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# Hard Mounts for Quadrupole Nanopositioning in the Next Linear Particle Collider

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**Abstract:**

In the next generation of particle colliders, the electromagnets (quadrupoles) will be heavy structures (up to 500 kg), required to be stable at the nanometre scale, insensitive to external forces, and capable to move by steps of some tens of nanometres at a rather high frequency (say 50 Hz). This paper explores the capabilities of piezoelectric hard mounts to support the quadrupoles, and fulfil these requirements. It is shown experimentally, on a single degree of freedom set-up, that the same active supports can be used to decrease the level of the ground vibration by a factor 3 in a sensitive range around 1 Hz, or alternatively move the quadrupoles according to the requirements.

Keywords: Low frequency vibration isolation, nano-positioning, hard mounts.

## Introduction

In the Compact LInear Collider (CLIC) currently under study, electrons and positrons will be accelerated in two linear accelerators to collide at the interaction point with an energy of 0.5- 3 TeV [1,2]. To acquire such a high energy, the total length of the machine is expected to be up to 48 km. This linear accelerator will consist of a succession of accelerating structures and heavy quadrupoles. The former are used to accelerate the particles to increase their energy; the latter are used to maintain the beam (cross section: 1n height, 40 nm width) inside the vacuum chamber (alternating gradient) and to reach the required luminosity at the collision point. This paper presents a new approach to support the quadrupoles, based on commercial stiff piezoelectric actuators. The first part of the paper gives the main requirements for the quadrupole and its supports in this future machine. Based on these requirements, the support strategy is then explained in details. Finally, a validation of the strategy is presented on a single degree-of-freedom scaled test bench.

## Requirements

*1. Stability*

In the current configuration of the machine, any oscillation of one quadrupole deflects the beam, and reduces the luminosity. For this reason, an important requirement is the stability. Actually, the integrated Root Mean Square (RMS) of the quadrupole vertical displacement $\sigma_x(f)$, defined as

$$\sigma_x(f) = \sqrt{\int_f^\infty \Phi_x(f)df} \tag{1}$$

should not exceed 1 nm at 1 Hz [3,4]. In Equ.(1), $f$ is the frequency, $x$ is the vertical displacement of the quadrupole and $\Phi_x(f)$ its power spectral. Figures 1 and 2 show respectively the typical power spectral density of the ground displacement $\Phi_w(f)$ in the LHC tunnel [5], and the associated RMS integrated $\sigma_w(f)$, calculated using Equ.(1).

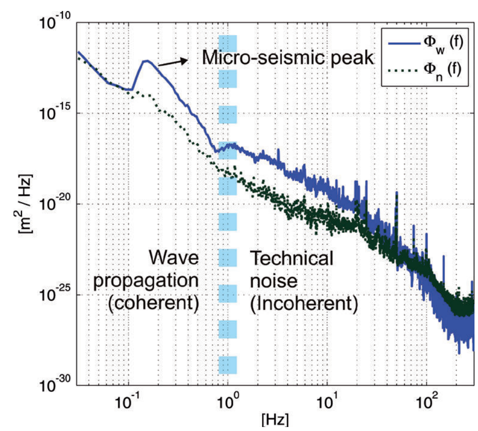


***Fig. 1:*** *Typical power spectral density $\Phi_w(f)$ of the ground vibration in the LHC tunnel, and power spectral density of the measurement noise $\Phi_n(f)$.*

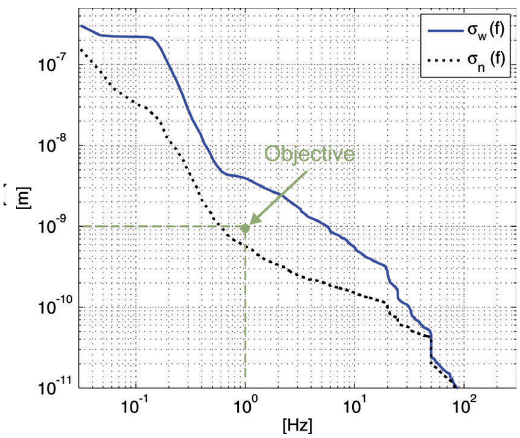


***Fig. 2:*** *Integrated RMS vertical displacement $\sigma_w(f)$ in the LHC tunnel calculated using Equ.(1); Integrated RMS of the sensor noise $\sigma_n(f)$, and objective of the stabilisation.*

These measurements have been performed using broadband seismometers [6]; $\Phi_n(f)$ is the power spectral density of the sensor noise, and $\sigma_n(f)$ is its RMS integrated. One sees that, in order to reach the stability objective, the mechanical stabilization has to reduce the vibrations transmitted by the support by roughly a factor four. This reduction concerns essentially the frequency range between 1 and 20 Hz. Below 1 Hz, the ground motion corresponds essentially to coherent (*micro-seismic*) waves propagating on the surface of the terrestrial crest; above 20 Hz, the ground motion does not provide any significant contribution to $\sigma_w(f)$ at 1 Hz (Fig.2).

*2. Nano-positioning*

In order to maintain the alignment of the machine, the quadrupoles should have the capability to move by steps of some tens of nanometers every 20 ms with a precision of +/- 1nm. This requirement has to be fulfilled in alternance with the first one. As an alternative to this requirement, it is possible to maintain the alignment of the beam by using corrector dipoles (kickers), fixed on each quadrupole. It has the advantage to decouple this requirement to the stabilization, but would engender an increase of the length of the accelerators, substantial additional costs.

*3. Available space*

The size of the tunnel is very restricted, and the space available for the mounts should not exceed a height of 15 cm.

*4. Compatibility with accelerator environment*

The direct environment of the future CLIC collider is subjected to radiations and stray magnetic fields. In order to ensure a full compatibility, this requirement excludes the use of electromagnetic equipments (electromagnetic actuators and sensors using coils likes commercial seismometers).

*5. Robustness*

In operating conditions, the quadrupoles are also subjected to several types of disturbances, commonly referred to as *technical noise*: acoustic noise, cooling system, ventilation. The supports should accordingly ensure a sufficient robustness to the external forces generated by these disturbances.

**Support strategy**

There exist basically two categories of strategies for active isolation: soft mounts [7-12] and hard (or stiff) mounts [13-16]. Soft supports can include one or several stages. The actuator is either electromagnetic, or a piezoelectric stack in series with a compliant element (leaf spring or rubber). The main advantage of a soft mount is to benefit from the active isolation at high frequency. On the other hand, the main disadvantage is to be sensitive to external forces, especially at low frequency. An exception can be found in [17,18]. On the other hand, hard mounts are inherently robust to external forces, and provide positioning capabilities. Both soft and stiff strategies have been applied for the mechanical stabilization of quadrupoles (see a comparison in [16]).

This paper proposes a holistic approach to fulfill all the requirements using the same device. The mount is mainly constituted of a stiff piezoelectric stack actuator. In order to study the performances of such a support, let us consider the system depicted in Fig. 3. It consists of a small mass $m$, mounted on a piezo-electric stack actuator, exerting a force $f$ on the mass.

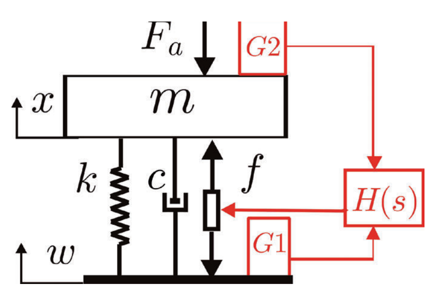


***Fig. 3:*** *Simplified model of a quadrupole, supported by an active mount $f$, subjected to a direct disturbance force $F_a$ and ground vibrations $w$.*

The mass, representing a scaled, single degree-of-freedom quadrupole, is subjected to a direct disturbance force $F_a$ and ground vibrations $w$. Several control strategies can be developed to achieve a reduction of the transmissibility $T_{wx}(f)$ between the ground and the mass, like force feedback, position feedback, adaptive feed-forward, or combinations of these [19]. Properly filtered to ensure sufficient stability margins, all of these strategies could theoretically provide a sufficient isolation at low frequency. However, to cope with resolution issues of accelerometers and force sensors at low frequency, it has been decided to implement a position feedback, using a broadband seismometer [6], $G2$ in Fig.3. The controller, $H(s)$, consists of a first-order high pass filter to remove the input signal drifts, a first order low-pass filter to integrate the signal, and a lag. The closed loop transmissibility $T_{wx}(f)$ is shown in Fig. 4.

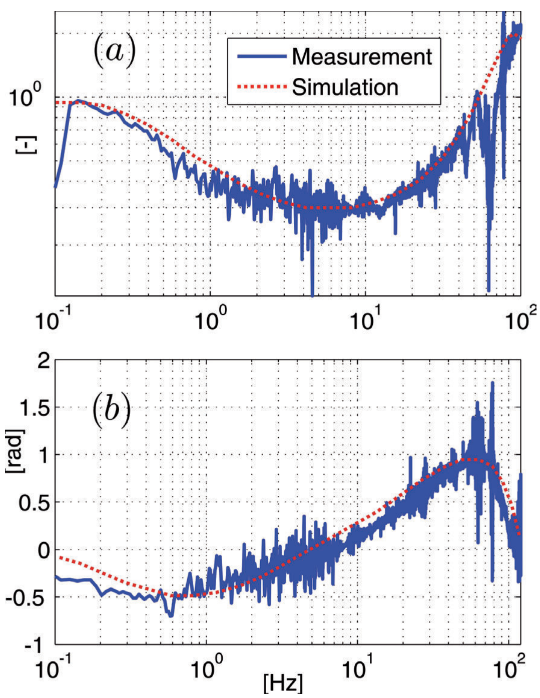


***Fig. 4:*** *Amplitude and phase of the closed loop transmissibility* $T_{wx}(f)$ *with a displacement feed-back.*

The figure shows that it leads to a reduction of the transmissibility by a factor 3 around 10 Hz. In order to test this strategy experimentally, a small test bench has been constructed, and shown in Fig. 5. It consists of a piezoelectric stack [20], clamped in a membrane like vertical guide. The vibrations at both sides of the actuator are measured by two seismometers. In this set-up, the mass $m$ is the mass of the seismometer mounted on the top of the membrane.

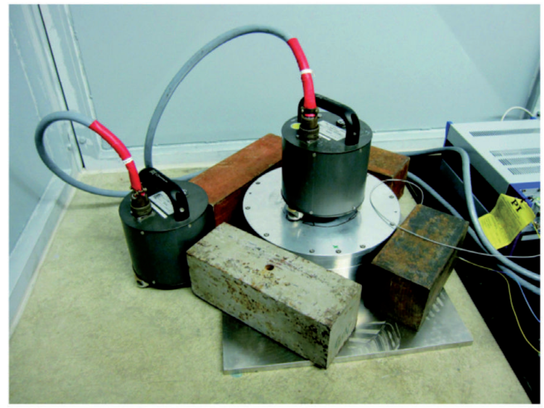

***Fig. 5:*** *Picture of the experimental set-up.*

The real time control system is based on a card *PXI* [21] for data acquisition. The characteristics of the card are as follows: 32 single ended or 16 differential input channels (18 bit resolution), 4 analog outputs (16 bit resolution). More details on the test bench can be found in [5] and [22].

The measured closed loop transfer function $T_{wx}(f)$ was recorded using the same value of the gain, and is compared with the theoretical curves in Fig.4. Higher values of the gain do not lead to better results, essentially because of resolution limitations at low frequency. The positioning capability of the actuator has been tested in open loop, by sending a square signal at 50 Hz, with an amplitude of 10 nm. Figure 6 compares the output of the PXI and the travel of the actuator measured by a capacitive sensor.

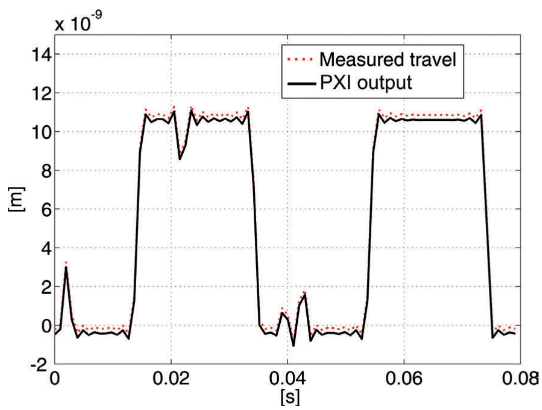


***Fig. 6:*** *Nano-positioning experiment in open loop: comparison of the requested displacement and the integrated difference of the geophones.*

The figure confirms that such a support is able to fulfill the nanopositioning requirement. This result has been further confirmed by integrating the signals from the seismometers.

**Conclusions**

The requirements for the quadrupole of the future particle collider CLIC have been first listed. Based on these requirements, the support strategy has been presented. Its performances have been evaluated theoretically. Then, these results have been compared with experimental results obtained on a single degree of freedom test bench.

It has been shown that a support strategy based on extremely hard piezoelectric mounts can theoretically fulfil the requirements. Experimental results are promising, but the full validation still needs additional efforts in terms of robustness and resolution. Then, it is also planned to validate the strategy experimentally on a multi-degree-of-freedom heavy quadrupole.

**Acknowledgments**

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**References**

[1] http://clic-study.web.cern.ch/clic-study/
[2] http://clic-stability.web.cern.ch/clic-stability/
[3] G. Riddone, D. Schulte, H. Mainaud-Durand, I. Syratchev, W. Wuensch, R. Zennaro, R. Nousiainen, and A. Samoshkin, Proceedings of the EPAC 08 (2008).
[4] K. Artoos, O. Capatina, C. Collette, M. Guinchard, C. Hauviller, F. Lackner, J. Pfingstner, H. Schmickler, M. Sylte, M. Fontaine, B. Bolzon, L. Brunetti, G. Deleglise, N. Geoffroy, and A. Jeremie. Proceedings of the Particle Accelerator Conference, Vancouver, Canada (2009).
[5] K. Artoos, O. Capatina, C. Collette, M. Guinchard, C. Hauviller, M. Sylte, B. Bolzon, and A. Jeremie, Proceedings of the Particle Accelerator Conference, Vancouver, Canada (2009).
[6] Guralp CMG-6T. Guralp catalogue.
[7] A. Stochino, B. Abbot, Y. Aso, M. Barton, A. Bertolini, V. Boschi, D. Coyne, R. DeSalvo, C. Galli, Y. Huang, A. Ivanov, S. Marka, D. Ottaway,V. Sannibale, C. Vanni, H. Yamamoto, and S. Yoshida, Nuclear Instruments and Methods in Physics Research A 598 (2009) 737–753.
[8] S. Redaelli. PhD thesis, University of Lausanne (2004).
[9] B. Bolzon. PhD thesis, University of Savoie (2007).
[10] S. Allison, L. Eriksson, L. Hendrickson, T. Himel, and A. Seryi, Particle Accelerator Conference, Chicago, USA (2001).
[11] J. Frisch, A. Chang, V. Decker, E. Doyle, L. Eriksson, L. Hendrickson, T. Himel, T. Markiewicz, R. Partidge, and A. Seryi, 22nd International Linear Collider Conference, Germany (2004).
[12] D. Schubert, A. Beard, S. Shedd, M. Earles, A. Von Flotow, US patent No 5823307 (1998).
[13] H. Luo, C.D. Young, US patent No 0138338 A1 (2007).
[14] C. Montag. PhD thesis, Hamburg University, (1996).
[15] T. de Poel, J. van Dijk, B. Jonker and H. Soemers, International conference on advanced intelligent mechatronics (2007).
[16] C. Collette, K. Artoos, K. Kuzmin, M. Sylte, M. Guinchard and C. Hauviller, Twelfth IASTED International Conference on Intelligent Systems and Control, Cambridge, USA (2009).
[17] M. Vervoordeldonk, H. Stoutjesdijk, Proceedings of the 6th eu**s**pen International Conference, Baden bei Wien, Austria (2006).
[18] K. Miu, MSc thesis, Massachusetts Institute of technology (2008).
[19] A. Preumont. Vibration control of active structures Kluwer academic publisher, second edition (2002).
[20] Physik instruments catalogue.
[21] PXI‑ 6289, National instruments catalogue.
[22] C. Collette, K. Artoos, M. Guinchard, A. Kuzmin, M. Sylte, F. Lackner and C. Hauviller, CLIC Workshop, Geneva, Switzerland (2009).