Stabilization and Fine Positioning to the Nanometre Level of the CLIC Main Beam Quadrupoles

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STABILIZATION AND FINE POSITIONING TO THE NANOMETRE LEVEL OF THE CLIC MAIN BEAM QUADRUPOLES*

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Abstract

The CLIC main beam quadrupoles need to be stabilized to 1.5 nm integrated R.M.S. displacement at 1 Hz. The choice was made to apply active stabilization with piezoelectric actuators in a rigid support with flexural guides. The advantages of this choice are the robustness against external forces and the possibility to make fast incremental nanometre positioning of the magnet with the same actuators. The study and feasibility demonstration is made in several steps from a single degree of freedom system (s.d.o.f.) with a small mass, a s.d.o.f. with a large mass, leading to the demonstration including the smallest (type 1) and largest (type 4) CLIC main beam quadrupoles. The paper discusses the choices of the position and orientation of the actuators and the tailored rigidities of the flexural hinges in the multi degree of freedom system, and the corresponding MIMO control system. The compatibility with the magnet support and micrometre alignment system is essential. The status of the study and performed tests will be given.

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 energy of 3 TeV [1]. RF power is extracted from a high intensity drive beam and used in structures (ACS) to accelerate the main beam. This extraction scheme is repeated in 20924 two metre long "modules" over the total length of 42 km of the two LINAC. To reach the design luminosity 5.9×10^{34} $cm^{-2}s^{-1}$ of CLIC, the transverse beam dimensions at the interaction point should be 1 nm in vertical and 45 nm in the horizontal direction. For this purpose, about 4000 modules will contain Main Beam Quadrupoles (MBQ). Four different types of MBQ are defined with a length between 420 mm (Type 1; 100 kg) and 1915 mm (Type 4; 400 kg).

Following beam dynamics studies, it was specified [2] that the movements of the MBQ magnetic axis should be limited to the nanometre level in order to minimize the beam size and emittance growths. More precisely, if $\Phi_x(f)$ is the power spectral density of the vertical displacement of the quadrupole, the integrated Root Mean Square (RMS) $\sigma_x(f)$, defined as:

$$\sigma_x = \sqrt{\int_f^\infty \Phi_x(\nu)d\nu} \qquad (1)$$

should not exceed 1.5 nm at f=1 Hz (rounded down to 1 nm). In the same way, the quadrupole lateral stability should be better than 5 nm at 1 Hz.

The frequency of 1 Hz was estimated as the limit between beam based feedback and mechanical stabilization. Below 1 Hz, the quadrupole jitter can be measured by the beam position monitors (BPM) and corrected with corrector dipoles, both attached to the quadrupoles. Some technical issues of implementing the corrector dipoles led to the study of the alternative solution of mechanically fine positioning the MBQ [3] to steer the beam. For this alternative solution a requirement was set to move the MBQ between two beam pulses (50 Hz) with steps up to 50 nm in a range of ±5 µm in lateral and vertical direction with a precision of 2 nm.

VIBRATION SOURCES

Dynamic mechanical disturbances act on the quadrupole magnet via the ground through the support and by forces acting directly on the magnet. Recent ground motion measurements with broadband seismometers [4], [5] confirm that the integrated RMS at 1 Hz on the floor in typical accelerator environments, including in deep tunnels, is by some factors larger than the required 1 nm. Vibration measurements on accelerator components show that the vibrations on the floor are further amplified on the components at the resonant frequencies of their support. Direct forces are transmitted to the MBQ via vacuum bellows, electrical continuity of the beam pipe, power leads with cooling water, ventilation and acoustic pressure.

STABILIZATION STRATEGY

Support Stiffness

Two possible categories of strategies are possible for the active vibration stabilization: soft mounts and stiff mounts [7]. Soft supports benefit from passive attenuation and this strategy was applied in the first CLIC stabilization studies [6] with a commercial stabilization system and provided good isolation at 4 Hz. It did not reach however the 1 nm stability at 1 Hz for the MBQ.

The main drawback of soft supports is that the support is very sensitive to forces acting directly on the quadrupole. This makes the approach less adapted to the micrometric alignment requirements of the MBQ with respect to the beam.

A stiff support (hard mount) is less sensitive to external forces and furthermore opens the possibility to use the actuators for fast positioning of the magnet to the

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nanometre level. This paper discusses the rigid solution that was selected at CERN for the CLIC MBQ stabilization. Both soft and stiff stabilization strategies were applied for accelerator quadrupoles and were compared in [7]. A general observation is the decrease with frequency of the ratio of integrated RMS displacement with and without stabilization. While several systems can indeed reduce vibrations by more than a factor 10 at several Hz, this decreases to only a factor 2 or 3 at 1 Hz.

Design of the Actuating Support

A stiff actuating support that can reach the defined stabilization and "nano-positioning" specifications in lateral and vertical direction should fulfil a certain number of requirements. First, the stability and positioning requirements apply for the integrated magnetic length of the magnet, i.e. that at least six degrees of freedom (d.o.f.) should be addressed. In order to stabilize the MBQ to 1 nm integrated RMS vertical displacement at 1 Hz as expressed in (1), a vertical resolution of about 0.1 nm is needed. For the positioning, the combination of actuators, guidance and sensors should result in movements with a precision and repeatability of 1 nm. Parallel mechanisms with inclined actuators mounted with rotary joints as e.g. Stewart platforms, are stiff structures with high accuracy and load capacity and hence well adapted. Such parallel configurations are more precise than stacked serial configurations where guidance imperfections are difficult to correct. For the mentioned resolution and precision, the rotary joints need however to be replaced by flexural hinges to avoid friction, hysteresis and backlash. A second advantage of using flexural joints is that they give a way to deal with so-called workspace singularities of parallel manipulators [8]. In certain configurations, a structure with rotary joints will win a d.o.f. and the structure can move with all actuators locked. With flexural joints, the structure will maintain certain stiffness at a singularity configuration. The flexural stiffness of the joints introduces however bending forces and shear forces acting on the piezo actuators during operation but even more during assembly due to parts tolerances. Very sturdy, preloaded high load HVPZT piezo actuators with the required resolution were selected for the first testing [9]. A parametric design of the flexural joints was made to find an optimum between angular stiffness, assembly induced stresses and high longitudinal stiffness for overall structure stiffness. The design (fig. 1) allows also different angular stiffness of the hinge for perpendicular directions.

The design of the architecture of the parallel structure, i.e. number, position and orientation of the actuator legs, is a trade-off between the number of addressed d.o.f., the combined stiffness of the actuating structure and quadrupole, the required resolution, available space and the cost of the actuating support. As the tolerances for stabilization and nano-positioning are defined for the plane transverse to the beam, the longitudinal d.o.f. can be blocked and the architecture is evolving to a design with inclined actuator pairs in the same plane. The "roll" or rotation around the longitudinal axis is not suitable and should hence also be blocked by the guidance.

Figure 1: Actuator with two prototype hinges.

Finally, it is essential that the micrometric alignment system under the stabilization and the MBQ itself are as stiff as possible. The alignment system under the MBQ will therefore be based on eccentric cams positioned at the "Airy" points of the magnet to minimise sag. The stabilization actuator pairs should be positioned above the cams with a stiff intermediate structure.

Sensors and Control System

Tri-axial broadband seismometers [10] are used to measure the velocity before and after the stabilization support. They have been characterised and have the required resolution and frequency range for the stabilization. Initially, a seismometer is placed on the magnet for each actuator pair. For the nano-positioning, displacement transducers based on strain gauges or capacitive gauges are integrated in the actuators.

The real time controller is for the moment based on a NI PXI controller with 6289 acquisition card with 18 bit input and 16 bit output resolution. This hardware has been sufficient to start the study but custom built electronics with better resolution, lower ADC and DAC noise level and other improvements are studied.

The controller design is well advanced and the same controller can be used at the moment on each actuator pair as described in [11].

Compatibility with the Accelerator Environment

The actuating support should be compatible with the accelerator environment, i.e. radiation hard and insensitive to magnetic fields. This subject will be addressed later and is not discussed in this paper.

STEPS TOWARDS FEASIBILITY

Several R&D steps were defined for the stabilization and nano-positioning of the MBQ. At first, a single d.o.f. system with a small weight was built. The small mass of 2.5 kg (a seismometer) is supported vertically by a piezo actuator. The vertical movement is guided by a double flexural membrane. The ratio of the mass and stiffness of the actuator with guidance is scaled to the equivalent mass per leg and the stiffness of the actuator selected for the parallel structure. The vibrations at both sides of the actuator are measured by two seismometers. A stabilization of 1 nm integrated RMS at 1 Hz was experimentally demonstrated with this system (figure 2).

Although the best result was obtained with small ground excitation during the night, tests during the day with a higher background showed an integrated RMS decrease of more than a factor 3. The experimentally determined transfer function corresponds well with the numeric model. The black dotted line of the seismometer noise shows that the result is close to what can be achieved with this seismometer.

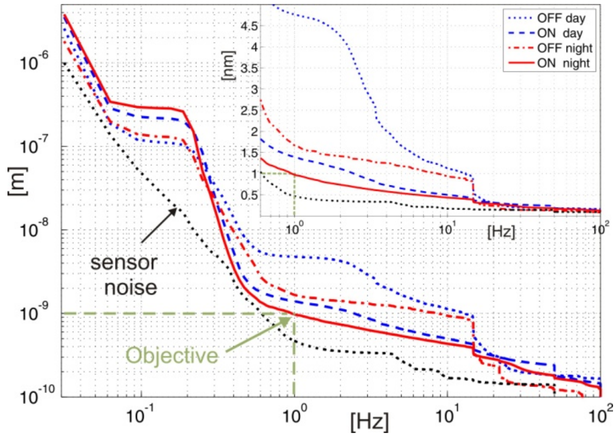

Figure 2: Measured vertical integrated RMS displacement of a small mass in a single degree of freedom system with and without stabilization.

The nano-positioning was experimentally demonstrated on the same s.d.o.f. system with small mass (figure 3) by sending a square wave at 50 Hz with an amplitude of 10 nm. The result was measured by a capacitive gauge and shows how the actuator even reproduced the imperfections of the generated square wave.

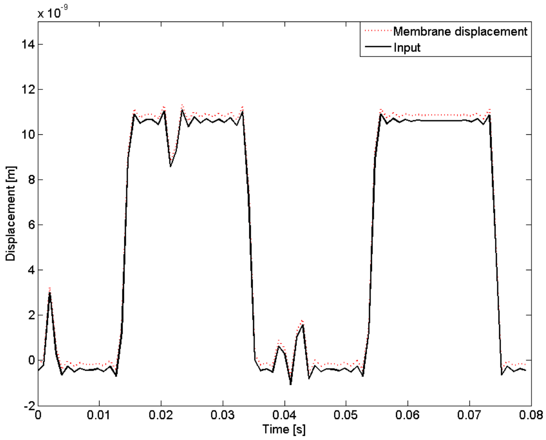

Figure 3: Measured "Nano-positioning "at 50 Hz.

For the next R&D step, a single d.o.f. system was built with the mass of a type 1 quadrupole (100 kg) on three supports ("tripod") of which one is a vertical actuator. First tests show very promising results and tests with a low background level will be performed soon.

For the next phase, a system with two and more d.o.f. will be constructed by gradually adding inclined actuators mounted on flexural hinges in order to validate and compare different architectures for the parallel manipulator.

The final R&D step is a full feasibility demonstration on a 2 m long type 4 MBQ prototype before the end of 2010.

CONCLUSION

Two different options to stabilize quadrupole magnets with soft or stiff supports have been compared. For both options, former studies have shown a decrease with frequency of obtained ratio of integrated RMS displacement. The choice was made for a stiff actuating support, robust against external forces and hence compatible with the micrometric alignment. This choice also opens the option of fast positioning with nanometre resolution for beam based feedback. A parallel structure with inclined actuators on flexural hinges fulfils best the listed requirements for the actuating support. Selection of the degrees of freedom directed the study to inclined actuator pairs that are in the same plane with decentralised controllers with a broadband seismometer as sensor. Several R&D steps towards the demonstration on a type 4 CLIC MBQ prototype were decided. With the first step, a single degree of freedom system with scaled mass to stiffness ratio, the objectives were experimentally and numerically obtained, demonstrating the technical feasibility for both stabilization and nano-positioning.

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