CLIC FINAL FOCUS SYSTEM ALIGNMENT AND MAGNET TOLERANCES

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Abstract

The design requirements for the magnets in the Compact Linear Collider (CLIC) Final Focus System (FFS) are very stringent. In this paper the sensitivity for the misalignment and the magnetic imperfections for the different magnets in the FFS and the crab cavity are presented.

INTRODUCTION

CLIC[1] requires a small vertical emittance and beam size at the interaction point (IP) in the nanometer range to achieve its nominal luminosity. The small beam size will be delivered by the FFS, which has a complicated chromaticity corrected optics scheme. The beam size and beam position will be affected by the magnetic and position imperfections of the FFS magnets. Studies have been performed to determine and summarise the tolerances for the most sensitive FFS magnets.

CLIC FFS

The main task of the linear collider FFS is to focus the beam to the small sizes required at the IP. To achieve this, the FFS forms a large and almost parallel beam at the entrance of the Final Doublet (FD), which contains two strong quadrupole lenses, named QD0 and QF1. For the nominal energy, the beam size at the IP is $\sigma = \sqrt{\beta^* \epsilon}$, where ϵ is the beam emittance and β^* is the betatron function at the IP. However, for a beam with an energy spread σ_δ, the beam size is diluted by the chromaticity of these strong lenses. The chromaticity is defined as:

$$\xi = \frac{d\beta^*/\beta^*}{dE/E} \tag{1}$$

and it scales approximately like $\xi \sim \frac{L^*+L_q/2}{\beta^*}$, where L^* is the distance from the IP to the last quadrupole and L_q is the quadrupole length. Thus the chromatic dilution of the beam size $\sigma_\delta \frac{L^*+L_q/2}{\beta^*}$ may be very large. The design of the FFS is driven primarily by the necessity of compensating the chromaticity of the FD.

There are two different approaches to the compensation of the chromatic effects, the traditional scheme, based on dedicated chromatic correction sections for each plane; and the local correction scheme, based on the local correction of the chromaticity[2]. This paper will focus on the local correction scheme, see Fig. 1, which is the CLIC baseline.

The CLIC FFS is characterized by the parameters shown in Table 1. The CLIC FFS uses sextupoles next to the final doublets to correct the local chromaticity. A bend upstream generates dispersion across the FD, which is required for the sextupoles and non-linear elements to cancel the chromaticity. The dispersion at the IP is zero and the angular dispersion is about 1.4 mrad, i.e. small enough that it does not significantly increase the beam divergence. Half of the total horizontal chromaticity of the final focus is generated upstream of the bend in order for the sextupoles to simultaneously cancel the chromaticity and the second-order dispersion. The horizontal and the vertical sextupoles are interleaved in this design, so they generate third-order geometric aberrations. Additional sextupoles upstream and in proper phases with the FD sextupoles partially cancel these third order aberrations. The residual higher order aberrations are further minimized with octupoles and decapoles.

The crossing angle at the IP is 20 mrad. Crab cavities are required to rotate the bunches for a head on collision. They apply a z-dependent horizontal deflection to the bunch that is nominally zero at the centre of the bunch. Without crab

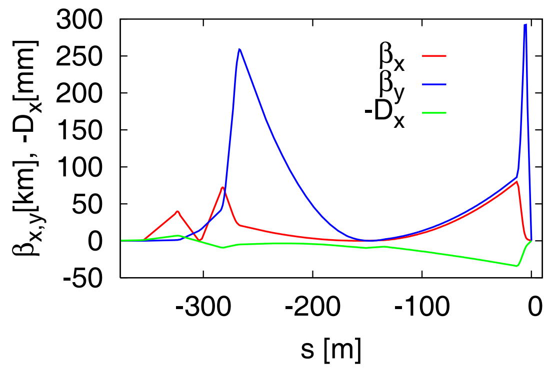

Figure 1: Optics of the CLIC Final Focus local correction scheme.

Table 1: Key Parameters of the CLIC FFS at the IP

Parameter	Units	Value
Total (peak 1%) lumi.	$cm^{-2}s^{-1}$	$5.9(2.0) \cdot 10^{34}$
Beam energy	TeV	1.5
Last drift L^*	m	3.5
Nom. beam size σ_x/σ_y	nm	45/1
Nom. beta func. β_x/β_y	mm	10/0.07
Nom. bunch length σ_z	μm	44
Bunch population		$3.7 \cdot 10^9$
Train repetition rate	Hz	50
Crossing angle	mrad	20

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cavities 90% of the achievable luminosity would be lost. It is important that the relative centre of rotation is identical for the two bunches in order not to miss each other at the IP. Therefore, the RF phases of the two cavities must be perfectly synchronised.

TOLERANCES

Since the beams at the collision point are so small, and since there are strong sextupoles to cancel the chromaticity and geometric aberrations with a high precision the performance of the final focus optics is sensitive to many forms of perturbations. In this paper the main imperfections are studied for the most sensitive elements, which are the last four quadrupoles QD0, QF1, QD2, QF3 and the last two sextupoles SD0, SF1, which are just before QD0 and QF1 respectively. The imperfections that are considered are position offsets, both vertically and horizontally, magnetic strength errors and higher order components. In addition, the phase offset and voltage amplitude of the crab cavity is studied. Simulations are done with PLACET[3] and Guinea-Pig[4].

It should be noted that the tolerances and luminosity performances presented should be regarded for pulse to pulse stability, since static or low frequency changes can to a large extent be corrected for by the orbit feedback, IP position feedback and beam tuning with sextupole knobs[5]. Tolerances for a pulse to pulse stability are given, and in every case only one beamline is perturbed while the other is kept unperturbed. In addition, some simulations are performed with the IP feedback on. This means that the beam offset is corrected and the remaining luminosity loss is only due to beam aberrations.

Offset Tolerances

One of the most important errors are those related to changes in the particle trajectory due to quadrupole and sextupole position jitter. A vibrating quadrupole deflects the beam so that it changes its transverse position at the collision point. The tolerances are tighter in the vertical plane due to the smaller beam size. The change in the IP position Δy^* due to a change in a vertical (horizontal) quadrupole position by y_q is

$$\frac{\Delta y^*}{\sigma_y^*} = -y_q K_q \sqrt{\beta \epsilon_y} |\sin(\psi_y^* - \psi_{y,q})|, \qquad (2)$$

where σ_y^* is the beamsize at the IP, K_q is the integrated quadrupole strength and $\psi_y^* - \psi_{y,q}$ is the phase advance between the quadrupole and the IP. The tightest tolerance is almost always in the FD, as a vertical displacement y_q causes a displacement in the IP of the same magnitude. For the CLIC FD this means a tolerance of the nanometer level.

In Fig. 2 the vertical offsets for the last four quadrupoles are plotted versus relative peak luminosity. As expected the final doublet has the most sensitivity. However, when the beam offset at the IP is corrected for by the IP position feedback, see Fig. 3, then QD2 and QF3 are the most sensitive. The reason is that in addition to an offset at the IP, the offsetted beam traverses a bend and the two sextupoles SF1 and SD0, which will cause beam aberrations. In Table 2 the tolerances for the 2% peak luminosity loss are shown, as well as for the horizontal direction, the last two sextupoles, SD0 and SF1, and the relative strength error tolerances.

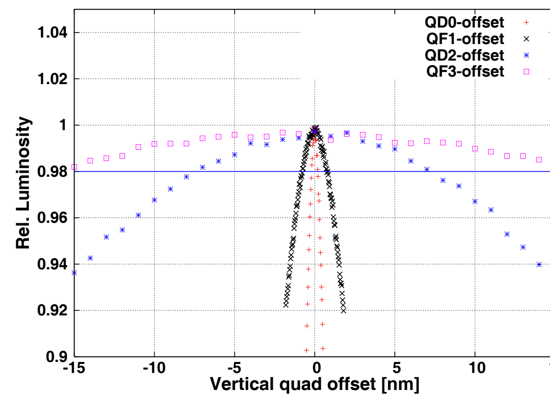

Figure 2: Vertical quadrupole offsets versus relative peak luminosity for the last four quadrupoles.

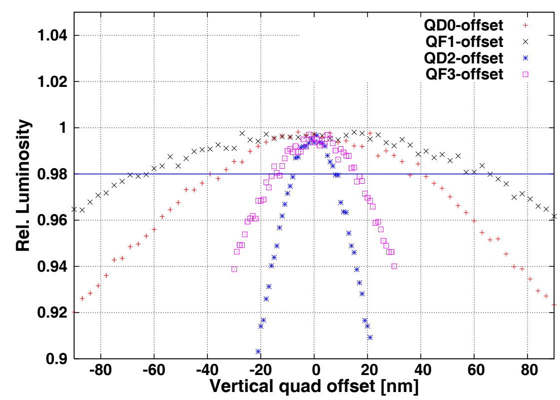

Figure 3: Vertical quadrupole offsets versus relative peak luminosity for the last four quadrupoles with IP feedback.

Table 2: Offset tolerances (in nm) and strength errors (relative) for the last magnets in the CLIC FFS for a relative peak luminosity loss of 2%.

Magnet	Hor.	Vert.	Vert. IP offset corr.	Strength error
QD0	3	0.2	40	$0.7 \cdot 10^{-5}$
QF1	5	0.8	60	$2 \cdot 10^{-5}$
QD2	70	8	10	$1 \cdot 10^{-3}$
QF3	55	16	15	$2 \cdot 10^{-3}$
SD0	400	60	60	—
SF1	150	50	50	—

Multipolar Components

A recent prototype of the QD0 have been produced and the multipolar components of this magnet has been

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measured[6]. In the studies presented here we use the multipolar components measured with a current in the QD0 prototype of 6 kA, which corresponds to nominal operation at 1.5 TeV beam energy.

The multipolar components have been simulated and the main results are given in Table 3. For octupolar and higher order components, the measured values are not problematic. For a_3 and b_3 however, the losses due to these components are at the moment found to be too high, and will require further studies. It should be noted that the numbers presented here are without any tuning of the errors from the QD0. With all components included, a tuning using SD0 and SF1 showed that we can get back to at least 94% of the original luminosity. Hence, the b_3 measured can also be considered acceptable if no improvement can be found.

Table 3: Uncorrected luminosity losses from QD0 multipolar components as measured in the prototype.

Included components	Luminosity $[L/L_0]$	Peak Luminosity $[L_p/L_{p0}]$
Oct. and higher	0.988	0.980
Normal sext.	0.945	0.947
Skew sext.	0.781	0.785
All	0.719	0.726

In Fig. 4, we simulated the luminosity loss from a_3 and b_3 only, and compared to the measured values. The normal sextupolar component can if positive provide some local chromaticity correction, which is the reason for a luminosity above 100% for a slightly positive value of b_3.

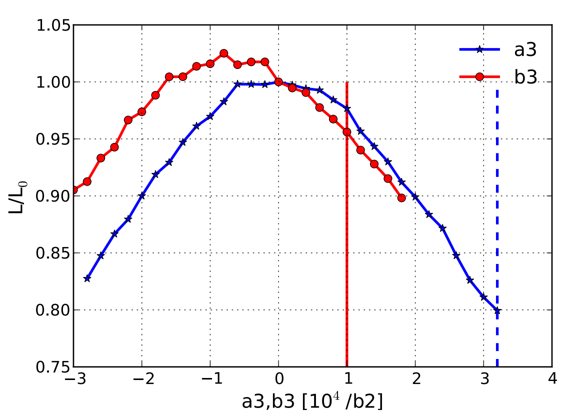

Figure 4: Luminosity loss due to sextupolar components in QD0. a_3 in blue (dashed), b_3 in red (solid). Values are given as relative to b_2 divided by 10^4, for a radius of 1 mm. The vertical lines show the measured values in the prototype.

Crab Cavities

The crab cavities are meant to recover head on collisions at the IP. Any voltage or phase error will be translated into a loss of luminosity. In [7] the admissible phase error to ensure a maximum luminosity loss of 2% is calculated analytically to be $\phi_{\mathrm{rms}} = 0.025$ degrees. In Fig. 5 the relative luminosity variation is plotted versus phase and voltage errors. The simulated luminosity variation due to phase error agrees quite well with the analytical estimations in [7], while the voltage error is predicted to produce only a 1% luminosity loss for a 2% voltage variation.

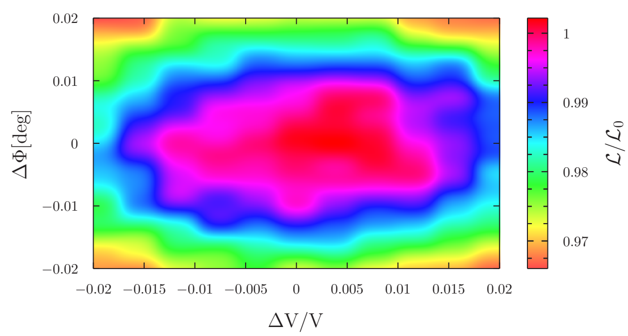

Figure 5: Crab Cavity phase offset and voltage tolerances.

CONCLUSIONS

This paper summarises several design and stability requirements for the crab cavities and some of the most stringent magnets in the Compact Linear Collider (CLIC) Final Focus System (FFS). Tolerances for a pulse to pulse stability are determined. Stability requirements on longer timescales for which the orbit and IP feedback can correct for most of the beam offset at the IP are also given. For longer timescales, the FFS tuning is expected to compensate some of the luminosity loss. Although no single requirement is deemed infeasible, care must be taken in the design. In addition, more integrated and comprehensive studies are required to fully understand the intricate interaction between the different perturbations.

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