RECENT IMPROVEMENTS OF THE ORBIT CONTROLLER AND GROUND MOTION MITIGATION TECHNIQUES FOR CLIC

J. Pfingstner, Doctoral School TUG, Graz, Austria, and CERN, Geneva, Switzerland
J. Snuverink*, A. Latina, D. Schulte, CERN, Geneva, Switzerland

Abstract

The Compact Linear Collider (CLIC) has strong stability requirements on the position of the beam. In particular, the beam position will be sensitive to ground motion. A number of mitigation techniques have been proposed - quadrupole stabilisation and positioning, final doublet stabilisation as well as beam based orbit and interaction point feedback. Integrated studies of the impact of ground motion on the CLIC Main Linac and Beam Delivery System that model the latest hardware designs have been performed. Furthermore, additional imperfections have been introduced and the robustness of this system is discussed in detail.

INTRODUCTION

CLIC [1] requires a small vertical emittance and beam size in the nanometer range to achieve its nominal luminosity. The small emittance is affected by static and dynamic imperfections. The dominant luminosity degradation by dynamic imperfections is caused by ground motion (GM). The luminosity is reduced by two effects: a beam-beam offset at the interaction point (IP) mainly due to the movement of the girders close to the IP and an emittance growth (filamentation) along the beamline due to offsets of the main linac (ML) quadrupoles. GM is site-dependent and for several sites measurements have been performed to fit model parameters. Here only model B10 is used, which is based on model B [2] with an amplified param. to match measurements from LAPP (Annecy) and the CMS hall.

To counter the impact of the GM several mitigation techniques are deployed in CLIC: each quadrupole will be equipped by an active stabilisation system [3], [4], the sensitive final doublet magnets will be put an a large mass-spring system to stabilise these magnets [5], a dedicated orbit controller has been designed [6] and additionally an IP feedback system (IP-FB) will be deployed [7], [8]. An overview of the simulations integrating these mitigation techniques has been given in [9]. These simulations are performed tracking the beams with PLACET [10] through the ML and Beam Delivery System (BDS) and GUINEA-PIG [11] for beam-beam interactions.

This paper will give an update of the status of these simulations. The luminosity performance for new frequency responses provided by the CLIC stabilisation group are evaluated. Additional imperfections are introduced in the simulations and the robustness of the orbit controller in particular is investigated.

* jochem.snuverink@cern.ch

STABILISATION FREQUENCY RESPONSE

The stabilisation frequency responses that were previously used have been improved by the CLIC stabilisation group. In this section we show the updated simulation results with these new frequency responses. Measurements were done on a realistic setup of the ML quadrupole with water cooling and magnetic field switched on [4]. In addition, their targeted future design has been reviewed. The old and new frequency responses are shown in Fig. 1. Note that for the measured frequency responses a fit of the data to the theoretical model is shown and deployed in the simulations. It can be seen that the new measured frequency response has improved compared to the previous one, especially in the important regions above a few Hz, while in addition the peak near the micro-seismic peak has been largely reduced. This results in a luminosity loss reduction from 13% to about 6%. For the targeted future design the new and the old version show a similar very low luminosity loss of 1%. For the simulations the GM model B10 and the nominal BPM resolution of 100 nm in the ML and 50 nm in the BDS was used.

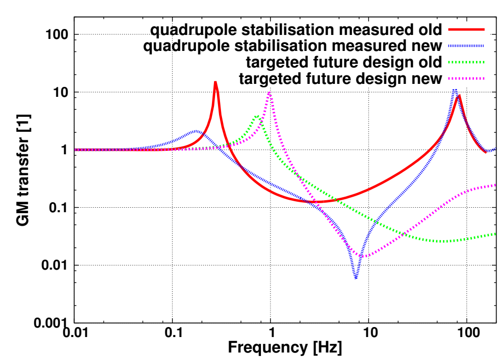

Figure 1: Updated frequency responses of the stab. system.

IMPERFECTIONS AND ROBUSTNESS

In this section, the effect of different static and dynamic imperfections on the performance and robustness of the orbit controller of CLIC is investigated. The most important imperfections are energy errors of the beam, corrector and BPM breakdowns, imperfections of the quadrupole stabilisation system (noise, positioning errors) and BPM scaling errors. Note that the important imperfection of BPM measurement noise has already been covered in [9] and the results are not restated here. The impact of the other tested imperfections is minor and also summarised below.

Energy Errors

Energy errors of the beam can occur due to an initial energy jitter at the entrance of the ML or due to imperfections in the gradients and/or phases of the accelerating structures. The resulting deviation of the beam energy from its nominal value causes large transversal beam offsets especially in the dispersive collimation area of the BDS. These offsets are measured by the BPMs used by the orbit controller that calculates corrections to steer the beam back onto its nominal orbit. As the energy error is assumed to be a white stochastic process, the orbit controller steers the beam incorrectly in the next time step and worsens thereby the luminosity performance significantly as can be seen in Fig. 2 (blue curve).

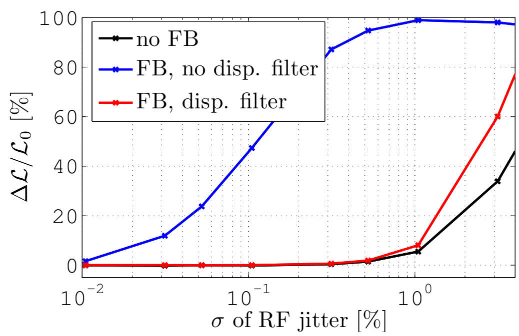

Figure 2: Relative luminosity loss $\Delta\mathcal{L}/\mathcal{L}_0$ due to white, Gaussian jitter of the acceleration gradients of each decelerator with a relative standard deviation of σ.

To counter this problem, the dispersive beam orbits caused by the energy deviations are filtered from the BPM measurements $\boldsymbol{x}[k]$, where k is the time step index. Then the corrected measurements $\tilde{\boldsymbol{x}}[k]$ are used by the orbit controller for the orbit correction. This filtering is given by

$$\tilde{\boldsymbol{x}}[k] = \boldsymbol{x}[k] - f_D[k]\boldsymbol{x}_D \quad \text{with} \tag{1}$$

$$f_D[k] = \frac{\boldsymbol{x}[k]^T \boldsymbol{x}_D}{\boldsymbol{x}_D^T \boldsymbol{x}_D}, \tag{2}$$

where $\boldsymbol{x}_D$ is the dispersive orbit that can be obtained in practice via averaged measurements. With the help of this technique, the luminosity loss due to the coupling of the orbit controller action to energy error effects is reduced significantly. The additional luminosity loss due to the orbit controller action (difference between the red and black curve in Fig. 2) is below 0.5% up to an acceleration gradient error of 0.5%. The same tolerances are valid for a static acceleration gradient error. The additional luminosity loss with respect to GM due to the dispersive orbit filtering is only in the order of 0.1% and hence negligible. It should be mentioned that the factor $f_D[k]$ can potentially also be used to measure the beam energy of each beam train. Due to the filtering of the dispersive orbit also the initial energy jitter has a negligible impact on the luminosity loss.

Corrector and BPM Breakdowns

To analyse the robustness of the orbit controller algorithm, some breakdown studies of individual components have been performed. The breakdowns of the stabilisation system (e.g. a broken GM sensor), of the correctors and the BPMs have been modelled and evaluated in the integrated simulations. This was done by applying GM model B10 and comparing the luminosity results with and without the malfunctioning of the individual component. Note that the orbit controller was not updated and acted as though the component was still working. The impact of individual corrector failures is always below 0.2%. A stabilisation failure has a more severe impact, especially for some quadrupoles in the last part of the BDS, see Fig. 3. As has been mentioned, the last two final doublet quadrupoles QF1 and QD0 have a dedicated stabilisation system and are therefore not shown. Most of the BPM breakdowns have hardly any impact, however some of them are very severe, because the orbit controller relies heavily on these BPMs located at the end of the BDS and will missteer if the BPM reading is wrong. However, it should be mentioned that if a BPM breakdown is known, then the orbit controller can be easily adapted and this will result in a much smaller luminosity loss, which is a topic for further study. In any case, the crucial components should be very robust and/or redundancy has to be foreseen. For the ML the impact of component breakdowns is more relaxed and many multiple breakdowns can be accustomed for.

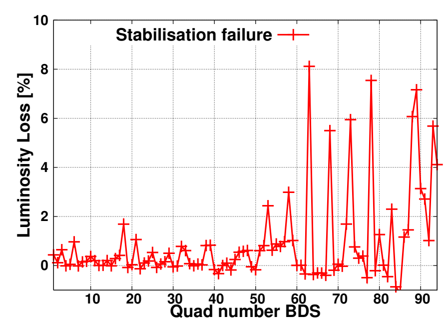

Figure 3: Relative luminosity loss due to a failure of the stabilisation system for an individual quadrupole in the BDS.

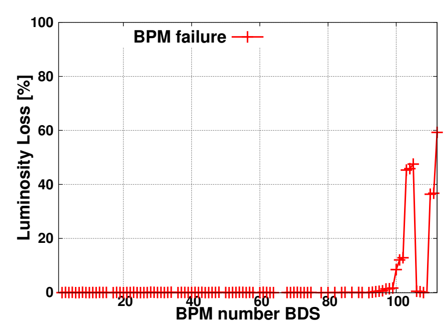

Figure 4: Relative luminosity loss due to a failure of the stabilisation system for an individual BPM in the BDS.

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Quadrupole Stabilisation Imperfections

The quadrupole stabilisation system is not only used to stabilise the quadrupoles with respect to the GM, but also as actuators for the orbit controller. Due to hardware imperfections the actually applied corrections differ from the corrections calculated by the orbit controller. To evaluate the impact of this effect, simulations were performed in which the positioning error is modelled as white Gaussian noise. For the evaluation of the luminosity loss, the action of the orbit controller has to be included in the simulations, which corresponds to the dashed lines in Fig. 5. It can be observed that the tolerances for the ML are more relaxed than the one for the BDS. The two last quadrupoles QF1 and QD0 of the final focus are not used by the orbit controller, since they are very sensitive to positioning errors as can be seen from the green curve in Fig. 5 (only QF1 included). For a maximal luminosity loss of 0.5% the positioning error should not exceed a standard deviation of 0.25 nm.

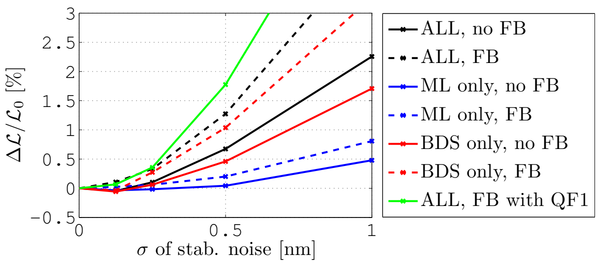

Figure 5: Relative luminosity loss $\Delta\mathcal{L}/\mathcal{L}_0$ due to white, Gaussian jitter of the corrector actuations in the ML, the BDS and both with a standard deviation σ.

The solid curves in Fig. 5, which include no feedback action can be used to estimate the effect of the sensor noise of the quadrupole stabilisation system on the luminosity loss. In this case the orbit controller action is included in a different manner. The power spectral density of the noise curve of the stabilisation sensor is folded with the squared magnitude of the noise frequency response of the stabilisation system (provided by the stabilisation group) and the sensitivity function of the orbit controller. The integration of this spectrum over all frequencies delivers an estimate of the expected standard deviation of the quadrupole motion due to the stabilisation sensor noise including the orbit controller of 0.2 to 0.4 nm. Comparing this value with the black solid curve in Fig. 5 gives an estimated luminosity loss due to the sensor noise of 0.1 to 0.5%, which is acceptable.

Other Imperfections

Apart from the already mentioned imperfections, several other effects have been investigated. The effect of the measurement noise of the post-collision line BPM used by the IP-FB has been evaluated for different variants of the IP-FB. For all tested IP-FB algorithms the luminosity loss stays well below 0.5% as long as the BPM resolution is below 10 μm, which is well above the specification of about 1 to 3 μm. On the other hand, the scaling errors of BPMs and correctors are restricted by the orbit controller action. For a relative luminosity loss of 0.5% one can allow for a corrector scaling error up to 30%, while the BPM scaling error tolerance for the same luminosity loss is as small as 1%. The tolerances for static and jitter-like quadrupole strength errors are known to be very tight due to the lattice design. The action of the orbit controller does not worsen these tolerances in a notable way. Also the tolerances for the incoming beam jitter at the entrance of the ML are hardly altered by the orbit controller operation.

CONCLUSIONS

In this paper, improvements of the integrated GM simulations and robustness studies for the CLIC orbit controller have been presented. More realistic GM frequency responses of the stabilisation system, provided by the CLIC stabilisation group, have been evaluated with respect to their luminosity performance. An improved frequency response based on measurements resulted in a reduction of the luminosity loss from 13% to 6%.

Furthermore the robustness of the orbit controller due to many different imperfections has been studied and no critical problems have been encountered. A potential problem due to beam energy variations has been identified and resolved. Breakdown studies of BPMs, correctors and the stabilisation systems revealed sensitivity to malfunctions of certain stabilisation systems and BPMs in the BDS. An especially robust design for these systems is advisable and possibly also redundancy has to be foreseen. For the positioning capability of the stabilisation system, a tolerance of 0.25 nm has been identified. Also the scaling error of the BPMs will have to be about 1%. All other tested imperfections have a negligible effect.

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