STUDY OF ORBIT FEEDBACK SYSTEMS FOR THE TESLA LINEAR COLLIDER

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Abstract

In order to reduce the influence of magnet vibrations which can cause luminosity reduction in the TESLA Linear Collider, several feedback loops are planned to control the beam orbit and to keep the beams in collision. The complete control system for orbit correction can be divided into three different feedback systems: in the main linac a slow feedback system is intended to cancel perturbations in the low frequency range which are mainly due to ground motion. In the beam delivery section a fast feedback system is to be installed to compensate disturbances containing higher frequency components, mainly from pulse-to-pulse quadrupole vibrations and potentially also due to microphonics and Lorentz-force detuning in the superconducting cavities. At the interaction point a fast feedback system will keep the two beams in collision, using the beam-beam-deflection signal. The paper summarizes design studies for all three orbit correction schemes and the main components are discussed in detail.

1 INTRODUCTION

TESLA 500 is a e^+e^- linear collider study using superconducting Nb accelerating structures operating at 1.3 GHz [1]. Very low wakefields and a high accelerating efficiency with a gradient of 25 MV/m are major advantages of this design. At a center of mass energy of 500 GeV TESLA 500 is aiming for a nominal luminosity of $6 \cdot 10^{33}$ cm^{-2} s^{-1}, where at the interaction point (IP) the requested transverse beamsizes are $\sigma_x^\star = 845$ nm and $\sigma_y^\star = 19$ nm. The repetition rate is 5 Hz and the bunch train consists of 1130 bunches separated by 708 ns.

In order to keep the two beams in collision and to avoid emittance growth due to motions of different components several feedback loops will be installed in TESLA. Due to the flat shape of the beam the vertical movement of quadrupoles and above all the jitter of the final doublet is of particular significance.

The conceptual design of the orbit control in TESLA consists of three different feedback systems:

In the lower frequency range the beam is perturbed by vibrations mainly due to ground motion which is almost natural noise below 1 Hz [2]. A slow feedback system in the main linac working at the repetition frequency of 5 Hz will cancel their influence on the beam orbit up to a tenth of the repetition rate. The beam offset will be steered by means of corrector coils.

Assuming a noisy environment, after a certain time the pulse to pulse beam movement can result in unacceptable beam seperation at the IP. Therefore a fast feedback is necessary, working in the MHz-range, to regulate the beam offset after a few bunches of a train and to keep the two beams in collision. Due to the bunch spacing of 708 ns - another main advantange of TESLA - the fast feedback will provide a bunch to bunch correction of the beam orbit. The fast feedback will also compensate disturbances in the kHz range caused by quadrupole vibrations within a pulse, and potentially by Lorentz force detuning and microphonics in the superconducting cavities. It does not need to correct the relativly large orbit changes over many pulses which are already eliminated by the slow feedback system.

Two fast feedback systems are planned: before the beam enters the final focus system, a feedback in the beam delivery section (BDS) will eliminate the beam offset caused by the movement of upstream elements, especially in the linac. A fast IP - feedback will keep the two beams in collision using the beam-beam-deflection signal. Fast kicker magnets will provide the requested kicks for steering the beam.

All feedback systems will be digital allowing the realization of an advantageous data base driven feedback. The data received are recorded and can be used for further statistics. Figure 1 shows the schematic concept of a digital feedback. In case of the fast feedback, all operations in the different blocks of Fig. 1 and the signal transmission have to be done within the bunch spacing. In this paper a brief description of all three feedback systems, of their main components and of the considered feedback algorithms is given.

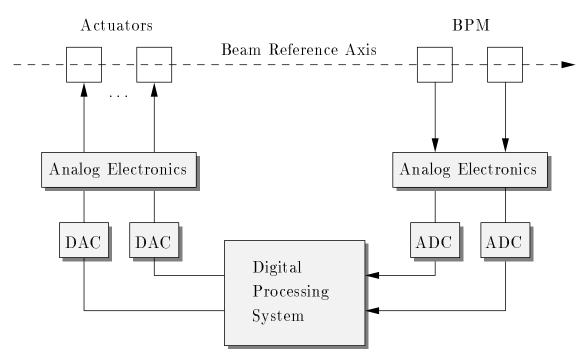

Figure 1: Schematic diagram of digital feedback systems

2 MAIN COMPONENTS

2.1 Beam Position Measurement

The first device in the feedback loop shown in Fig. 1 is an electromagnetic pick-up to obtain a signal proportional to the beam position. Cylindrical cavities excited in the first dipole-mode by an off-axis beam are under consideration for this purpose in all feedback systems.

In the main linacs the slow feedback system will make use of the beam position monitors (BPM) installed at every cold quadrupole. To avoid interferences from the accelerating cavities, they were designed for a resonant frequency of 1.517 GHz. A loaded Q of about 900 is realized by using CrNi as a cavity material to measure individual bunches. Design details and test results at the TESLA Test Facility Linac (TTFL) are summarized in [3].

Monitors which are under development for the free-electron laser at the TTFL [4] might be installed in the BDS. Their signal processing scheme for detecting the 12 GHz signal will be slightly modified: another field-sensitive filter using waveguide components will be installed at the electronics front-end resulting in an improved common-mode rejection. In addition, all components especially the analog-to-digital conversion have to be optimized with respect to the processing time.

A cavity with a TM_{110}-frequency of about 2 GHz is designed for the IP, mainly because of the beam pipe diameter. The signal processing scheme is similar to the TTFL-monitors, but has to be optimized with respect to the processing time. In addition, special care has to be taken of the signal resulting from the incoming beam (see also section 2.4).

Table 1 summarizes some important design parameters of these three cavity monitors. The stability per day should be in the order of the resolution for all monitors.

	location of the BPM		
parameter	**Linac**	**BDS**	**IP**
Bunch separation	708 ns		
Resolution	10 μm	1 μm	5 μm
Bandwidth	1.5 MHz	12 MHz	5 MHz
TM_{110}-frequency	1.52 GHz	12.0 GHz	1.95 GHz
Cavity radius	115.2 mm	14.6 mm	90 mm
Cavity length	52 mm	8.6 mm	50 mm
Beam pipe radius	39 mm	5 mm	24 mm

Table 1: Design parameters for all cavity monitors

2.2 Slow Feedback

Disturbances in the low frequency range are mainly due to ground motion, causing quadrupole displacement and leading to beam emittance growth. In order to eliminate the effects of displaced elements a slow feedback system working on the repetition frequency of 5 Hz has been developed [6].

For the orbit correction the position and the angle of the beam trajectory in both transverse plans will be controlled. The conceptual design of this pulse-to-pulse orbit control is based on tools of Optimal Control Theory taking into account the stochastic nature of the beam movement and of the sensor noise. The feedback loop can be divided into four main operations: measurement taken by BPM's – estimation of the beam's position and angle – calculation of actuator strength – correction by use of corrector coils. The loop contains an optimal filter (Kalman Filter) to estimate the beam's position and angle and an optimal controller to determine the corrector settings [7].

Results of simulation runs show that the feedback algorithm provides a good orbit control in the requested range. The feedback loop damps frequency disturbances up to 0.4 Hz quite well, where a DC bias rejection of -50.8 dB was achieved. Including an integral part in the controller improves the DC bias rejection, but its disadvantage is a higher amplification in the frequency range between 0.5 Hz and 1.9 Hz. An assumed beam offset of $5\ \sigma_y$ at the end of the linac requires a kick of 0.55 μrad; for a 250 GeV beam the corrector must provide a magnetic field of $4.57 \cdot 10^{-4}$ Tm. This can be done by the standard correction coils installed in the linac.

2.3 Fast Feedback in the BDS

A fast feedback system will be located in the tuning and diagnostic section of the BDS to correct the orbit before the beam enters the final focus system. This bunch to bunch feedback is also able to compensate disturbances like fast vibrations of quadrupoles, microphonics and Lorentz-force detuning caused by the superconducting cavities which cannot be detected and controlled by the slow feedback system. It will consist of two monitors to detect the beam position and angle and fast kickers to provide the requested kick for steering the beam. The feedback is determined with tools of classical control theory. The closed loop includes also a noise filter to suppress the sensor noise affecting the beam position measurements. This noise filter is based on the Maximum Likelyhood estimator which is equivalent to least square fitting if the noise is independent, gaussian distributed and with constant standard deviation [8]. In contrast to the Kalman Filter used in the slow feedback, the dynamic of the noise does not have to be known. Results of simulations are shown in Fig. 2: the influence of sensor noise, obviously, can be decreased by the noise filter.

2.4 IP Feedback

The vertical offset of the two beams at the IP is the most harmful effect of misplaced elements. A 2% luminosity reduction from beam centrouid motion is expected to occur in 1 ms, assuming a ground motion model on noisy environment. Therefore a fast feedback system is necessary to keep the beams in collision. The offset of the two colliding beams will be measured precisely with the beam-beam scattering method which has already been used in the SLC for single bunches [5]. For TESLA the kick angle α per $\sigma_y^\star$ estimated from beam-beam simulations is approximately given by

$$\alpha \quad \text{[mrad]:} \quad (\Delta y_{IP}/\sigma_y^\star) \times 0.047\ \text{mrad} \tag{1}$$

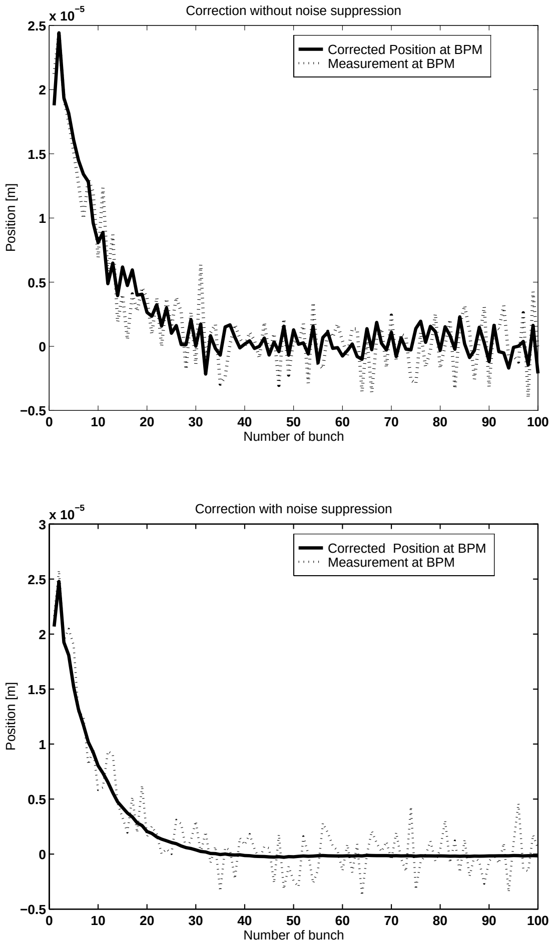

Figure 2: Simulation plots of fast feedback (BDS): Position and measurement 1) without and 2) with noise suppression. For scaling reasons, the offset of the pilot bunch (45 μm) is not shown.

with $\sigma_y^\star = 19$ nm beam spot size and Δy_{IP} beam-beam separation at the IP.

In order to reduce the processing time of the feedback loop, the locations of the BPM's and the kickers have to be as close as possible to the IP. If the BPM is located at the position of the final doublet separated by 3 m from the IP, a separation of one $\sigma_y^\star$ will result in an offset of about 140 μm. Therefore the required resolution of the BPM can be relaxed and will be about 5 μm. Within one pulse a bunch-to-bunch measurement of both outgoing beams can be used to get a precise measurement of the offset of the two colliding beams.

The sinusoidal part of the trajectory is given by the difference of the pick-up signals for one bunch taken before and after the IP; the sum determines the requested kick to steer the beam calculated by tools of classical control theory. The orbit feedback at the IP shall be able to remove a separation up to $10\,\sigma_y^\star$. Assuming a distance of 4 m between a kicker and the IP this will result in a requested kick of 0.023 μrad for each kicker. Therefore a magnetic field of $2 \cdot 10^{-5}$ T is required for an energy of 250 GeV.

2.5 Correctors

In the digital system, fast Digital-to-Analog Converters will convert the signals back into analog values for the correctors. These signals have to be amplified in a broadband power amplifier. In the slow feedback system corrector coils are used to steer the beam from pulse to pulse. For the fast feedback system the installation of feedback kickers successfully used in the HERA ring at DESY is planned [9]. The magnetic field of the 0.9 m long stripe line kicker is about 10^{-4} Tm providing a kick of $0.12\,\mu$rad at an energy of 250 GeV.

3 ACKNOWLEDGEMENTS

It is a pleasure to thank our colleagues from DESY Hamburg for their help and for their hospitality. Special thanks are extended to R. D. Kohaupt and R. Brinkmann for the uncountable discussions and intensive help, and H. Henke from TU Berlin for his support.

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