SYSTEM CONTROL FOR THE CLIC MAIN BEAM QUADRUPOLE STABILIZATION AND NANO-POSITIONING *

S. Janssens †, K. Artoos, C. Collette, M. Esposito, P. Fernandez-Carmona, M. Guinchard, C. Hauviller, A. Kuzmin, R. Leuxe, J. Pfingstner, D. Schulte, J. Snuverink, CERN, Geneva, Switzerland

Abstract

The conceptual design of the active stabilization and nano-positioning of the CLIC main beam quadrupoles was validated in models and experimentally demonstrated on test benches. Although the mechanical vibrations were reduced to within the specification of 1.5 nm at 1 Hz, additional input for the stabilization system control was received from integrated luminosity simulations that included the measured stabilization transfer functions. Studies are ongoing to obtain a transfer function which is more compatible with beam based orbit feedback; it concerns the controller layout, new sensors and their combination. In addition, the gain margin must be increased in order to reach the requirements from a higher vibration background. For this purpose, the mechanical support is adapted to raise the frequency of some resonances in the system and the implementation of force sensors is considered. Furthermore, this will increase the speed of repositioning the magnets between beam pulses. This paper describes the improvements and their implementation from a controls perspective.

INTRODUCTION

In order to reach the required luminosity levels for the Compact Linear Collider (CLIC), the vibration levels of the Main Beam Quadrupoles (MBQ) must be limited. From beam dynamics simulations, a first estimation was made that the integrated Root Mean Square (r.m.s.) vibrations [1] should not exceed $\sigma_x = 1.5$ nm at 1 Hz vertically and $\sigma_y = 5$ nm at 1 Hz laterally. Two main types of vibration sources act on the MBQ's. Ground motion, which is transmitted through the support to the magnet and external forces which work directly on the magnet (ventilation, watercooling, etc.). A stiff active vibration isolation system was designed to reach the required vibration level [1][2]. A commercially available broadband seismometer, used to measure ground motion, was used in a feedback loop to measure the quadrupole velocity $\dot{x}$, reaching the required integrated r.m.s. values [1]. The combination of the stabilization with other mitigation techniques in simulations showed possibilities to enhance the performance in terms of luminosity [3]. This paper shows four ways of improving the vibration isolation system. First, the effect of increasing the stiffness of the system is presented. Then active damping is added to enhance the gain margin. A second seismometer is added for Feedforward control and a new configuration based on a reference mass is presented. The effect on the integrated luminosity for the different solutions is compared.

* 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

VIBRATION ISOLATION STRATEGY

The quadrupole on the active isolation support (see Fig. 1(left)) can be considered as a mass spring system with one degree of freedom (1 d.o.f.), representing either vertical or lateral direction, as shown in Fig. 1(right). The equation of motion for the spring mass system can be rewritten in the Laplace domain as

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

with m being the mass of the quadrupole, k the spring stiffness of the active support and F the induced forces on the magnet by water cooling and other direct forces.

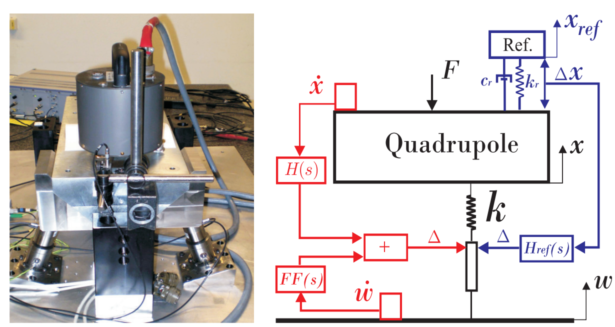

Figure 1: Picture of the 2 d.o.f. vibration isolation set-up based on piezo actuators (left); Schematic representation of an active isolation system with a piezo actuator (right).

For the feedback system with the seismometer, the elongation of the actuator is given by $\Delta = -H(s)sX(s)$. The controller $H(s)$ includes an integrator, a double lag, a high pass filter and the sensitivity curve of the seismometer shown in Fig. 2. From eq. 1 the transfer function between the ground and the quadrupole can be calculated

$$T_{wx} = \frac{G(s)}{1+G(s)sH(s)} = T_{FB} \quad (2)$$

with $G(s) = k/(ms^2+k)$. In the same way, the transfer function between the induced forces $F(s)$ and the quadrupole motion $X(s)$ is $T_{FX} = (1/k)T_{FB}$ showing the importance of stiffness k for robustness against forces.

The performance of the feedback stabilization system, a function of the maximum feedback gain g, is limited by the stability of the control loop. The margin of the actual gain to this maximum gain is called the Gain Margin (GM). Moreover, approaching the maximum gain causes peaks to

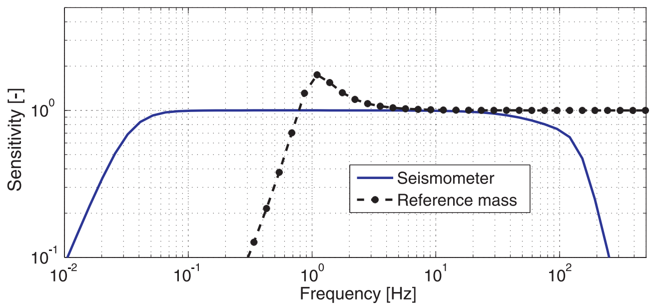

Figure 2: Sensitivity curves for the seismometer and the sensitivity S of the reference mass.

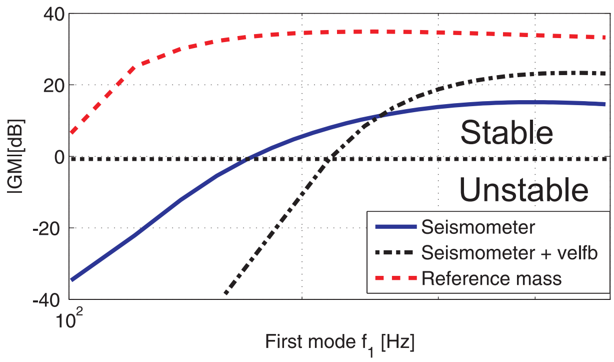

Figure 3: Stability margins for a vibration isolation system with a seismometer, a seismometer with velocity feedback and a reference mass, all with a fixed gain, in function of the first mode of the system.

appear at the borders of the isolation bandwidth, amplifying the vibrations [3]. These are the two limiting factors for the luminosity performance and can therefore be improved.

IMPROVEMENTS

The first option to improve the stability of the system is to raise the stiffness of the support structure k and consequently the first mode of the system $f_1 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$. Figure 3 shows that the gain margin can increase up to 15 dB by increasing the position of the first mode. Raising the stiffness also increases the tracking capability of the system for the nano-positioning.

The performance of the system can be further enhanced by adding active damping using velocity feedback. This enlarges the Gain Margin by 8 dB for a system with a first mode higher than 240 Hz but decreases at lower frequencies (see Fig. 3). It is caused by the combination of the higher gain near the first mode with the phase drop of the lag filters. Extra damping will also improve the nano-positioning [2]. Active damping through integral force feedback is still under investigation.

To enhance the performance of the isolation system without requiring the increase of the gain of the feedback system, a seismometer is added on the ground in Feedforward configuration as is shown in Fig. 1. The elongation of the actuator is then $\Delta = -FF(s)sW(s) - H(s)sX(s)$. This transforms eq. 2 into

$$T_{wx} = \frac{G(s)}{1 + G(s)sH(s)}(1 - sFF(s)) = T_{FB}T_{FF} \quad (3)$$

The controller $FF(s)$ includes a high and low pass filter, an integrator and the sensitivity curve of the seismometer. As this configuration is not a loop, it cannot become unstable. Figure 4 shows an increased performance for T_{wx}, compared to the feedback alone, in a bandwidth between 1 and 30 Hz for both the simulation and a test performed on one of the available test benches. Additionally, the transfer function between the induced forces $F(s)$ and the quadrupole $X(s)$ remains unchanged as the seismometer on the ground does not sense the induced forces.

To overcome the stability limitation due to the complex commercial seismometer, it can be replaced by a simple inertial reference mass [4] with a suspension frequency of 1 Hz and a damping ratio $\xi_r = 30\%$. The relative displacement Δx between the reference mass $X_r(s)$ and the quadrupole $X(s)$ is measured and fed back through a controller (see Fig. 1). The elongation of the actuator for this configuration is given by

$$\Delta = -H_r(s)(X(s) - X_r(s)) = -H_r(s)X(s)(1 - G_r(s)) \quad (4)$$

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 towards the quadrupole displacement of the reference mass is given by $S = (1 - G_r)$ and is shown in Figure 2. The controller $H_r(s)$ consists of a high pass filter, a double lag and a lead. Equation 2 then transforms into

$$T_{wx} = \frac{G(s)}{1 + G(s)H_r(s)(1 - G_r)} = T_{FBrm} \quad (5)$$

The resulting Gain Margin in function of the first mode of the system for the same fixed gain is shown in Figure 3. The reference mass configuration has an enlarged gain margin of about 35 dB and is also less susceptible to the first mode. The transfer between the induced forces and the quadrupole motion becomes $T_{FX} = G(s)\frac{1}{k}T_{FBrm}$ indicating once again the importance of a high stiffness for the robustness against external forces. The transmissibility of the system with a reference mass for almost maximum gain is shown in Fig. 4. The peak performance is reduced but the overall performance is improved in a wide frequency bandwidth and this with only one sensor.

EFFECT ON LUMINOSITY

To fully evaluate the merit of the improved transfer functions, they have to be analyzed with full-scale simulations. These simulations include, amongst others, ground motion, stabilization, beam-based feedback and beam-beam interactions. For more detailed information see [3]. Due to CLIC's low repetition rate of 50 Hz, beam-based feedback

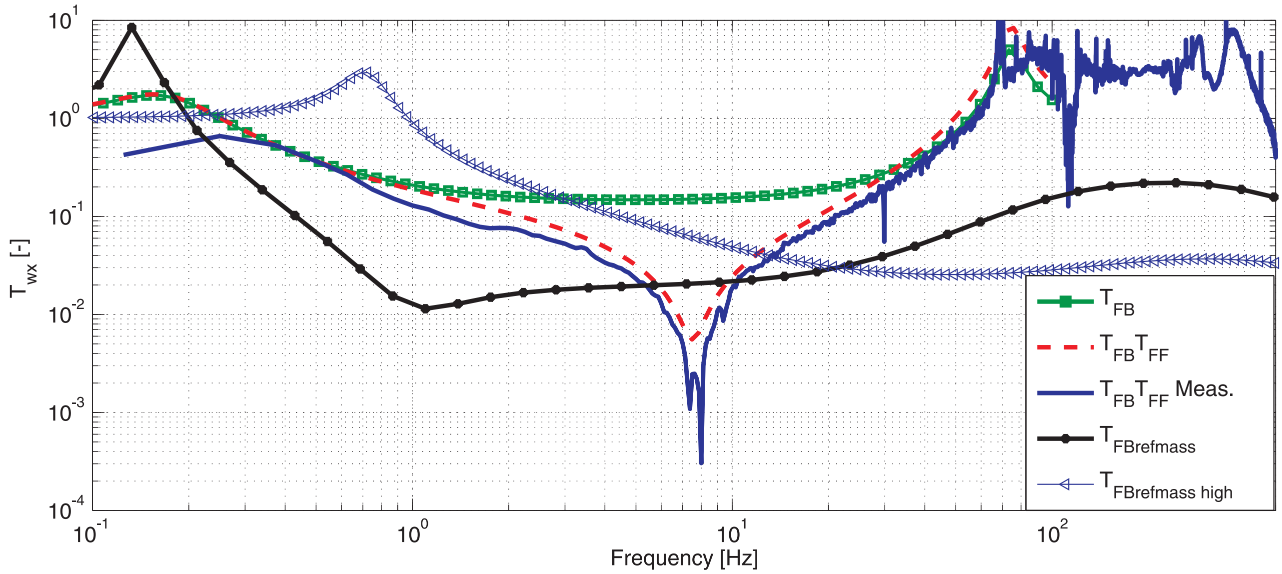

Figure 4: Transmissibilities between ground and quadrupole for the theoretical and measured feedforward combined with feedback system using a seismometer and the feedback using an inertial reference mass.

Table 1: The Luminosity Loss for Several Transfer Functions of the Stabilisation for Ground Motion Model B10

	Luminosity loss (%)
No stab.	68
$T_{FB}(s)$ max gain	13
$T_{FB}(s)$ medium gain	6
$T_{FB}(s)T_{FF}(s)$	7
$T_{FBrm}(s)$	11
$T_{FBrm}(s)$high pass fil.	3

is less effective for frequencies above a few Hertz. For these high frequencies stabilization has to take over. Note that frequencies close to (multiples of) the repetition rate are of less importance as they do not impact the beam, frequencies of 25 and 75 Hz are inherently problematic for beam-based feedback to correct.

The so-called ground motion model B10 was used for the simulations. Based on measurements from the Fermilab site, the peaks are amplified to match the technical noise level measured in the CMS hall. For CLIC it is the most challenging model currently under study. The figure of merit is the average luminosity performance. In the performed studies 30 s of CLIC operation were simulated for 20 ground motion seeds.

The transfer functions from equations 2, 3 and 5 have been simulated and the results are shown in Table 1. All proposed transfer functions are well above the nominal CLIC performance, as the allowed luminosity loss budget for dynamic imperfections is around 20%. The high gain feedback suffers from the high amplification near 0.2 Hz, which coincides with the so-called microseismic peak of the ground motion. This is significantly reduced in the improved transfer functions. Somewhat surprisingly the feed forward system does not ameliorate the result. It turns out that this is caused by amplification at the important high frequencies around 75 Hz. The reference mass system also has a peak close to 0.2 Hz limiting its performance in terms of luminosity. Including an extra high pass filter moves the peak higher up. This enhances the performance considerably to only 3% luminosity loss.

Note that the deployed beam-based feedback is not optimized with respect to the transfer functions of the stabilization or the ground motion model.

CONCLUSIONS

The vibration isolation system for the CLIC main beam quadrupoles, based on a commercial seismometer, reached the required vibration levels. In this paper it has been shown that the performance in terms of luminosity can be improved by increasing the stiffness of the system, adding a second sensor in feedforward configuration or replacing the seismometer with an inertial reference mass. The reference mass including an additional high pass filter has the highest performance in terms of luminosity. It reduces the luminosity loss from 68% to 3 %.

REFERENCES

[1] 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

[2] 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

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

[4] R. Saulson, "Vibration isolation for broadband gravitational wave antennas", 1984, Review of Scientific instruments, issue 55, pp. 1315-1320