THE BEAM-BASED INTRA-TRAIN FEEDBACK SYSTEM OF CLIC*

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Abstract

The design luminosity of the future linear colliders requires transverse beam size at the nanometre level at the interaction point (IP), as well as stabilisation of the beams at the sub-nanometre level. Different imperfections, for example ground motion, can generate relative vertical offsets of the two colliding beams at the IP which significantly degrade the luminosity. In principle, a beam-based intra-train feedback system in the interaction region can correct the relative beam-beam offset and steer the beams back into collision. In addition, this feedback system might considerably help to relax the required tight stability tolerances of the final doublet magnets. For CLIC, with bunch separations of 0.5 ns and train length of 156 ns intra-train feedback corrections are specially challenging. In this paper we describe the conceptual design and simulation of an intra-train feedback system for CLIC. Results of luminosity performance simulation are presented and discussed.

INTRODUCTION

In the future linear colliders several imperfections of the machine can generate relative displacement of the colliding beams at the IP and in consequence degrade the luminosity. In principle, this displacement can be counteracted by using fast intra-train FB systems near the IP.

For the Compact Linear Collider (CLIC) [1], which is a so called "warm-RF" based linear collider with a novel double beam acceleration scheme and normal conducting radiofrequency cavities, intra-train FB corrections at the IP are specially challenging due to its particular beam time structure with extremely small nominal bunch separation of 0.5 ns. Some relevant CLIC design beam parameters are shown in Table 1.

In this paper, first we describe and discuss the general characteristics of a beam-based ultra fast intra-train FB system for the CLIC IP, and by means of computer simulations we study the CLIC luminosity performance with this feedback system. Finally, we pay special attention to how a IP beam-based intra-train FB system can help to relax the tight vibration tolerance of the final doublet (FD) quadrupole.

THE CLIC IP INTRA-TRAIN FEEDBACK SYSTEM

The key components of the system are a beam position monitor (BPM) for registering the beam orbit of the outcoming beam, and a kicker for applying the necessary position correction to the opposite incoming beam.

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Table 1: CLIC Parameters for 3 TeV Centre-of-mass Energy

Centre-of-mass energy (TeV)	3
Design luminosity (10^{34} cm^{-2}s^{-1})	6.0
Energy spread (%)	1
Linac repetition rate (Hz)	50
Particles/bunch at IP ($\times 10^9$)	3.72
Bunches/pulse	312
Bunch length (μm)	45
Bunch separation (ns)	0.5
Bunch train length (μs)	0.156
Emittances $\gamma\epsilon_x/\gamma\epsilon_y$ (10^{-8} rad·m)	66/2
Transverse beam sizes at IP σ_x^*/σ_y^* (nm)	45/0.9

Since the IP-FB system has to operate in a high radiation background environment, the choice of the position of the IP-FB components is a compromise between the reduction of the latency time and the minimisation of the background/backsplash effects on the FB electronic components. Figure 1 shows a scheme of the CLIC IP, indicating the position of the FB BPM and kicker. Considering the optics lattice with $L^* = 4.3$ m, where the quadrupole QD0 is partially inside the detector, the FB kicker is downstream of QD0 at approximately 3 m from the IP. The beam crossing angle at interaction is $\theta_c = 20$ mrad. The FB BPM is at 3 m from the IP in the post-collision extraction line of the opposite beam. Although in principle only one such system is needed at the IP for steering the electron and positron beams into collision, the hardware configuration shown in Fig.1 could be duplicated on the opposite side of the IP so as to provide a backup system.

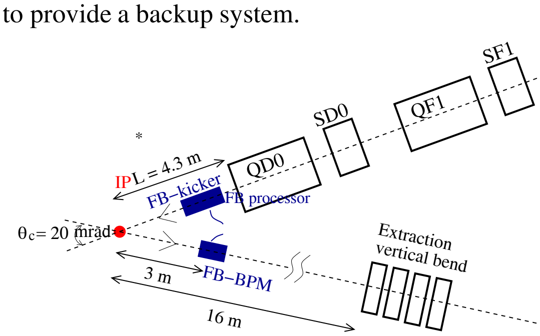

Figure 1: IP-FB BPM and kicker positions in the CLIC interaction region.

For CLIC, with bunch separation of 0.5 ns and train length of 0.156 μs, with the current technology we can not apply bunch-to-bunch corrections, but make a few iterations per train. In this case, the intra-train FB system is based on analogue FB processor.

Important R&D efforts have been dedicated to the hardware prototype development of intra-train feedback systems. The FONT (Feedback On Nano-second Timescales) [2, 3] project has made excellent progress in developing and demonstrating the necessary components to meet the required goals with both digital and analogue technologies for intra-train feedback systems of future linear colliders.

Table 2 shows tentative latency time contributions for a possible CLIC IP-FB system. The latency time is dominated by the time-of-flight of the beams between the IP and the FB components. The BPM processor and the kicker responses have been assumed to be similar to those obtained by the FONT3 project [2].

Table 2: Latency Time of a CLIC Beam-based IP Intra-train FB System

Source of delay	Latency [ns]
Time-of-flight from IP to BPM	10
Time-of-flight from kicker to IP	10
BPM processor	5
Kicker response	5
Delay on cables	7
Total	37

Control Loop

The IP-FB system for CLIC is based on an analogue FB board. We have simulated the control operation of this FB system by means of a simple proportional algorithm using a single gain factor g:

$$\delta y/\sigma_y^* = g \cdot \theta/\sigma_{y'}^* \;, \tag{1}$$

where δy is the feedback change of the beam position at the IP after the measurement of the beam-beam deflection angle θ by the downstream BPM located at a distance $d_{\mathrm{BPM}} = 3$ m from the IP. In this expression the position is normalised to the vertical beam size σ_y^* at the IP, and the angle θ is normalised to the angular divergence $\sigma_{y'}^*$ at the IP. The angle θ can be inferred from the position y_{BPM} measured by the BPM:

$$y_{\mathrm{BPM}} = y^* + (y'^* + \theta_{\mathrm{bb}}(\Delta y^*))d_{\mathrm{BPM}} + \delta_{\mathrm{res}} + \delta_{\mathrm{mis}} \;, \tag{2}$$

where y^* and y'^* are the vertical position and angle, respectively, of the reference beam at the IP. The term δ_{res} refers to the measurement error due to the BPM resolution σ_{BPM}. We have assumed δ_{res} to be white noise, i.e. a Gaussian random sequence with zero mean, and $\sigma_{\mathrm{BPM}} = 1$ μm width. On the other hand, δ_{mis} refers to the measurement error due to BPM misalignment. In the following simulations we have assumed $\delta_{\mathrm{mis}} = 0$, i.e. perfect BPM alignment respect to the beam axis.

By design (with the BPM at 3m downstream of the IP, in the post-collision line) the measured beam position is dominated by the angular term $\theta d_{\mathrm{BPM}} = (y'^* + \theta_{\mathrm{bb}}(\Delta y^*))d_{\mathrm{BPM}} \gg y^*$. Assuming $\theta_{\mathrm{bb}}(\Delta y^*) \gg y'^*$, we have $\theta \simeq \theta_{\mathrm{bb}}(\Delta y^*) \simeq y_{\mathrm{BPM}}/d_{\mathrm{BPM}}$.

We can use the beam-beam deflection curve $\theta_{\mathrm{bb}}(\Delta y^*)$ (Fig. 2) to obtain the necessary information on the beam-beam separation Δy^*. In the range $[-10, 10]\ \sigma_y^*$ we can do the following linear fit:

$$\theta_{\mathrm{bb}}(\Delta y^*) \simeq -18.02\Delta y^*/\sigma_y^*\ [\mu\mathrm{rad}] \;. \tag{3}$$

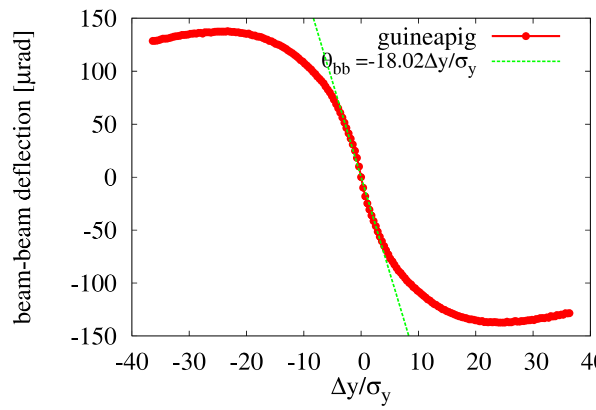

Figure 2: Beam-beam deflection curve for CLIC at 3 TeV centre-of-mass energy simulated with the code GUINEA-PIG [4].

LUMINOSITY PERFORMANCE

We have studied the IP-FB system performance in terms of correcting relative vertical beam-beam position offsets generated by dynamic imperfections, such as high frequency ground motion (GM).

In order to illustrate the time structure of the feedback correction, Figure 3 shows the luminosity recovery as a function of time. This particular example corresponds to a simulation applying a single random seed of a very noisy case of GM (A. Seyi's model C [5]). In our simulations the time interval used to sample the GM is 0.02 s, corresponding to the frequency at which CLIC trains are delivered (50 Hz). If we take into account the nominal CLIC beam parameters: 312 bunches/train and 0.5 ns bunch separation, the IP-FB system (with 37 ns total latency) makes one correction iteration every 74 bunches, i.e. 4 iterations per train. The luminosity loss for a given beam-beam offset at the beginning of the pulse is reduced by a factor 4 (corresponding to a IP beam jitter tolerance increase by a factor 2).

BPM Resolution

In order to determine the instrumentation noise tolerance imposed by the BPM measurement resolution, we have evaluated the Luminosity loss $\Delta L/L_0$ (respect to the nominal luminosity L_0) as a function of BPM resolution. The result is shown in Fig. 4. Each point represents the average luminosity loss over 100 simulated pulses. The error bars represent the standard error $std(\Delta L/L_0)/\sqrt{100}$, be-

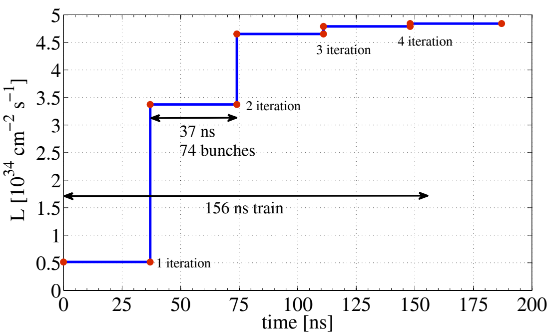

Figure 3: Simulation of the luminosity performance with IP-FB, applying a single random seed of GM model C.

ing $std(\Delta L/L_0)$ the standard deviation of the luminosity loss distribution.

If a maximum tolerable limit of about 2% luminosity loss is stablished, for the CLIC IP FB purposes it is enough to operate with a BPM resolution $\lesssim$ 30 μm. In principle, for the simulations we have assumed a BPM resolution of about 1 μm. Resolutions of the order of micrometre can be obtained using for example stripline based BPMs.

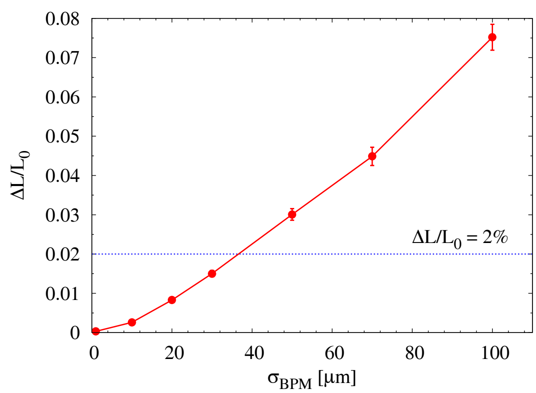

Figure 4: Luminosity loss as a function of the IP feedback BPM resolution.

Luminosity Loss Due to FD Jitter

The stability of the final quadrupoles that focus the beams at the IP is a main concern. A vertical displacement of these quadrupoles causes roughly the same beam position offset at the IP. Special effort has been put on the stabilisation of the final doublet quadrupoles by means of active control methods, see for example [6]. For CLIC the required FD position jitter tolerance in the vertical plane is $\sim$ 0.1 nm. A fast FB system could help to relax this tight tolerance.

Figure 5 compares the average luminosity loss versus the QD0 vertical position jitter for the cases with and without IP-FB correction. In this simulation we have applied vertical vibration only to QD0 of the electron beam line, and considered perfect alignment for QD0 in the positron beam line. Without IP-FB correction, about 0.25 nm QD0 jitter tolerance has been obtained (vibration only in one beam line). In total, about 0.12 nm QD0 jitter tolerance (considering vibration in both opposite beam lines). Notice that the IP-FB correction can increase the jitter tolerance by a factor 2, relaxing thus the requirements for the mechanical stabilisation of the FD quadrupoles.

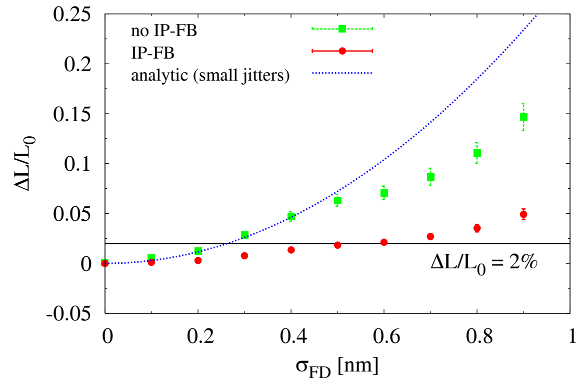

Figure 5: Luminosity loss versus vertical FD position jitter. The square points represent the simulated luminosity without IP-FB correction; the dotted line is the analytical approximation of the luminosity loss due to small QD0 position jitter; and the round points represent the simulated luminosity applying IP-FB correction.

SUMMARY AND OUTLOOK

A conceptual design of a beam-based intra-train feedback system for CLIC has been presented. This FB system is conceived to cure the relative beam-beam offsets at the IP.

By means of computer simulations, with realistic assumptions, we have shown that a CLIC IP-FB system can reduce the luminosity loss by approximately a factor 4 for a given beam-beam offset at the beginning of the pulse. The CLIC IP-FB system can also increase the FD quadrupole position jitter tolerance by a factor 2.

The study of the hardware details of this FB system is in progress. The aim is to harmonise the design according to the mechanical configuration of the CLIC interaction region.

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