HARDWARE FOR THE LEP TRANSVERSE FEEDBACK SYSTEM

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Abstract

A transverse feedback system is being constructed for LEP to increase the threshold current for the Transverse Mode Coupling Instability. The system, consisting of parallel plate magnetic kickers driven by a current pulsing network, will be capable of producing a coherent tune shift ΔQ_{FB} of at least the value of the synchrotron tune (0.1). Because of its location close to the kicker in a radiation environment, the pulser uses vacuum tubes to provide the necessary current. Computations and subsequent measurements of the magnetic field showed that the field quality can be significantly improved by the addition of 'lips' at the edges of the kicker electrodes.

Limitation of LEP Performance

The current per bunch and hence the luminosity of all recent large e^+e^- storage rings is limited by a fast transverse blow-up of single bunches called the Transverse Mode Coupling Instability. In these machines the betatron frequency is much greater than the synchrotron frequency and betatron motion (m = 0 mode) modulated at the synchrotron frequency gives closely spaced first sidebands (m = ±1 modes). For increasing bunch current, the frequency of the m = 0 mode decreases whereas the frequency of the m = -1 mode increases. At a certain threshold current the two frequencies overlap and instability occurs. The predicted threshold current at injection in LEP (20 GeV) is 0.75 mA/bunch.

Transverse Feedback System

It has been shown by both computer simulations and an experiment at PEP that the threshold current can be increased by compensating the frequency shift of the m = 0 mode using a reactive feedback system. The technique is described as follows.

A transverse deflecting kicker and pick-up spaced by a multiple of π in phase advance, are located reasonably close to each other in the machine. The output signal from the pick-up which is proportional to the transverse displacement of the centre of gravity of the bunch is transmitted to the nearby kicker via a time delay and amplifier stage. This signal fires the kicker on arrival of the bunch, approximately one turn later.

$$\text{The kick} \quad \Delta y'_k \propto y_{pu}$$
$$\propto y_k \quad (\pi \text{ phase advance})$$
$$\propto y'_k \quad (\pi/2 \text{ phase advance})$$

Feedback systems where $\Delta y'_k \propto y_k$ produce frequency shifts and are called reactive, whereas for $\Delta y'_k \propto y'_k$ damping is obtained and the system is resistive [1],[2]. For LEP, the design of the feedback system is such that the signals from two pick-ups spaced by $\pi/2$ in phase advance can be amplified with variable gains and combined to power a single kicker. In this way both the damping and the frequency shift of the m = 0 mode can be provided.

Requirements of LEP Transverse Feedback System

System bandwidth

The bandwidth must be large enough to treat each bunch of the two counter-rotating beams independently.

min. $\Delta f \approx$ (minimum time between e^+ and e^- bunches)$^{-1}$

In LEP the feedback is located approximately 435 m from the intersection points giving for four-bunch operation

$$\Delta t_{MIN} \approx 2.9\ \mu s \equiv \Delta f_{MIN} = 345\ \text{kHz}.$$

System gain

The system gains are functions of the damping time τ_{FB} for a resistive feedback system and of the coherent Q shift ΔQ_{FB} for a reactive feedback system. Using the Twiss parameters and introducing feedback in the form of a kick $\Delta y'_k = g_1 y_1 + g_2 y_2$, where g_1, g_2 are the gains of the two pick-up/kicker feedback loops, the single turn matrix for coherent motion with respect to one of the two pick-ups can be written

$$\binom{y}{y'}^* = (S)\binom{y}{y'}$$

where * refers to the reference pick-up after one turn.

Calculation of the eigenvalues of S gives:

$$g_{\substack{1\\2}} = \frac{\mp(2/\tau_{FB}\cdot f_{rev})\sin\mu_{\substack{k2\\k1}}\,[\cos(\mu_0+\Delta\mu_{FB})-\cos(\mu_0)]}{\sqrt{\beta_{\substack{1\\2}}\beta_k}\ \sin\mu_0\sin\mu_{12}}$$

Maximum field strength

The kick required

$$\Delta y'_k = \frac{ec}{E} B_\perp L \qquad \text{for a magnetic kicker}$$

where E is the energy of the beam to be deflected. Using the previous expression for the kick in terms of the system gain, the magnetic field required

$$B_\perp L = \frac{E}{ec}(g_1 y_1 + g_2 y_2) = h_1 y_1 + h_2 y_2$$

In LEP, the following values apply to the vertical kicker and pick-ups.

Q_1	Q_2	Q_k	$\beta_{1,2}$	β_k	Q_0
1.11	1.39	2.29	84.1	135	70.35

For a purely reactive feedback system ($\tau_{FB} = \infty$) assuming $\Delta Q_{FB} \approx Q_s \approx 0.1$, the required gains for electrons are $g_1 = -0.00504$ and $g_2 = 0.00776$. Assuming $y_1 = y_2 = 0.5$ mm, the maximum magnetic field required at injection (E = 20 GeV) is

$$B_\perp L = 4.3\ \text{G.m}$$

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Choice of Hardware

The major consideration in the choice of the hardware was cost. Choices, or factors affecting the choice included (a) deflection by electric or magnetic systems, (c) coupling impedance to the beam, (d) minimum electronics in the tunnel and (e) absence of space in midarcs.

It was decided that a parallel plate magnetic kicker inside the vacuum system as shown below driven by a simple current pulsing circuit would best satisfy the imposed constraints.

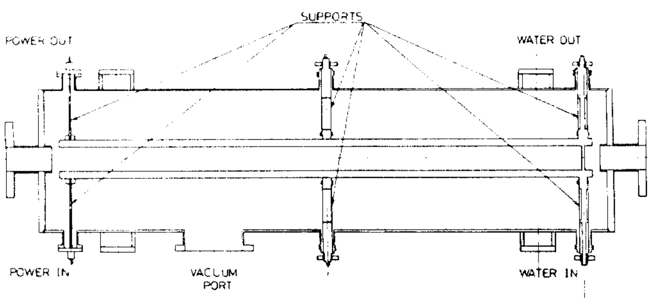

Fig. 1

Design of the Electronics

Pick-up and signal transmission

For transmission purposes the analog pick-up signal is converted into a 140 MHz phase modulated signal. This is sent on a high quality coaxial cable from the pick-up electronics in the LEP tunnel to the receiving electronics in the klystron gallery. The signal is phase demodulated, amplified and converted into an amplitude modulated pulse. The amplitude is 0 V for the bunch position of -30 mm and 3 V for +30 mm, which gives 50 mV/mm. The noise on the signal is typically ±1.5 mV corresponding to ±30 μm.

Digitizing, signal processing and FFT

A block diagram of the layout is shown in Fig. 2.

The total time available for feedback signal transmission and processing is of the order of 85 μs. The signal delays are about 25 μs, leaving about 60 μs for signal processing. The analog beam position signal from the pick-up is digitized with an 8-bit flash analog to digital converter (FADC) giving a resolution of 240 μm/bit in the vertical plane. Under normal running , however, the reference voltages may be changed to obtain a zoom of four giving 60 μm/bit with an acceptable 1/2 bit differential linearity. The pickup signal contains both the closed orbit and betatron oscillations. The feedback system only requires the betatron signal. The digital signal processor (DSP) calculates the closed orbit by averaging input values over about the previous 1000 revolutions and subtracts it from the instantaneous pick-up value to give the betatron amplitude. The result is converted into mm (max. ±0.5mm) and when multiplied with the gain constants h_1 and h_2, gives a signal proportional to the required field strength. The DSP has a cycle time of 150 ns. The synchronisation of the FADC and the DSP is assured by the bunch synchronizer, so that the right pick-up signal is applied to the right bunch. The Q value of the betatron oscillations is calculated by a self-contained FFT using the output of one of the FADC. The FFT can perform 1024 points in 3 ms.

The output of the DSP is transferred to a Digital to Delay Converter, which is a simple preset counter (relative to the synchronous bunch clock) which modulates the phase of the constant amplitude sinusoidal current pulser which feeds the kicker.

Line driver and current pulser

Since the kicker plates and the current pulser make up an integral part of the pulse-forming network they have to be situated as close together as possible to reduce the influence of the inductance of the connecting cables. For this reason the pulser is placed under the kicker tank. Even in this position the radiation level is too high for semiconductors, so a tube switch is used in the pulse-forming network.

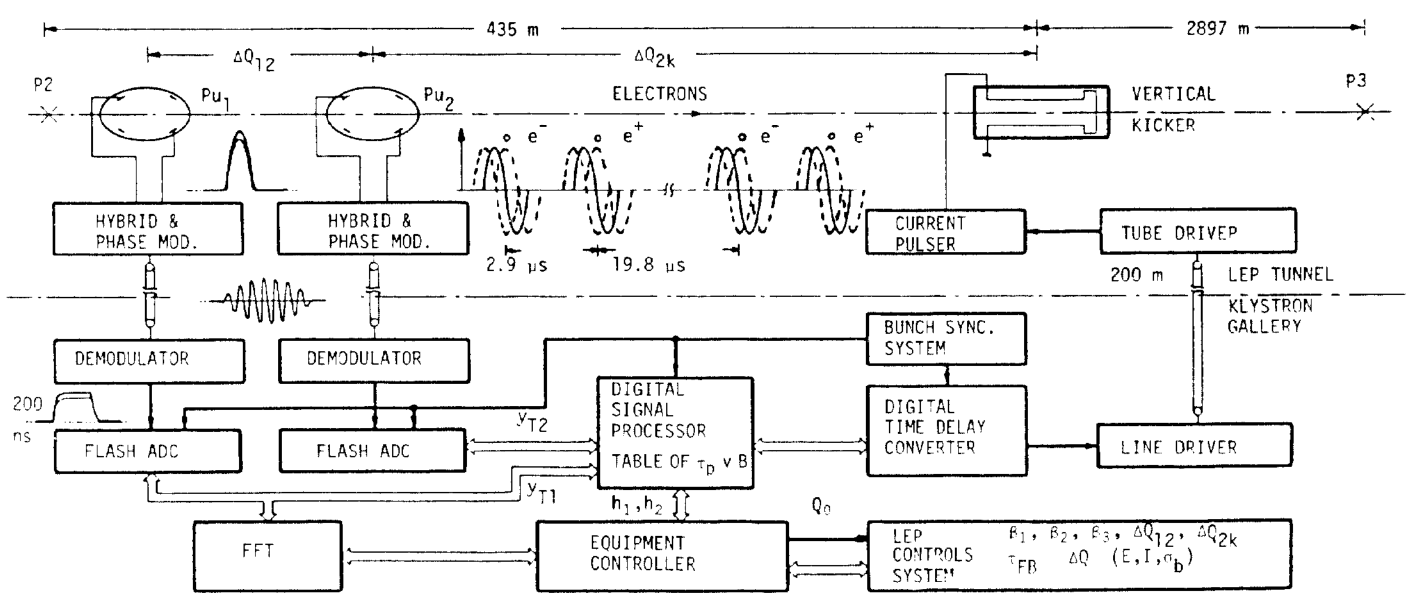

Fig. 2

Since the distance between the current pulser and the processing electronics in the klystron gallery is ≈ 200 m, the trigger pulse has to be boosted with a medium level (100 V) line driver. Despite this driver the pulseform may still be distorted at the end of the coaxial cable due to the cable capacitance, and a regeneration of the pulse is necessary using a tube amplifier capable of driving all the tubes of the current pulser.

Fig. 3 shows a circuit diagram of the current pulser which operates as follows. By closing the switch which is formed by modules of 10 parallel pentodes and diodes, the charging capacitor is discharged in series with the kicker inductance so creating the sinusoidal current pulse in the kicker plates. The diodes take the negative part of the pulse current. At the end of the pulse, the switch is opened to recharge the charging capacitor through the inductance in the anode circuit, and the four damping pentodes are closed to clamp the voltage over the kicker.

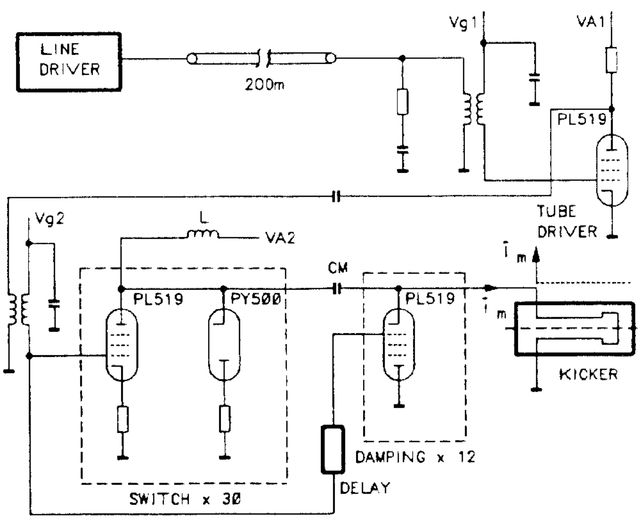

Fig. 3

Using three modules of ten plus four pentodes and ten diodes, the pulser can provide up to 40 A. Each pentode can carry 1.5 A peak current.

Design of the Kicker

Plate dimensions

For maximum efficiency, the plates of the kicker should be as close to the beam as possible. The vertical aperture Y for a beam of $\pm 10\sigma$ is calculated as follows:

$$\hat{Y} = Y_{co} + 10 \left[\beta \varepsilon + \left(\frac{D\sigma_e}{E} \right)^2 \right]^{\frac{1}{2}}$$

where Y_{co} is the closed orbit distortion

β, D are the local betatron and dispersion functions

ε, σ_e/E are the emittance and energy spread for $\pm 1\sigma$.

The minimum distance between plates $H = 2\hat{Y}$. For the vertical kicker in LEP the plates are positioned at the vertical beam stay clear dimensions of ±34 mm. A similar calculation in the horizontal plane shows that the distance over which the kicker field should be uniform is ±40 mm.

Current

The electrical characteristics of the kicker were analysed using the computer program TRANSM [3]. For 100 mm wide plates, 68 mm apart in a tank of 400 mm diameter, the program calculates that a current $I = 19$ A is required for a field on axis $B = 1.0 \times 10^{-4}$ T. The measured current was found to be 22 A.

Field quality

It was found from the TRANSM field calculations that a more homogeneous field could be obtained over ±40 mm by extending the plates to ±50 mm and bending the edges inwards. The beneficial effect of these 'lips' on the field quality is given in Fig. 4. Magnetic field measurements made on the kicker using a simple loop probe showed good agreement with the theory.

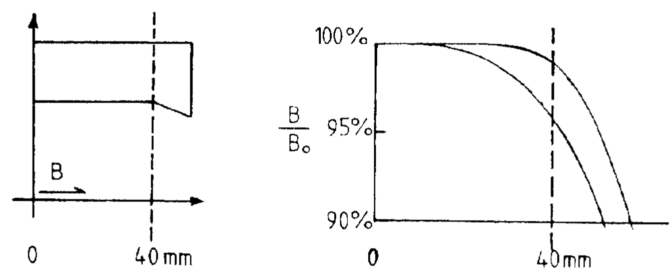

Fig. 4

Cooling

It has been estimated [4] that about 200 W will be dissipated in the kicker tank due to higher order mode losses at 3 mA beam current. These losses increase with the square of the current and thus it is foreseen that the electrodes could if necessary be cooled with high quality demineralised water.

Mechanical construction

The kicker tank and electrodes are made from stainless steel. Making the electrodes hollow provides both a stiff lightweight structure and an efficient network of cooling channels. Small bellows at each end of the ceramic support bars permit differential axial displacements between the tank and the electrodes.

References

[1] C.W. Olsen et al., IEEE Trans. Nucl. Sci. NS-28, p.2296, 1981.
[2] D. Heins et al., DESY M-79/06, May 1979.
[3] A. Khursheed, a CERN Transmission Line Program.
[4] H. Henke, private communication.

Acknowledgement

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