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Status of a Study of Stabilization and Fine Positioning of CLIC Quadrupoles to the Nanometre Level

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Abstract

Mechanical stability to the nanometre and below is required for the Compact Linear Collider (CLIC) quadrupoles to frequencies as low as 1 Hz. An active stabilization and positioning system based on very stiff piezo electric actuators and inertial reference masses is under study for the Main Beam Quadrupoles (MBQ). The stiff support was selected for robustness against direct forces and for the option of incrementally repositioning the magnet with nanometre resolution. The technical feasibility was demonstrated by a representative test mass being stabilized and repositioned to the required level in the vertical and lateral direction. Technical issues were identified and the development programme of the support, sensors, and controller was continued to increase the performance, integrate the system in the overall controller, adapt to the accelerator environment, and reduce costs. The improvements are implemented in models, test benches, and design of the first stabilized prototype CLIC magnet. The characterization of vibration sources was extended to forces acting directly on the magnet, such as water-cooling induced vibrations. This paper shows the achievements, improvements, and an outlook on further R&D.

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STATUS OF A STUDY OF STABILIZATION AND FINE POSITIONING OF CLIC QUADRUPOLES TO THE NANOMETRE LEVEL*

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Mechanical stability to the nanometre and below is required for the Compact Linear Collider (CLIC) quadrupoles to frequencies as low as 1 Hz. An active stabilization and positioning system based on very stiff piezo electric actuators and inertial reference masses is under study for the Main Beam Quadrupoles (MBQ). The stiff support was selected for robustness against direct forces and for the option of incrementally repositioning the magnet with nanometre resolution. The technical feasibility was demonstrated by a representative test mass being stabilized and repositioned to the required level in the vertical and lateral direction. Technical issues were identified and the development programme of the support, sensors, and controller was continued to increase the performance, integrate the system in the overall controller, adapt to the accelerator environment, and reduce costs. The improvements are implemented in models, test benches, and design of the first stabilized prototype CLIC magnet. The characterization of vibration sources was extended to forces acting directly on the magnet, such as water-cooling induced vibrations. This paper shows the achievements, improvements, and an outlook on further R&D.

INTRODUCTION

A subject common to several future high-energy physics R&D programmes is the generation of beams with very small emittance and beam size [1] and concomitantly the alignment and stabilization of accelerator components with ultimate precision. In the CLIC machine currently under study, the dynamic offsets of the quadrupole magnets with respect to the beam axis, created by ground motion and technical vibrations, should be very small. A limit for the integrated root-mean-square (r.m.s.) [2] vertical displacement was set at 1.5 nm at 1 Hz for the MBQs and 0.2 nm at 4 Hz for the final focus magnets. In the lateral direction the limit is 5 nm. More significant than such limits is the integrated luminosity obtained in simulations [3] [4] combining the stabilization system transfer functions with beam-based orbit and interaction point (IP) feedback, and the appropriate ground motion model.

Feasibility Demonstration

In particle accelerators, static and dynamic forces typically act directly on the quadrupole magnets through water-cooled power cables and beam chamber interconnections. Therefore, the CLIC magnet stabilization study focused on vibration isolation with very stiff actuating supports [2]. Stabilization based on soft supports with passive damping at high frequencies is less robust against direct forces and less compatible with alignment. Another advantage of a stiff actuating support is the fast "nano-positioning" or repositioning capacity with nanometre resolution of the quadrupoles between beam pulses (50 Hz), studied as an alternative to dipole correctors.

A development of a stabilization system based on a parallel structure with very stiff actuators and flexural joints was made. Two test benches were constructed: a single degree of freedom (d.o.f.) bench (Fig. 1 left, membrane) and a two d.o.f. bench (Fig. 1 right, tripod) with a dummy magnet of 100 kg. Seismometers were used as sensors in a feedback configuration (i.e. placed on top of the stabilization support).

Figure 1: Two demonstration benches: left: single d.o.f. system (membrane), right: two d.o.f. system (tripod) with 100 kg dummy magnet mass.

The technical feasibility to reach the stability limits and to reposition with nanometre resolution was demonstrated on both benches. The two d.o.f. bench can stabilize and nano-position in the vertical and lateral direction effectively reaching 0.9 nm integrated r.m.s. displacement in the vertical direction with the initial feedback configuration [2]. This paper describes the progress that was made after the feasibility demonstration.

R&D THEMES

Although the feasibility had been demonstrated, several limitations were found with the two test benches. A work plan was made to further develop the test benches into a mature technical system. The development work is based on five themes:

- Performance increase: raise the gain of the stabilization control in order to reach the requirements in an environment with a higher level of vibrations. Enhance the resolution of the system to stabilize to even smaller vibration levels;

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- Compatibility with accelerator environment: the system must work in a magnetic field and in an environment with radiation;
- Cost optimization;
- Overall system analysis: integration with other CLIC components, interaction with the beam-based orbit and IP feedback to optimise luminosity;
- Pre-industrialization: capability to build and operate reliably for large quantities (about 4000 systems).

Development of the Mechanical Support

From the stabilization requirements it was decided to block the actuating support in the longitudinal beam direction and in the roll direction around the longitudinal axis [5]. The stabilization support is based on inclined actuator pairs in the same plane, mounted on flexural universal joints. This so-called four-linked bars system has little lateral roll and longitudinal stiffness. Each actuator pair will therefore be installed inside an x-y guide. The magnet will be connected to two rigid plates with eight flexural pins (Fig. 2). These flexural pins placed at a distance from the intersection of the actuators' axes, raise the lateral and roll stiffness. The x-y guide also increases the longitudinal stiffness and makes it possible to introduce a longitudinal lock for transport. A prototype was designed and is under construction. Calculations for the prototype showed an increase of lateral stiffness from 0.1 N/μm to 50 N/μm for one actuator pair. A full mechanical model including the magnet, actuators, and x-y guide was made and is implemented in the system controller.

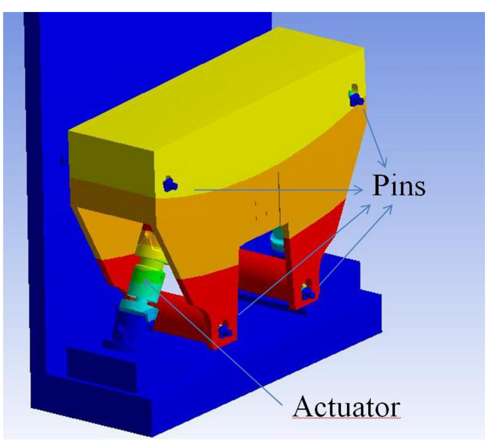

Figure 2: The x-y guide prototype with one stiff plate hidden. Deformation for a lateral force.

In order to reach the required stability from a larger vibration background, the stability of the controller needs to be higher. One of the factors that determine controller stability is the presence of low frequency resonances [4]. This was also observed on the 2 d.o.f. test bench. Adding the x-y guide should improve this.

The x-y guide also improves the installation of the displacement sensor for the nano-positioning. Such sensors require a stiff support, very precise installation, and parallelism between sensor and moving part.

Controller and Sensor Design

Apart from low frequency resonances, the controller stability can increase using other methods, described in Ref. [4]. By including feedforward from a seismometer on the floor, the performance was enhanced (see results below).

By measuring the relative displacement between an inertial reference mass and the magnet (or ground) rather than the velocity, both performance and compatibility with beam-based feedback are improved [3] [4]. The use of commercially-available high-resolution and low-noise displacement instrumentation such as capacitive gauges or interferometers in such a sensor would allow stabilizing to even smaller integrated r.m.s. displacements. The development of an inertial reference mass sensor was therefore started and the testing on a first prototype gave encouraging results. An additional objective is to make the sensor non-magnetic by removing the coil used in seismometers for measurement and damping the reference mass [6]. Finally, without the active damping of the reference mass, it would become possible to remove all electronics from the sensor and by doing so, make it radiation hard.

Electronics

For the feasibility demonstration, a PXI RealTime controller was used as controller hardware. The delay created by ADC, DAC and an iteration of the controller was measured to be 43 µs. This delay decreased the gain margin of the system. A fully analogue controller circuit was therefore designed and built [7]. It increases the performance and is successfully used on the test benches (see section Results). The use of an analogue controller entails a cost reduction of the stabilization system of about 10 %. It also reduces the power consumption of the stabilization by about 95 %. Finally, the analogue controller needs much less space and is less sensitive to single events due to radiation. A drawback is the loss of flexibility for the tuning of the controller. A hybrid controller combining the analogue circuit with a digital part for communication and tuning of the analogue controller is under development to solve this [7].

Characterization of Vibration Sources

The characterization of the influence of direct vibration sources was started with the modal analysis and the measurement of water-cooling-induced vibrations on the type 4 MBQ [8]. The main outcome was the confirmation of the necessity to have a stiff alignment and stabilization support.

RESULTS

Some of the enhancements (feedback + feed forward, analogue controller) mentioned above were implemented on the two test benches. The current performance is shown in Fig. 3. The ratio of the vertical integrated r.m.s. displacement on the ground (*off*) and on top of the stabilization bench (*on*) is an important figure of merit. It increased from between 2 and 3 (with feedback only and a digital controller) to more than 7 during the day. This means that the objective of 1.5 nm at 1 Hz can now be reached with a safety margin from a *high* vibration back ground. The best obtained stability is 0.3 nm at 1 Hz on the single d.o.f. test bench from 1.8 nm on the ground (r.m.s. ratio 6). At 4 Hz the result is 0.2 nm, the requirement for the final focus magnets. The performance of the 2 d.o.f. bench is slightly lower (r.m.s. ratio from 5 to 6) because the controller gain could not be raised as much [4] due to the presence of a resonance below 100 Hz. The best-obtained stability on the tripod was 0.5 nm at 1 Hz.

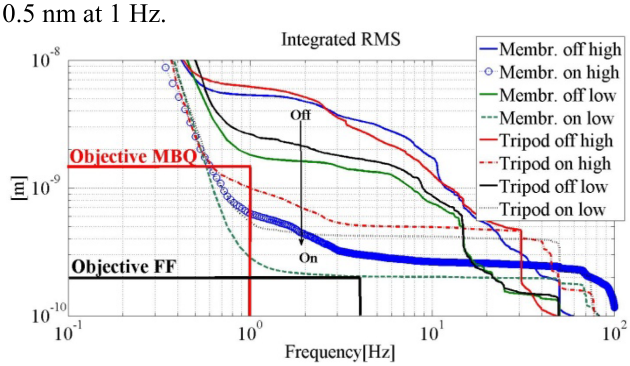

Figure 3: Vertical integrated r.m.s. displacement measured on the two test benches and objectives.

Long-term measurements were made and the stability stayed well below the requirements during 40 hours. The temperature stayed within 1 °C during this test. Tests with larger temperature changes are being prepared.

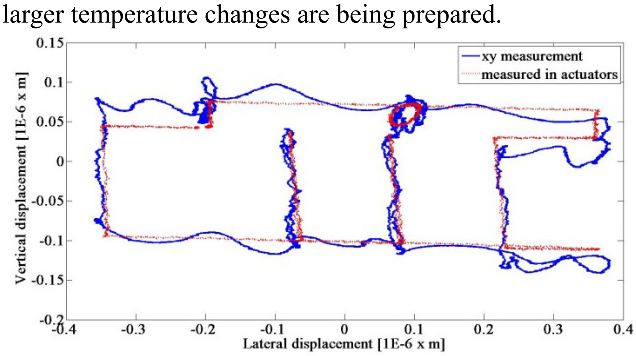

Figure 4: Fast positioning in the vertical and lateral direction measured with actuator elongation and sensors in x (with correction) and y direction.

The nano-positioning was tested without position feedback on the two d.o.f. bench with improved trajectories that avoid high-frequency components (s shaped in time domain). The 0.15 μm high CLIC trajectory was followed in 0.9 s with the 100 kg type 1 dummy magnet on the inclined actuators (Fig. 4). The elongation of the actuators was measured with integrated strain gauges and recalculated to the displacement in vertical (y) and lateral (x) direction (Fig. 4). The displacements were also directly measured in the x and y direction with capacitive gauges and with an interferometer (blue curve Fig. 4). The displacement in the x direction was corrected by a factor 2.7 because of the poor alignment of the capacitive sensor. Stiff sensor supports and tolerances of the design of the x-y guide should ensure better alignment and hence better measurement.

CONCLUSIONS

The technical feasibility of stabilizing the CLIC quadrupole magnets to the required integrated r.m.s. displacement of a nanometre and below at 1 and 4 Hz with a very stiff stabilization support and seismometers was experimentally demonstrated on two test benches. To evolve from an experimental set-up to a technical system in a particle accelerator, five research and development themes were identified: performance increase, accelerator compatibility, cost reduction, overall system integration, and the capability to build in large numbers. The ongoing developments that combine the five themes were mentioned. Two improvements were implemented on the two test benches and resulted in a significant performance increase. An r.m.s. ratio of more than 7 and stabilization to 0.3 nm at 1 Hz was obtained.

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REFERENCES

[1] J. P. Delahaye, "A review of the possible future HEP accelerator projects", ICHEP2010, Paris, 2010.
[2] 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 (95-101), 2011
[3] J. Snuverink, "Status of ground motion mitigation techniques for CLIC", IPAC'11, San Sebastian, Spain, 2011.
[4] S. Janssens *et al.*, "System control for the CLIC main beam quadrupole stabilization and nano-positioning", IPAC'11, San Sebastian, Spain, 2011.
[5] K. Artoos *et al.*, "Stabilization and fine positioning to the nanometre level of the CLIC main beam quadrupoles", IPAC'10, Kyoto, Japan, 2010.
[6] M. Zumberge *et al.*,"An optical seismometer without force feedback", *Bulletin of the seismological society of America* 100 (2010), pp. 598-605.
[7] P. Fernandez Carmona *et al.*, "Study of the hybrid controller electronics for the nano-stabilization of mechanical vibrations of CLIC quadrupoles", Topical Workshop on Electronics for Particle Physics TWEPP, Vienna, Austria, 2011.
[8] K. Artoos *et al.*, "Modal analysis and measurement of water cooling induced vibrations on a CLIC main beam quadrupole prototype", IPAC'11, San Sebastian, Spain, 2011.