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Nanometer scale active ground motion isolator

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ABSTRACT

Vibration isolation is a critical issue in various precision engineering fields. A new design of an active isolation system operating heavy loads (up to 50 kg) is presented in this work. This system provides state of the art vibration isolation at the nanometer scale for magnets of a future particle accelerator and is more compact than other studies in this field. The choice of sensors and actuators, the mechanical design and the acquisition electronics are investigated in order to reject ground motion efficiently. A dynamic experimental characterization is performed. Based on the identified model, a specific controller, giving an attenuation between 10 Hz and 100 Hz was designed and experimentally qualified.

1. Introduction

In the field of high-resolution metrology and micromachining, vibration isolation is a critical issue. The high-performance of these precision instruments is dramatically influenced by small vibrations [1]. Because of the increase in accuracy requirements coming from ever increasing instrument precision, advanced isolation components are required. To isolate the base vibrations, active isolation systems must be used [2]. Vibration isolation systems are also used in other domains like high energy physics that use particle accelerators. Future accelerator projects plan on using nanometer size particle beams. Such accelerator modules need to be isolated from the ground motion vibrations. The latter can be larger than the beam size itself thus being problematic for beam collision at the center of the experiment.

1.1. CLIC

The future compact linear collider (CLIC) is an accelerator that is currently under preliminary development with collaborators from many institutes world-wide, CERN (European Organization for Nuclear Research) being one of the major ones [3,4]. Two nanometer size particle beams are accelerated and steered into collision to create high energy collisions between electrons and positrons. These events are observed by a large detector at the interaction point. To achieve the expected performance, the beams need to be vertically stabilized at the nanometer scale [5]. CLIC is composed of different sections comprising focusing magnets. The sections where stabilization is required are the linac and the final focus. The particles are accelerated to the desired energy along the two 21 km long linacs. The two final focus sections, including the beam delivery system, are approximately 3 km long and end with the final focus magnets named QD0, where the particles are focused to the right beam size for collisions. This work studies the stabilization of these two QD0s.

At the nanometer scale, three main types of vibration disturbance sources have an influence on the focusing magnets: the ground motion [6], the acoustic pressure [7] and internal perturbations due to surrounding processes [8,9] (cooling systems, motors, etc.). Ground motion is the most important issue for future colliders [6] and has been the most studied, partly because the other sources are more difficult to evaluate before full scale mockups are built. Vibrations are especially significant at low frequencies, but become negligible at the nanometer scale above 100 Hz [10]. Furthermore, if the different parts of the accelerator had a correlated motion, the collisions performances would not be altered by the ground motion. Unfortunately, the ground motion is uncorrelated above a few meters and 3 Hz in civil engineering structures used for such particle accelerators [11]. In CLIC, the two QD0 are separated by a dozen meters and have then to be isolated from the uncorrelated ground motion.

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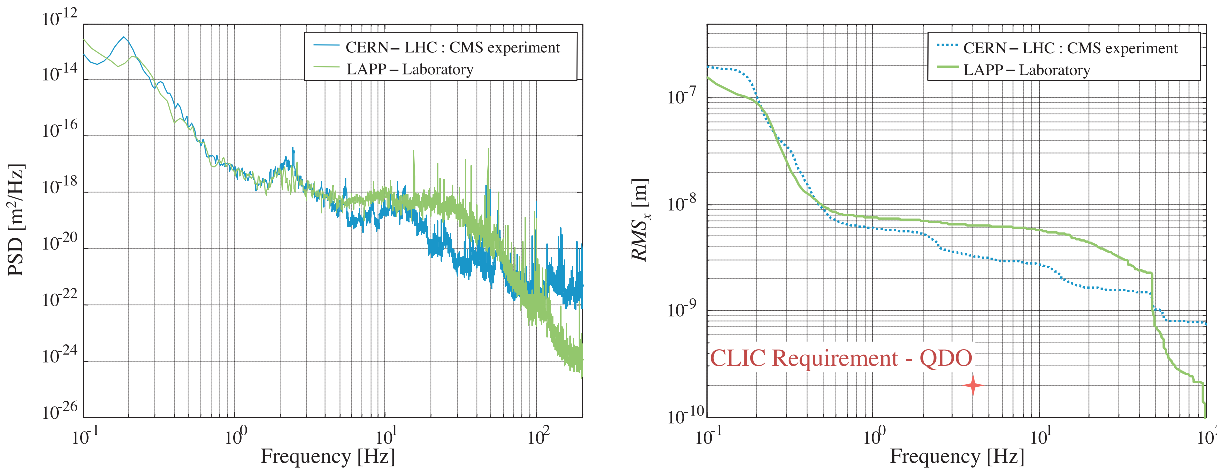

(a) Power spectral density (b) Partial displacement RMS

Fig. 1. Ground motion in two sites: in a laboratory environment at Annecy and in the LHC tunnel close to the CMS experiment [11].

1.2. Requirement

The desired performances are expressed in terms of the partial displacement RMS (root mean square), which is the square root of the integral of the power spectral density (PSD) within a given frequency range, as detailed in Eq. (1):

$$RMS_x(f_{min}) = \sqrt{\int_{f_{min}}^{\infty} PSD_x(f)df} \quad (1)$$

where x is the signal to analyze. $RMS_x(f_{min})$ is the square root of the energy of the signal x calculated in the frequency range $[f_{min}, \infty[$. It is worthy to note that $RMS_x(0)$ is the true RMS value of the signal x.

The ground motions are spectrally characterized in terms of the partial root mean square ($RMS_{G_m}(f)$). To guarantee collisions of the two nanometer size particle beams at the interaction point, the vertical displacement at 1 Hz should be lower than 1.5 nm for the linac quadrupoles (i.e., $RMS_{u_{iso.}}(1) \leq 1.5$ nm) and lower than 0.2 nm at 4 Hz for the QD0 final doublets (i.e., $RMS_{u_{iso.}}(4) \leq 0.2$ nm). Approximately 4000 quadrupoles have to be stabilized in the linac section and only 4 quadrupoles in the final focus section. To give an idea of the challenging issue of stabilization, the $PSD(f)$ and the $RMS_x(f)$ of ground motions are shown in Fig. 1. The two sites represented are respectively the ground motion of LAPP laboratory in Annecy where experiments about the isolation system are done and the ground motion measured in the LHC tunnel next to the CMS experiment [11] which is expected to represent a typical ground motion for CLIC. Although the site of Annecy is not in a tunnel, this laboratory environment is quite similar to an accelerator environment as compared to measurements done on accelerators worldwide [10]. The typical ground motion order of magnitude is usually less than 1mm at 0.1 Hz ($RMS_{G_m}(0.1) \leq$ 1mm).

At nanometer scale, passive isolation has been used in some studies for large physics instruments [12,13]. The proposed systems used several stages of passive isolator. Such passive approaches are known to be good for ground isolation but poor to reject perturbation coming from the system itself. Moreover their size is typically several meters high, which is not compatible with the available space around the QD0.

Some studies about quadrupole stabilizations for linear colliders have already been performed [14,6,15], but for looser requirements. The nano-motion control system presented in [16] is dedicated to the stabilization issue in the CLIC linac section. Its hexa-pod structure can possibly handle 6 degrees of freedom. It has been experimentally validated in [17] for 2 degrees of freedom positioning and vibration control (lateral and vertical motion).

In the final focus section, the space available for the stabilization system is smaller than in the linac section, and the previously mentioned 15 centimeters high hexa-pod system cannot be used. In this paper, we propose a much more compact isolation system whose height is less than 6 centimeters, suitable for the final focus quadrupole. The ground motion attenuation will be theoretically and experimentally investigated along the vertical axis only, but the system can possibly address three degrees of freedom.

The aim of this paper is to present the design and experimental validation of a novel compact isolation system (IS) with advanced actuating capabilities. Moreover, from the control system point of view, the feasibility of the closed loop control is demonstrated using seismic sensors that are usually not dedicated for real time control but for ground motion monitoring.

1.3. Outline

The IS will be described in Section 2. In particular, the choices of the sensors and the actuators, the mechanical design and the data acquisition and control electronics will be presented. In Section 3, the open-loop driving of the IS is first performed, showing the ability of sub-nanometer motion. Then all relevant elements of the IS are characterized and modeled by the linear transfer function. The active control algorithm and its application to the experimental mockup are presented in the last section, where experimental results and theoretical simulations are compared.

2. Electromechanical design

As described in Fig. 2, the IS is composed of an electromechanical structure which includes actuators, actuator power amplifiers, two types of sensors measuring displacement and acceleration, instrumentation amplifiers and a real time hardware for rapid control prototyping.

2.1. Actuating part

Different actuator technologies can be used for active isolation systems, such as electromagnetic [18,19] or magnetostrictive actuators [20]. Piezoelectric actuators are often used because of their high resolutions, their wide bandwidths and their strong forces [21,22]. Their main drawback is their low strokes, which is not