linac quadrupoles and for the 2×2 final focus quadrupoles [2]. The SLC experience has shown that beam-based feedback systems can efficiently compensate *slow* motions up to $\approx 1/25$ of the pulse repetition frequency [3] (100 Hz for CLIC). *Fast* vibration above ≈ 4 Hz must then be mechanically stabilized to ensure the required luminosity performance. To achieve the ambitious CLIC stability goal, it is not possible to rely only on the stability of a given site because the natural ground stability is strongly increased by the accelerator environment (pumps, ventilation, cooling water, ...). This was demonstrated by vibration measurements at LEP [4], where the motion was increased from 0.2 nm to more than 20 nm. Dedicated stabilization technologies must therefore be developed to meet the requirements of future linear colliders.

In the last years, the magnet stabilization problem has attracted the interest of various high-energy physics laboratories and universities worldwide. At CERN, a CLIC stability study was started in 2001 [5] to investigate the feasibility of colliding nanometre-size beams in CLIC in a realistic accelerator environment. Following the encouraging results

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Table 1: Tolerance on the uncorrelated RMS motion above $f_{\min}$ of the CLIC quadrupoles for a 2 % luminosity loss

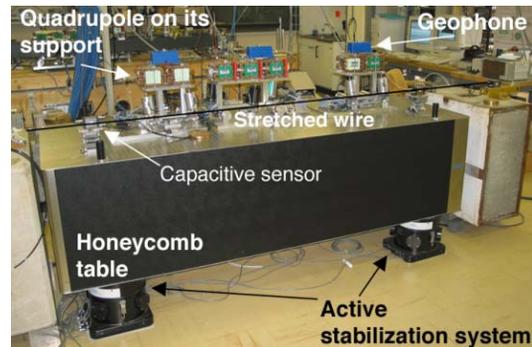| Magnet type	N_{magnet}	$f_{\min}$	I_x	I_y
Linac	2600	4 Hz	14.0 nm	1.3 nm
Final focus	2	4 Hz	7.8 nm	0.2 nm

Figure 1: Photograph of the CLIC stability study test stand, with the detail of a geophone installed on a quadrupole.

obtained in stabilizing low-energy nanobeams for electron transmission microscopy [6] and in various other domains, the CLIC study pursued the approach of using state-of-the-art stabilization devices to find out what level of magnet stability could be achieved by using the presently available technology from industry (see Fig. 1). This report summarizes the experimental achievements obtained from January 2001 to December 2003.

THE CLIC TEST STAND

Basic notation

Vibration measurements are performed with high-resolution *geophones*, which measure vibration velocities versus time. The employed sensors have a sub-nanometre resolution in the 4 Hz to 315 Hz range (e.g., 0.28 nm resolution on the RMS motion above 4 Hz). Detailed comparisons with several other vibration devices [7], indicate an error of 10 % on the geophone calibration provided by the manufacturer. Here, the basic notation for data analysis is briefly reviewed. The vibration velocity, $v(t_n)$, is measured at the discrete times $t_n = n\Delta t$, with $n = 1, 2, ...N$ ($\Delta t = 0.001$ s). The power spectral density of the displacement, $P(f_k)$, is defined for the discrete frequencies $f_k = \frac{k}{N\Delta t}$ as:

$$P(f_k) = \frac{N\Delta t^3}{2\pi^2 k^2} \left| \sum_{n=1}^{N} v(n)e^{-2\pi i \frac{kn}{N}} \right|^2. \qquad (1)$$

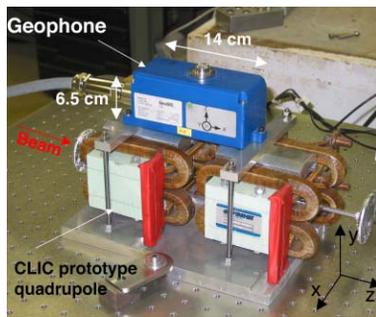The integrated RMS displacement induced by vibrations

Figure 2: A CLIC prototype quadrupole with a geophone to measure vibrations

above $f_{\min} = k_{\min}/(N\Delta t)$ is given by:

$$I(f_{\min}) = \sqrt{\frac{1}{N\Delta t} \sum_{k'=k_{\min}}^{k_{\max}} P(f_{k'})}. \qquad (2)$$

Here, $k_{\max}$ is the maximum measurable frequency and is equivalent to infinity for our purposes. The spectra $P(f)$ are calculated as the average of several consecutive data sets before integration. The reference frame (x, y, z) is shown in Fig. 2: x and y are the horizontal and vertical directions with respect to the beam trajectory, z.

Experimental setup

The CLIC experimental test stand was located on purpose in a normal working area of the CERN site, close to various sources of noise (streets, workshops, offices, running accelerators, ...). The vibration level of the chosen site was measured to be up to 12-15 nm, i.e. up to 70 times larger than the tightest CLIC tolerance (Table 1) and hence suitable for testing the efficiency of stabilization techniques. A photograph of the overall CLIC test stand for the vibration studies and magnet stabilization is shown in Fig. 1 (see [2, 7] for more details). The available equipment includes, amongst others: (1) Four high-resolution geophones for measuring sub-nanometre vibrations from 4 Hz to 315 Hz; (2) One low-frequency, high-resolution geophone for vibrations from 0.03 Hz to 50 Hz; (3) Two distinct devices for passive and active vibration damping: (a) a *stiff* system (STACIS2000 from TMC) consisting of four independent actively stabilized feet and (b) a *soft* system (PEPS-VX from TMC) based on four air-pressure pistons; (4) A honeycomb support structure (table, dimensions 2.4 m×0.8 m×0.8 m), used to support the magnets, with minimal structural resonances above 230 Hz; (5) Prototypes of CLIC quadrupoles (Fig. 2), with the possibility to connect them to an adjustable flow of cooling water; (6) A stretched wire system for measuring the magnet alignment with respect to the surrounding ground in a wide range of times (seconds to weeks). It is noted that by combining the measurements of the two available types of geophones, vibrations over four orders of magnitude, from 0.033 Hz to 300 Hz, can be measured. An example of ground vibrations is given in Fig. 3.
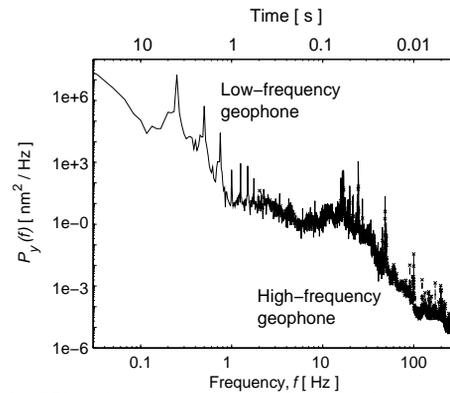

Figure 3: Vibrational spectrum of vertical ground motion versus frequency as measured in the CLIC test stand.

ACHIEVED QUADRUPOLE STABILITY

The best damping of quadrupole fast vibrations ($f \gtrsim 1\,\text{Hz}$) is obtained by directly fixing the magnets on the table, as in Fig. 2, and by using the stiff piezo-based isolators (the performance achieved with the soft system was reported in [2, 7]). The measured vertical and horizontal quadrupole motion is shown in Fig. 4. The motion of the supporting ground is also given as a reference. In Table 2 the total RMS motion above some lower frequency limits is summarized for all directions. These results were achieved in the CLIC test stand during working hours (02/2003).

Above 4 Hz, a CLIC quadrupole doublet was vertically stabilized to $(0.43 \pm 0.04)\,\text{nm}$ with a ground motion of $(6.19 \pm 0.62)\,\text{nm}$. This is the first time that an accelerator magnet is stabilized to the sub-nanometre level. The quadrupole vertical (y) vibration is within the CLIC linac tolerance (1.3 nm) and only a factor 2 larger than the final focus tolerance (0.2 nm). The horizontal (x) RMS motion above 4 Hz was $(0.79 \pm 0.08)\,\text{nm}$ compared to $(3.04 \pm 0.30)\,\text{nm}$ on the ground, i.e. factors 10 and 18 smaller than the linac and final focus tolerances (14.0 nm and 7.8 nm). The longitudinal (z) RMS motion above 4 Hz was $(4.29 \pm 0.43)\,\text{nm}$ compared to $(4.32 \pm 0.43)\,\text{nm}$ on the ground.

Table 2: RMS motion above different minimal frequencies (f) as measured on the ground and on a quadrupole prototype stabilized with the stiff isolation system.

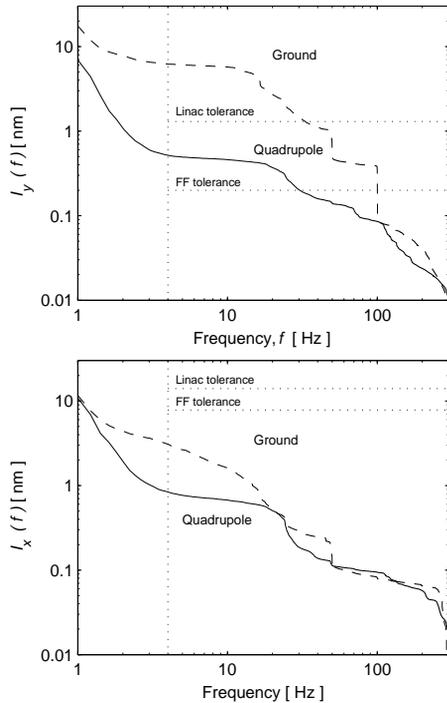| Vertical RMS motion [nm]		
	Ground	**Quadrupole**
$f \geq 4\,\text{Hz}$	6.19 ± 0.62	0.43 ± 0.04
$f \geq 20\,\text{Hz}$	2.67 ± 0.27	0.36 ± 0.04
$f \geq 60\,\text{Hz}$	1.01 ± 0.10	0.14 ± 0.01
Horizontal RMS motion [nm]		
$f \geq 4\,\text{Hz}$	3.04 ± 0.30	0.79 ± 0.08
$f \geq 20\,\text{Hz}$	0.50 ± 0.05	0.49 ± 0.05
$f \geq 60\,\text{Hz}$	0.20 ± 0.02	0.12 ± 0.01
Longitudinal RMS motion [nm]		
$f \geq 4\,\text{Hz}$	4.29 ± 0.43	4.32 ± 0.43
$f \geq 20\,\text{Hz}$	0.63 ± 0.06	0.63 ± 0.06
$f \geq 60\,\text{Hz}$	0.28 ± 0.03	0.14 ± 0.01

Figure 4: Vertical ($I_y(f)$, top) and horizontal ($I_x(f)$, bottom) integrated RMS motions versus frequency, f, as measured on the ground (dashed line) and on a stabilized CLIC quadrupole (solid).

The performance of the stiff stabilization device was continuously monitored over several consecutive days. The achieved vertical RMS motion above 4 Hz is displayed versus time in Fig. 5. The quadrupole was steadily kept below a maximum value of (1.00 ± 0.10) nm, with an average value of (0.77 ± 0.10) nm and (0.67 ± 0.06) nm during days and nights, respectively. The horizontal (x) and longitudinal motions were always below (1.47 ± 0.15) nm and (9.07 ± 0.91) nm, respectively.

The long-term alignment stability of the stabilized table was monitored with the stretched-wire system, which measures table drifts with respect to the ground. An example of measured vertical and horizontal table positions versus time is given in Fig. 6 (top graphs), together with the ambient temperature (bottom graph). The table position depends on the temperature due to the volume variations of the rubber used as a passive damper. A maximum vertical variation of $\approx 40\,\mu$m was measured. Horizontally, the variations are three to four times smaller. The slow temperature variations (e.g., $\approx 20\,\mu$m in 5 hours due to a variation of $\approx 1.5\,°$C, corresponding to ≈ 1 nm/s) will be efficiently compensated by beam-based feedbacks.

CONCLUSIONS

In the framework of the CLIC stability study, the principle feasibility of stabilizing accelerator magnets to the levels required by future linear colliders has been demonstrated by stabilizing a quadrupole vertically to (0.43 ± 0.04) nm in a normal working environment, with the sup-
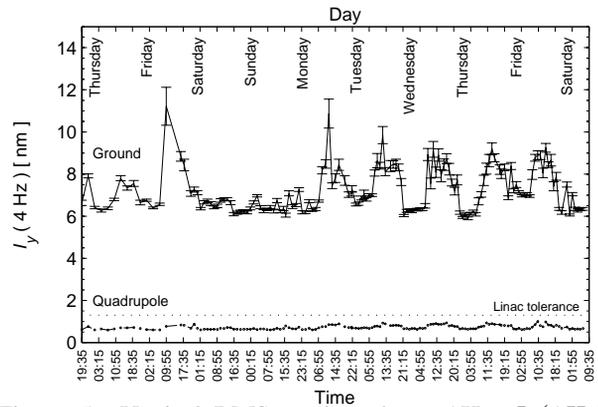

Figure 5: Vertical RMS motion above $4\,$Hz, $I_y(4\,$Hz$)$, versus time as measured on the ground and on a CLIC quadrupole. The first Thursday is a Geneva bank holiday.
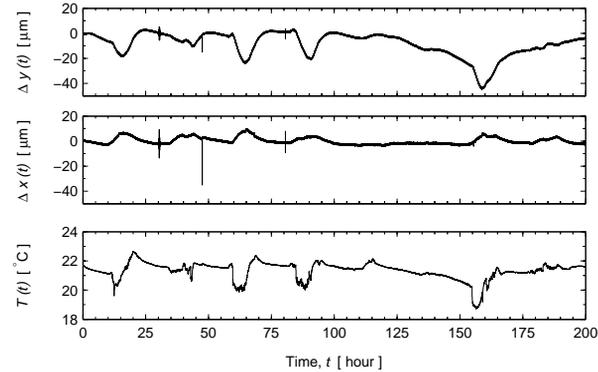

Figure 6: Vertical ($\Delta y(t)$, top graph) and horizontal ($\Delta x(t)$, middle) table positions and ambient temperature ($T(t)$, bottom) versus time, t.

porting ground moving ≈ 15 times more. Simultaneously, horizontal and vertical quadrupole motions of (0.79 ± 0.08) nm and (4.29 ± 0.43) nm were recorded. It has been verified that the device used is in principle suitable for an accelerator environment because it reliably stabilized a magnet below the 1 nm level for a period of several consecutive days. Detailed studies of vibrations from cooling water or structural resonances suggest that these effects can be kept under control with a proper magnet design. Some critical aspects, however, such as the effects of electromagnetic noise and radiation resistance, need further study. Future studies will be focused on implementing the stabilization technology in an experimental region, with more realistic magnet designs.

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