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Control strategies for the final focus of future linear particle collider

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ABSTRACT

This paper presents a simple model of the final focus of a linear particle collider. Adopting an integrated approach, several control strategies are tested to stabilize the mechanical parts, and control the beam. One of the key features of the model is that it has been updated using vibration spectra measured in the CMS experimental area of the LHC. Using this model, it has been possible to estimate objectively the performances of a final focus system, compare and propose new solutions to improve the mechanical design.

1. Introduction

During the last 50 years, the energy and size of the particle accelerators have been multiplied by five orders of magnitude. In the future, it is foreseen to continue to explore new physics with linear particle colliders. Two projects are currently under study: the International Linear Collider (ILC) [1] and the Compact Linear Collider (CLIC) [2]. In CLIC, electrons and positrons will be accelerated in two linear accelerators to collide at the interaction point with an energy of 0.5–3 TeV [3]. To acquire such a high energy, the total length of the machine will be 48 km, and constituted of a very large number (more than 20 000) of identical modules, the function of which is to accelerate and focus the beam of particles, towards the final section where the collision takes place. Hand in hand with the energy, the so-called *luminosity* of particle colliders (proportional to the number of collisions per second and unit area) has also followed the same historical trend, requiring to produce increasingly small, dense and stable beams [4]. In linear accelerators, the beam cross section is extremely flat, with a vertical size typically 100 times smaller than the horizontal size. Considering only the vertical direction (because it is the most critical), let us first define Δy as the average vertical distance between the two colliding beams at the Interaction Point (IP), such as

$$\Delta y = y^+ - y^- \tag{1}$$

where y^+ and y^- are the positions of the two beams at the IP [5,6]. It can be shown that the dependency of the luminosity, L, with the offset Δy is approximately given by [7]

$$L \approx L_0 e^{-\Delta y^2/16\sigma_y^2} \tag{2}$$

where σ_y is the vertical beam size at the IP and L_0 is the nominal luminosity (i.e. the luminosity in a perfect machine). For both ILC and CLIC, the nominal luminosity is $L_0 \approx 2 \times 10^{34}$ cm^{-2} s^{-1}. Eq. (2) shows that to mitigate the luminosity losses, the smaller the size of the beam, the more stable the *final focus* of the machine, just before the IP. For ILC, $\sigma_y = 5.7$ nm (and 640 nm in the horizontal direction). However, the permissible beam jitter is still about 50 nm [8,9], because it considers the possibility to recover the luminosity with an intra-pulse feedback [10]. As a comparison, for CLIC, $\sigma_y = 1$ nm (and 40 nm in the horizontal direction). Additionally, as the bunch separation is only 0.5 ns (instead of 176 ns for ILC), the intra-pulse feedback is less effective. As a consequence, the permissible beam jitter is as low as 0.15 nm at 4 Hz.

During the last two decades, several strategies to control the final focus have been investigated, and studied [5,7,11–15]. However, the performances of these strategies have not yet been objectively compared with a simple model, using realistic disturbances. In this paper, such a model is proposed, and updated using vibration spectra measured in the CMS experimental area of the LHC, which was identified as an environment representative of the final focus of a future linear particle collider. In the next

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section, we provide general considerations on final focus systems and on the opto-mechatronic approach followed in this study. Section 3 presents the simplified model of the final focus. In Sections 4–9, various control strategies are systematically tested and discussed. Section 10 summarizes the results, draws the conclusions and discusses the future work.

2. Final focus

The *final focus* of a particle collider is the part of the machine constituted of strong electromagnets, dedicated to focus the beams of particles to increase the density of the collisions. Each lattice of electromagnets ends with a pair of focusing (QF1) and defocusing (QD0) quadrupoles, which are often referred to as the *final doublet*. As there is one final doublet for each beam before the IP, the configuration of the magnet lattice near IP is typically QF1–QD0 IP QD0–QF1 (in principle, sextupoles are also added to reduce the chromaticity introduced by the quadrupoles). The capacity of the quadrupoles to produce a high luminosity depends on two factors: they must be extremely stable to avoid the jitters and sufficiently close to each other to maintain small beam cross-sections. The first one requires innovative control strategies and will be extensively discussed in this paper. The second one is essentially the design parameter L^*, which is the distance between QD0 and the IP. As the size of the detector cannot be down-scaled, machine designers have two possibilities: either placing the final doublets at the end of the tunnel floor (i.e. large L^*, but a stable support) [16], or trying to insert them inside the detector (i.e. small L^*, but unstable floor). In this paper, only the latter case is considered, as the former one is much easier to control. For this latter case, several solutions have been proposed. For ILC, two configurations are currently studied in parallel: the Silicon Detector (SiD) [17] and the International Large Detector (ILD) [18]. In SiD, the last quadrupole (QD0) is supported by the endcap doors of the detector. In ILD, QD0 is supported by a huge beam, itself fixed at one end to a big pillar. Both detectors have been adapted for CLIC [19] and have been given the names CLIC-ILD and CLIC-SiD. The QD0 support structure will consist of a huge beam directly cantilevered to the tunnel wall. A possible simplified layout of this final focus is illustrated in Fig. 1.

To reach the required luminosity, two types of controllers are combined. The first one acts on the structure. Using vibration sensors (geophones, capacitive sensors, lasers), it tries to stabilize the quadrupoles. It works continuously. The second one acts on the particle beams. Using the measurement of the position of each pulse, it modifies the magnetic field applied to the next pulse with dipole correctors (kickers) to steer the beam and maintain a high collision luminosity. As there is only one pulse every 20 ms, it works at 50 Hz. A general block representation of the controllers is shown in Fig. 2. These two subsystems can be studied separately. However, in order to improve the performances of the design, the information contained in one subsystem can be used in the other subsystem, and conversely. For example, the beam control strategy can rely on the measurement from the geophone measuring the vibrations of the quadrupoles (feed forward in Fig. 2), or the information from the beam position monitor could be used to change the position of the quadrupole

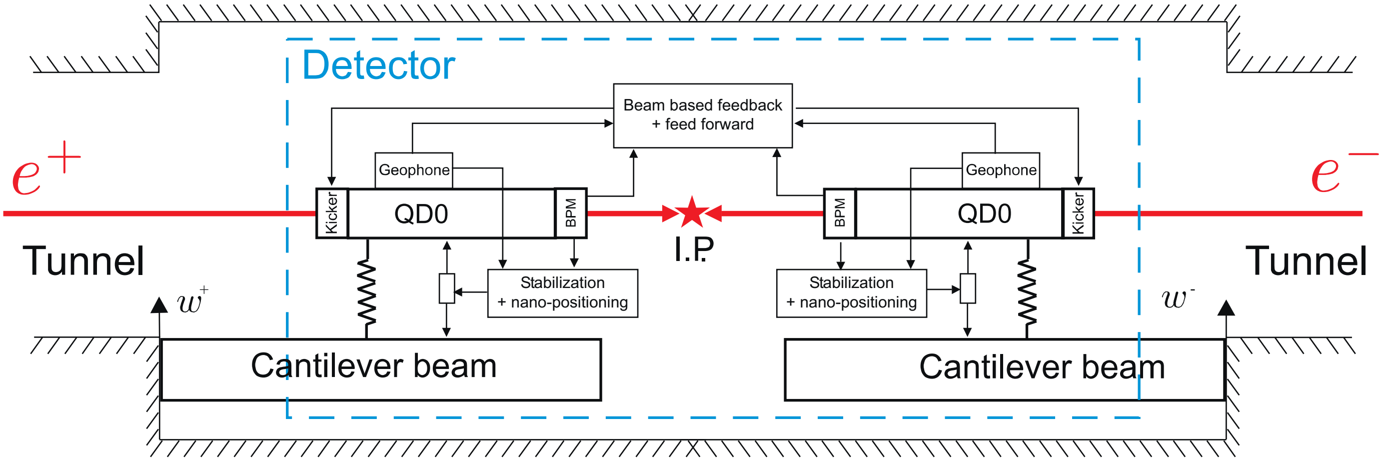

Fig. 1. Simplified layout of the final focus of a linear particle collider.

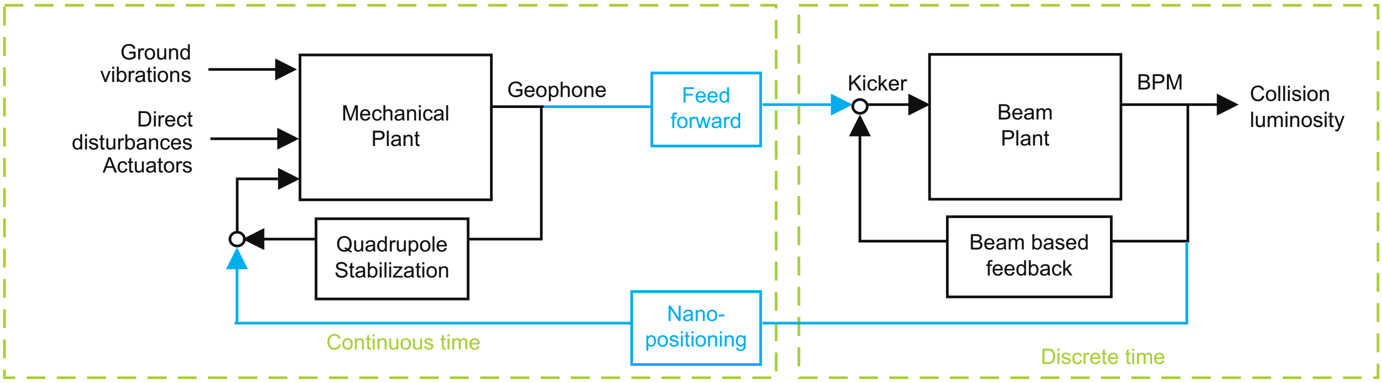

Fig. 2. Block diagram of the final focus hybrid system.