STABILIZATION AND POSITIONING OF CLIC QUADRUPOLE MAGNETS WITH SUB-NANOMETRE RESOLUTION*

Stef Janssens†, Kurt Artoos, Christophe Collette, Marco Esposito, Pablo Fernandez Carmona, Michael Guinchard, Claude Hauviller, Andrey Kuzmin, Raphael Leuxe, Raul Moron Ballester, CERN, Geneva, Switzerland

Abstract

To reach the required luminosity at the CLIC interaction point, about 2000 quadrupoles along each linear collider are needed to obtain a vertical beam size of 1 nm at the interaction point. Active mechanical stabilization is required to limit the vibrations of the magnetic axis to the nanometre level in a frequency range from 1 to 100 Hz. The approach of a stiff actuator support was chosen to isolate from ground motion and technical vibrations acting directly on the quadrupoles. The actuators can also reposition the quadrupoles between beam pulses with nanometre resolution. A first conceptual design of the active stabilization and nano positioning based on the stiff support and seismometers was validated in models and experimentally demonstrated on test benches. Lessons learnt from the test benches and information from integrated luminosity simulations using measured stabilization transfer functions lead to improvements of the actuating support, the sensors used and the system controller. The controller electronics were customized to improve performance and to reduce cost, size and power consumption. The outcome of this R&D is implemented in the design of the first prototype of a stabilized CLIC quadrupole magnet.

INTRODUCTION

In CLIC, electrons and positrons are accelerated in two linear accelerators to collide at the interaction point with an energy up to 3 TeV [1]. In order to reach the required luminosity – a measure of collision brightness – the beam size in the interaction point needs to be 1 nm in the vertical plane and 45 nm in the horizontal plane. This small beam size is achieved by focusing the beam with about 4000 Main Beam Quadrupoles (MBQs) in the main beam accelerator. There are 4 types of quadrupoles ranging from Type 1 with a length of 420 mm (100 kg) up to Type 4 with a length of 1915 mm (400 kg). Each quadrupole offset in relation to the beam, causes the beam size to grow at the interaction point, reducing luminosity. Offsets are introduced through quadrupole misalignment, ground motion and external forces on the magnet due to water cooling in the magnet, tunnel ventilation, etc. The static misalignment of the quadrupoles is reduced by an alignment system based on eccentric cams [2]. Two main mitigation techniques are used to reduce the effect of quadrupole vibrations on the luminosity. The first mitigation technique uses beam-based orbit feedback which measures the position of the beam with Beam Position Monitors (BPMs) and redirects it with dipole magnets. An alternate solution would be to reposition some of the quadrupoles between pulses (every 20 ms) to the nanometre level. The beam-based orbit feedback reduces the effect of the quadrupole's vibrations on the luminosity under 1 Hz and at multiples of the repetition rate of the beam (50 Hz).

The second technique reduces the vibrations of the quadrupole locally for each quadrupole by means of an active stabilization system which, along with the nano-positioning, is the subject of this paper. From beam dynamics simulations, a first estimate was made whereby the integrated root mean square (r.m.s.) for the power spectral density of the vibrations should not exceed 1.5 nm at 1 Hz vertically and 5 nm at 1 Hz laterally [3]. A vibration isolation system based on stiff piezo actuators has already been built, using commercial seismometers, reaching the required level [3][4]. This paper presents the existing and improved control systems for stabilization and positioning, their effect on the mechanical system and the influence of the accelerator environment on the global control scheme. Firstly, the configuration of the original stabilization controller based on the seismometer, a new system using an inertial reference mass as well as the controller for the positioning system is explained. Secondly, the constraints on the mechanical design due to the chosen control system are defined. Thirdly, the effect of the accelerator environment on the global control scheme and its lay out are described. Finally, the achievements of the different controller layouts in terms of the stabilization system's transmissibilities are revealed.

VIBRATION ISOLATION AND POSITION CONTROL SYSTEM

A stiff system based on piezo actuators was selected for the stabilization and positioning of the quadrupoles due to the expected external forces on the quadrupole magnet coming from the accelerator environment (tunnel ventilation, water cooling, interconnections of vacuum tubes,etc.). The quadrupole on the piezo actuators is represented as a 1 degree of freedom system (see Fig. 1). The equation of motion in the Laplace domain is given by

$$X(s) = \frac{k}{ms^2+k}W(s) + \frac{1}{ms^2+k}F(s) + \frac{k}{ms^2+k}\Delta(s) \quad (1)$$

with m being the mass of the quadrupole, k the spring stiffness of the active support and F the forces induced on the

* The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no.227579

† Stef.marten.johan.janssens@cern.ch

magnet by water cooling and other direct forces. The variable Δ represents the elongation of the actuators depending on the controller used. The different control configurations are described in the following paragraphs.

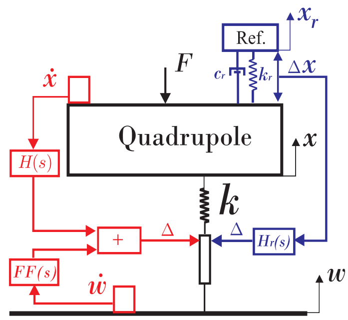

Figure 1: Schematic representation of an active isolation system with a piezo actuator.

Seismometer

The existing vibration isolation system uses commercial seismometers which measure the velocity of a magnetic reference mass with a coil. They have a bandwidth between 33 mHz and 100 Hz limited by several high order filters and are used in a feedforward/feedback configuration to reduce the vibration of the quadrupole. The elongation of the actuators is given by $\Delta = H(s)sX(s) + FF(s)sW(s)$. The feedback controller H(s) includes an integrator, a double lag to limit the bandwidth, a high-pass filter and the sensitivity curve of the seismometer. The feedforward controller FF(s) consists of a high and low-pass filter, an integrator and the seismometer sensitivity. The control system's main limitation is the feedback loop's instability caused by one set of poles coming from a high-order low-pass filter in the seismometer.

Inertial Reference Mass

A new sensor is under development which uses the relative displacement Δx between a reference mass ($X_r(s)$), with a suspension frequency of 1 Hz and a damping ratio $\xi_r = 30$ % achieved by actively damping the system, and the quadrupole position ($X(s)$) (see Fig. 1). This sensor will improve the stability of the controller as the additional poles of the seismometer are removed. Using a capacitive gauge or optical sensor as a measurement device in the inertial reference mass, allows it to be more suitable for an accelerator environment with stray magnetic fields than a seismometer using a coil. The elongation of the actuator for this configuration is given by $\Delta = -H_r(s)(X(s) - X_r(s)) = -H_r(s)X(s)(1 - G_r(s))$ with $G_r(s) = \frac{X_r(s)}{X(s)} = \frac{c_r s + k_r}{m_r s^2 + c_r s + k_r}$. The sensitivity curve looks like an under-damped high-pass filter.

Nano-Position Control

The nano-positioning is performed by a controller using the error ($e(s)$) between the requested quadrupole position ($R(s)$) and the actual relative quadrupole position ($Y(s) = X(s) - W(s)$). The actuator elongation is then given by $\Delta(s) = C(s)e(s)$. The controller $C(s)$ consists of a Proportional-Integral Controller (PI Controller). The limitation of the controller comes from the pole of the first mode of the system. In order to increase stability, a low-pass filter at 40 Hz is added.

MECHANICAL DESIGN CONSTRAINTS

The main limitations for the three different control systems come from instabilities in the feedback loop. The maximum performance of a feedback system is a function of the maximum feedback gain g at which the feedback loop becomes unstable. The margin of the actual gain to this maximum gain is called the Gain Margin (GM). The GM of the system is influenced by the poles related to the first mechanical mode in the system. In order to define the minimal mechanical characteristics of the system, the GM of the controllers with a fixed gain ($g = 10$ for the stabilization and $g = 105$ for the positioning) is set out to a range of first modes ($f_1 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$) in Fig. 2.

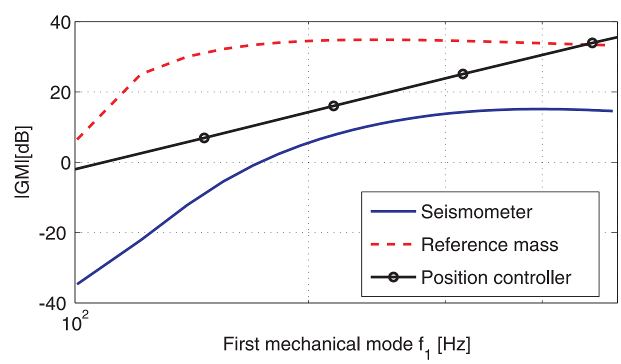

Figure 2: Stability margins for a vibration isolation system with a seismometer, a reference mass and the positioning controller, all with a fixed gain, in function of the first mode of the system.

It shows that the control system with the inertial reference mass has a higher gain margin than the commercial seismometer. Further, for both the inertial mass and the nano-positioning, the first mode should only be higher than 120 Hz in order to have sufficient performance in comparison to 250 Hz for the commercial seismometer. This input from the control system has been taken into account for the mechanical design in the form of an xy-guidance system to increase stiffness in the lateral direction [4] and puts requirements on the design of the alignment system on which the stabilization system will be mounted.

CONSTRAINTS ON GLOBAL THE CONTROL SCHEME

Working in a long linear particle accelerator brings its own set of challenges to the global control scheme for the local stabilization and position controller. The control centre is located kilometres away from the magnets that need

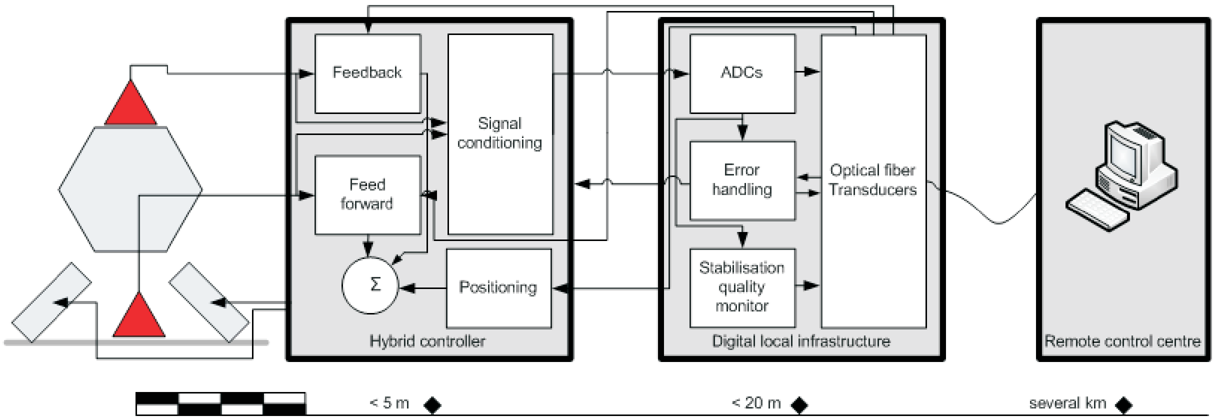

Figure 3: System level description of stabilization controller within CLIC control.

Table 1: Classification of Signals According to Timing Requirements and Direction

	Critical latency	Best-effort delay
Input	$\dot{x}$ or Δx	Self check
	$\dot{w}$	Emergency stop
	y	New position R
		Configuration parameters
Output	Δ	$\dot{x}$
		Error signal
		RMS vibration level of Magnet
		Performance figure

to be stabilized and positioned. It was demonstrated that the phase shift introduced by such a long communication path would be disastrous for the performance of the stabilization controller even when optical fibres are used [6]. To this end, the signals going into and coming out of the global control system are divided between delay critical and best effort delay signals (see Table 1). The signals for the stabilization and positioning controllers are time critical. This limits the distance allowed from the magnet to these controllers. However, the tunnel is an electromagnetically noisy environment and the sensor cables are a weak link. At the same time, putting the electronics closer to the magnet increases the radiation exposure. As a compromise, the stabilization and position controllers are put in a hybrid controller at a distance from the magnet in the order of metres as is shown in Figure 3. The final location will depend on civil engineering constraints. The hybrid mixed-signal electronic board is described in Ref. [5]. It is based on a low noise analogue circuit filtering, shaping, processing and generating the relevant control signals ($\dot{x}$ or Δx,$\dot{w}$ and Δ), and a digital part for the configuration of controller parameters (gain g, filter limits,...). A hybrid solution was chosen over a more classical digital construction using ADCs and DSPs or FPGAs for a number of reasons. ADCs with a resolution of at least 18 bits are required [6], which are not commercially available for radiation environments like CLIC. Latency was also shown critical for the stability and performance of the controller. To achieve the required delay, a very high sampling rate, without buffer, and hardware clock frequency is required. In addition, digital electronics are more sensitive to radiation, especially single events, than analogue electronics. The analogue cumulative errors are worse than those of a digital system but they can be partially compensated by gain corrections. All analogue components are chosen to have low noise and especially a low 1/f corner frequency, as the signal bandwidth of interest starts at 100 mHz (tantalum capacitors, metal thin layer resistors, etc.). Additionally a custom integrated control board has a lower cost, less power consumption, and reduced volume compared to a classic digital platform.

The best-effort delay signals include position, configuration parameters and status. They are processed at a local digital infrastructure which communicates with the remote control centre kilometres away. Only best-effort delay can be expected as these signals need to travel the distance to the remote control centre so a delay is unavoidable which is not a problem as long as the delay is kept constant.

SIMULATIONS AND TEST RESULTS

The effect of the ground vibrations on luminosity depends on the transmissibility of the vibrations from the ground to the quadrupole, the shape of the ground motion at that location and the beam-based orbit feedback, which works only below 1 Hz and at multiples of 50 Hz. Simulations for the transmissibilities of the local vibration controller were performed for a 100 kg mass (Type 1 magnet) on top of two piezo actuators resulting in a natural frequency of around 300 Hz in the vertical direction. Several different local controller configurations were simulated with both commercial seismometers and inertial reference mass (see Fig. 4). These seismometers were used in a feedback and feedback combined with feedforward configuration. The latter was tested on a prototype test bench, using a prototype of the hybrid controller, performing very close to the simulations. The transmissibility of this configuration was included in luminosity simulations [8] which showed that the peak at 80 Hz is undesirable as this is a location where the beam-based orbit feedback does not perform well. Using the reference mass reduces the performance locally at 7 Hz but gives a broader bandwidth as well as re-

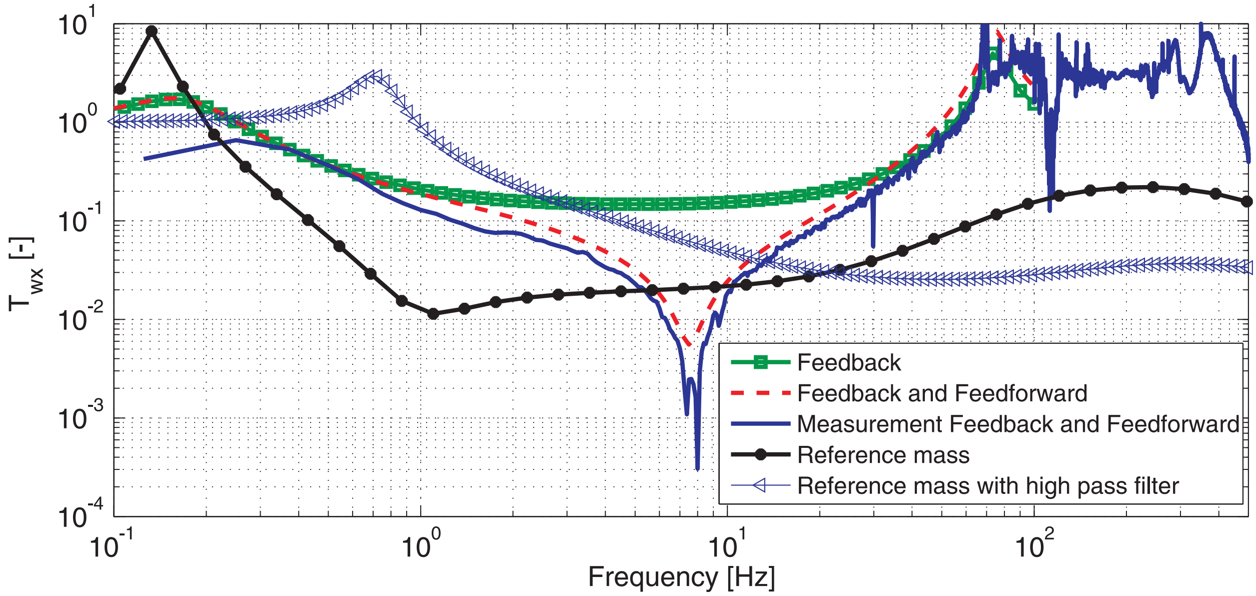

Figure 4: Transmissibilities between ground and quadrupole for the theoretical and measured feedforward combined with feedback system using a seismometer and the feedback using an inertial reference mass.

moving the unwanted peak at around 80 Hz. However, this configuration has a peak at around 0.2 Hz coinciding with the high ground motion due to incoming sea waves known as the micro seismic peak. Including a high-pass filter in order to move the low frequency peak away from the micro seismic peak resolves the problem. The transmissibility for this system also tested in a simulation of the whole accelerator including other mitigation techniques (beam-based feedback, etc.) with a ground motion model corresponding to the vibrations expected in the CLIC tunnel. It was found that the reference mass with the high pass filter gave the best performance reducing the luminosity loss from 68% to only 3 % although it is not the highest performing stabilization system at lower frequencies [7]. This shows that the interaction with the other mitigation techniques and local vibration levels are an important factor in defining the controller for stabilizing CLIC's main beam quadrupoles.

CONCLUSIONS

This paper has shown the effect of the different control systems on the mechanical system and the effect of the global control scheme due to the accelerator environment underlining that the first mechanical mode needs to be above 120 Hz for the position controller and if an inertial mass is used. The commercial geophones need a first mechanical mode higher than 250 Hz to keep it from destabilizing the stabilization controller in feedback configuration. Furthermore, the stabilization and position controller must be placed metres away from the magnet because of a performance drop due to latency and sensitivity to radiation and electromagnetic noise. The choice of a hybrid analogue/digital controller also contributes to reduce the latency. A digital connection was made which communicates with the remote control centre in order to keep some flexibility in the system for local changes in vibration levels and enable monitoring. A list of the interface signals was defined based on the critical delay and best-effort delay requirements. From beam simulations of the whole CLIC accelerator it was revealed that the shape of the stabilization controller is also defined by the interaction with the other mitigation techniques.

REFERENCES

[1] J.P. Delahaye,"Towards CLIC feasibility", IPAC' 10, Kyoto, May 2010, FRXCMH01, p. 4769.

[2] H. Mainaud Durand *et al.*,"Validation of a Micrometric remotely controlled pre-alignment system for the clic linear collider using a Test Setup with 5 degrees of freedom", IPAC' 11, San Sebastian, September 2011, MOP0029.

[3] C. Collette *et al.*, "Nano-motion control of heavy quadrupoles for future particle colliders: An experimental validation", Nuclear Instruments and Methods in Physics Research A, 643,(2011), pp. 95-101.

[4] K. Artoos *et al.*, "Status of a Study of Stabilization and Fine Positioning of CLIC Quadrupoles to the Nanometre Level", IPAC'11, San Sebastian, September 2011.

[5] P. Fernandez Carmona *et al.*, "Study of the hybrid controller electronics for the nano-stabilization of mechanical vibrations of CLIC quadrupoles", TWEPP' 11, Vienna, September 2011.

[6] K. Artoos *et al.*, "Study of the electronics architecture for the mechanical stabilization of the quadrupoles of the CLIC linear accelerator", TWEPP' 10, Aachen, September 2010, Jinst 5 C11014.

[7] S. Janssens *et al.*,"System control for the CLIC main beam quadrupole stabilization and positioning", IPAC' 11, San Sebastian, September 2011, TUPC014.

[8] J. Snuverink *et al.*, "Status of Ground Motion Mitigation Techniques for CLIC", IPAC' 11, San Sebastian, September 2011, TUPC023.