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STUDY OF THE STABILIZATION TO THE NANOMETER LEVEL OF MECHANICAL VIBRATIONS OF THE CLIC MAIN BEAM QUADRUPOLES

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Abstract

To reach the design luminosity of CLIC, the movements of the quadrupoles should be limited to the nanometre level in order to limit the beam size and emittance growth. Below 1 Hz, the movements of the main beam quadrupoles will be corrected by a beam-based feedback. But above 1 Hz, the quadrupoles should be mechanically stabilized.

A collaboration effort is ongoing between several institutes to study the feasibility of the “nano-stabilization” of the CLIC quadrupoles. The study described in this paper covers the characterization of independent measuring techniques including optical methods to detect nanometre sized displacements and analyze the vibrations. Actuators and feedback algorithms for sub-nanometre movements of magnets with a mass of more than 400 kg are being developed and tested. Input is given to the design of the quadrupole magnets, the supports and alignment system in order to limit the amplification of the vibration sources at resonant frequencies. A full scale mock-up integrating all these features is presently under design. Finally, a series of experiments in accelerator environments should demonstrate the feasibility of the nanometre stabilization.

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 at an energy of 0.5-3TeV. The total length of 13 km of the 0.5 TeV linear collider can be extended to 48.3 km for the 3 TeV collider. The RF power to accelerate the main beam will be extracted from a low energy, high intensity drive beam, running parallel to the main beam. Most of the length of the two parallel LINAC is composed of repeated 2 metre long “modules” with Accelerating Structures (ACS) in the main beam that are connected through waveguides to the Power Extraction and Transfer Structures (PETS) in the drive beam LINAC [1]. To reach the required luminosity of 2.3-5.9.10^{34}cm^{-2}s^{-1} at the interaction point, the transverse beam dimensions at the interaction point should be 1 nm in vertical and 40 nm in the horizontal direction. For this, the main beam should be kept small and to this effect about 4000 modules will contain a quadrupole magnet. Four different types of quadrupole magnets are defined between 420 mm and 1915 mm length. The main and drive LINAC are mounted on separate supports. The main beam quadrupoles are supported independently from the ACS girders by micro-movers on a separate support. The mechanical connection of the beam vacuum chamber between ACS and MBQ hence requires flexibility.

Both ACS and MBQ need to be aligned to the micron level to reduce emittance growth. After an initial pre-alignment, ACS and MBQ will be aligned with respect to the beam. This fine alignment to the micrometre of the MBQ is based on the reading from beam position monitors (BPM) that are fixed to the MBQ [2].

After alignment, the mechanical jitter of the quadrupoles should be stabilized to 1 nm vertical and 5 nm lateral integrated root mean squared (R.M.S.) displacements above 1 Hz [2][3].

Below 1 Hz, the jitter of the quadrupoles can be measured by the BPM. The beam based feedback [2] could be made with corrector dipole magnets. Another solution currently under study is to move a subset of the MBQ with mechanical movers by steps of about 5 nm. Piezo actuators are at the moment the most used technology that can make this possible. The limit of 1 Hz for such beam based feedback depends on the precision and band width of the components and could vary.

To study the stabilization, an integrated approach of the whole control system needs to be made. The structure, its actuators and sensors will be submitted to external disturbances that are studied. The behavior of the quadrupole magnets on the support and alignment system is characterized. The combined understanding of the above components will influence the choice of the control feedback law. Finally, the performance of such a control system should be measured by an independent method. To demonstrate the control system, a mock-up of a CLIC main beam quadrupole on its support and alignment system will be built. This mock-up includes a prototype magnet of 1915 mm length with a water cooled coil.

AN INTEGRATED APPROACH

Disturbances

Dynamic mechanical disturbances acting on the quadrupole magnets are composed of ground motion and forces acting directly on the quadrupole. Recent ground motion measurements are described in [3] and the integrated R.M.S. ground motion at 1 Hz is of the order of some nanometres. The so called micro-seismic peak at 0.1 to 0.2 Hz had an amplitude of 0.1 to 1 micrometre and this ground motion is coherent over a length of several kilometres. The ground motion is transmitted through the support, the alignment system and the stabilization system to the quadrupole. Forces acting directly on the quadrupole will be transmitted through the beam pipe, power leads with cooling water pipes and by acoustic pressure [4], not negligible for this level of required stability.

Transmittance

For a first approach, a single degree of freedom (d.o.f.) oscillator (Fig.1) representing one sixth of the quadrupole mass (m=393/6 kg) mounted on a single vertical support is modeled. The alignment is treated as very rigid compared to the stabilization stage.

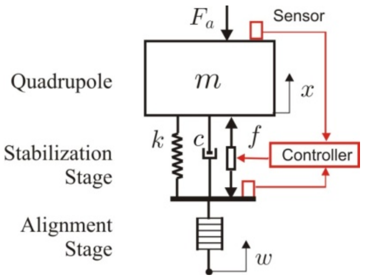

Figure 1: Model of a stabilized system with a single d.o.f.

Figures 2 and 3 show respectively the Power Spectral Density of the ground excitation considered for the study and the integrated R.M.S. displacement. The level of the seismometer noise is also shown in the same figures. That noise level was however not yet taken into account in the results below.

The vertical displacement x of the mass resulting from the ground motion w can be written as:

$$\Phi_x(f) = \left|T_{wx}(f)\right|^2 \Phi_w(f) \tag{1}$$

$T_{wx}(f)$ is the transmittance of ground motion to the mass m.

The objective of the stabilization is to have an integrated R.M.S. displacement at 1 Hz smaller than 1 nm:

$$\sigma_x(1) = \sqrt{\int_1^\infty \Phi_x(f)df} \le 1\,nm \tag{2}$$

For the results below, the rigidity of the support in vertical direction was chosen as 10^5 N/m to have a support resonant frequency around 6 Hz [5]. Five percent damping was chosen (c=256 Ns/m). Above the resonant frequency, ground motions will be attenuated. Below that frequency, the passive suspension cannot provide any isolation and the integrated R.M.S. at 1 Hz is higher than the ground motion. A support with a lower stiffness could seem more advantageous but a low stiffness support would be very sensitive to small forces F_a directly acting on the MBQ and is hardly compatible with the stringent alignment requirements. The chosen rigidity is not directly compatible with the stiffness of piezo actuators.

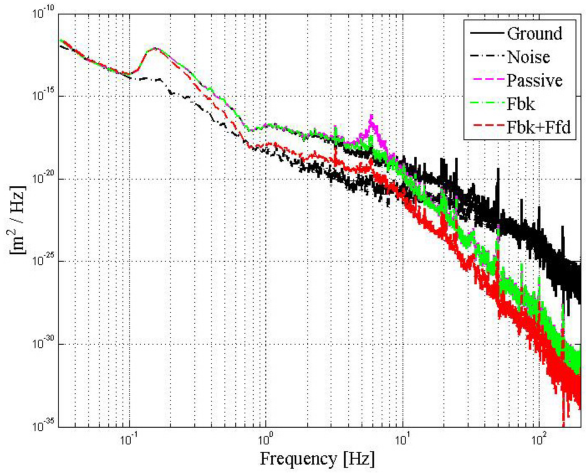

Figure 2: Power spectral density of the ground motion and magnet motion with passive or active damping.

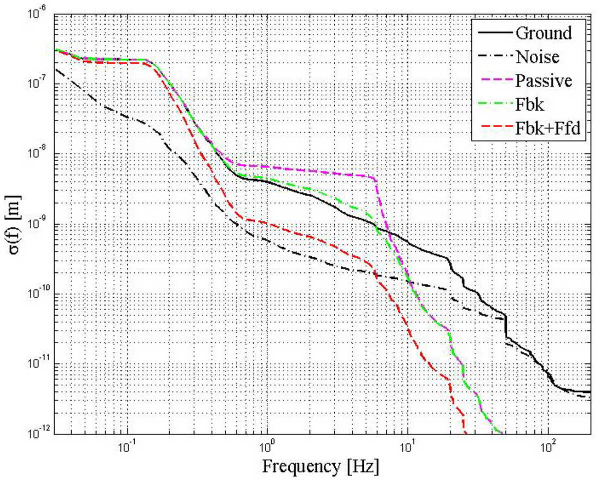

Figure 3: Integrated R.M.S. vertical displacement.

The first control strategy considered for active stabilization is a *sky-hook feedback* control [6] [7]. Results shown (Fbk) in figure 2 and figure 3 have been obtained using a gain g=5*c. While capable of removing the overshoot at the resonance, it does not provide a sufficient reduction of the integrated R.M.S. at low frequencies. To improve these performances, a second strategy of *feedforward*, has been implemented. Taking advantage of the ground excitation measurement, it consists in applying a force counteracting the ground excitation. Results (Fbk + Ffd) are shown using a compensation of 80% and sensors with a cut-off frequency of 0.1 Hz. The results indicate that the combination of both feedback and feedforward could stabilize theoretically the quadrupole at the desired level.

In parallel, a prototype was built to test the combination of active and passive isolation. It is composed of four passive feet supporting a mass. In addition, a triangular plate is controlled by three piezo electric actuators (CEDRAT^{TM}).

Finite Element (FE) simulations were performed in order to verify the Eigen frequencies of the magnet yoke. The first resonant frequency corresponding to the first bending mode is situated at 249 Hz. Furthermore, different support positions were simulated in order to minimize the sag due to deformation on self weight. The simulations showed e.g. for a set-up with four actuators that a minimum sag of 1 µm can be reached by supporting the magnet at two places at a distance of L/4.7. In an improved model, this 3D FE model of the quadrupole mounted on active supports will be included. Correlated ground excitation, sensor noise and positioning capabilities will also be taken into account. Finally, combinations of the above mentioned strategies with *active mass dampers* and *anti-resonant vibration isolators* are also under study to reduce the control budget.

Actuators and Transducers

Actuators based on PZT piezo ceramics, with a precision of 0.1 nm for a range of several micrometres are a well established technology and are commercially available but for loads at least 10 times smaller than required for the MBQ stabilization. The actuators are built with flexural guides to ensure precise movements. Such flexural guides need to be designed for the CLIC quadrupole actuators in order to obtain the required support rigidity. To avoid depolarization or damage to the piezo the guides should also support part of the quadrupole weight and avoid not allowed side loads on the piezo.

Because of the non linearity of the piezo material, hysteresis and creep, the precision and resolution of the actuator will depend mainly on the measured relative deformation of the actuator by an integrated transducer such as a capacitive gauge.

Currently, the only available devices to measure absolute displacements with nanometre resolution in a frequency band down to 1 Hz and below are low noise broadband seismometers. The calibration factor for nominal signals of the seismometers is used for signals close to the resolution. A reference bench for accelerometers and seismometers was constructed based on a PI^{TM} piezo actuator with 0.1 nm precision in a 25 µm range. The accelerometers and seismometers are cross checked with a Polytec^{TM} vibrometer and a capacitive displacement transducer. Preliminary results have shown the narrowing of the band width for low level signals for the seismic accelerometers.

Costly commercially available interferometers can measure picometre displacements in the required bandwidth but only as relative displacements. The MONALISA project uses more cost effective equipment to develop a system with nanometre resolution to measure relative motions between accelerator components [8]. Such optical measurements should constitute an independent way to demonstrate the performance of the MBQ stabilization.

The actuators and transducers and any components near the quadrupole to be stabilized should finally be evaluated in a real accelerator environment to estimate the influence of radiation, magnetic fields and other possible factors on the performance and life time of the components.

CONCLUSIONS

The stabilization to the nanometre level of a 2 m long CLIC main beam quadrupole should be demonstrated on a full scale quadrupole mockup, currently under design. The characterization of the disturbances and the components of the stabilized system are carried out. Reference benches are built to calibrate broadband seismometers and seismic accelerometers for low level vibrations and they indicated a change of band width for low level signals. Different control strategies are tested in a model that is gradually improved upon availability of characterization results. The combination of passive damping, feedback and feedforward allow in the model to reach an integrated R.M.S. vertical displacement of 1 nm in vertical direction. This model should however still be improved and should e.g. include the effect of instrumental noise. The physical implementation of the chosen parameters should be verified. The choices that yield the best results in the model will be applied on the full scale quadrupole mockup. Independent measuring techniques should then measure the obtained performance of the stabilization system.

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