4.8 Instrumentation and Controls

With the passage of time, the instrumentation and control systems have come to play a role of steadily increasing importance for the achievement of accelerator performance goals. They are no longer just the means for intermittent operator intervention; rather, they provide the complex of feedback loops necessary to performance. In this respect, the linear collider resembles the "fly-by-wire" characteristics of modern high performance aircraft. The lower frequency S-band approach ameliorates but does not avoid this situation.

The discussion to follow gives an overview of the beam instrumentation and feedback systems foreseen for the SBLC.

4.8.1 Beam Diagnostics

We begin with a summary of some of the basic ideas and numbers which lead to instrumentation needs, requirements, and device descriptions. Sections elsewhere in this report where detailed information can be found are referenced. This introduction concludes with a tabulation of issues and approaches.

The Linac

For the linac the main requirement which has been addressed is the preservation or control of the transverse emittance.

Transverse emittance (Section 4.3) is preserved by control of alignment of the quadrupoles, BPM's and cavities. In addition energy variation and energy spread must be controlled (i.e. longitudinal emittance).

RMS alignment tolerances of $100\,\mu$m for quads, BPMs, and accelerating structures have been chosen. These values are relative to the ideal beam line and are assumed to be valid over distances of up to 600 m. Beyond this distance, typical of a betatron wave length, sensitivities decrease rapidly.

Using the above alignment errors, single bunch vertical emittance growths is untolerable large for simple "one to one" beam steering (i.e., steering from the center of one detector to another). In the more time consuming beam-based alignment method, described later on together with the beam position monitor system, the center of the beam is found relative to the center of the quad and to the BPM. The total emittance budget is $20{\pm}10\,\%$ and can be achieved if the BPM resolution is $5\,\mu$m. (Section 4.3). A BPM resolution and stability of $\pm 2\,\mu$m for the linac has been chosen in order to be able to further decrease emittance dilution which is desirable for an upgrade of the luminosity and the energy. In principle this accuracy has to be achieved only by averaging of entire bunch trains, but at least a small number of special monitors should be able to resolve individual bunch positions.

The above emittance growth is based on a bunch energy spread necessary for BNS damping of 3×10^{-3} which results from the longitudinal wake-field and operating on the RF crest. Multibunch emittance growth with inter-bunch energy spread of 6×10^{-4} shows very little difference from the single bunch results (Section 4.3).

The effect of ground motion on orbit stability has been estimated. Beam resteering (1 to 1) should be performed every 25 minutes in order to limit vertical emittance dilution to less than 6% for ground motion frequencies $< 2.5\,\mathrm{Hz}$ (i.e., 50Hz/20 - the high cutoff frequency of the conventional beam steering feedback system).

The Beam Delivery System

The beam delivery system (BDS) reaches from the end of the linac to the IP and is 1400m long. The about 50 quads, sextupoles, and 16 bends per beam will each be provided with BPM's attached to the magnets and the assemblies placed on magnet movers for beam based alignment and tuning.

To make the following discussion easier to follow, functional sections are in order (see Section 4.7):

- (LMS) linac matching section,
- (CS) collimation section,
- (TDS) tuning and diagnostic section which is composed of the (SQSC) skew quad correction section and the (EMS) emittance measurement section,
- (BMS) beta matching section,
- (CCS) chromaticity correction section,
- (FT) final transformer.

The CS collimation section contains high beta and high dispersion regions with collimator pairs, energy measurement and correction, energy spread measurement, beam loss measurement for protection of the collimators.

The TDS tuning and diagnostic section provides for measurement and correction of transverse coupling in the SQSC and for measurement and minimization of emittance in the EMS. This is the major measurement and tuning area which sets, measures and adjusts the beam properties prior to the final transport to the IP. Six wire scanners are used for emittance measurement; four additional scanners are used at the skew quads are implemented with "u" angle wires as well as x, y wires. The emittance measurement station is capable of 1% measurement error. The carbon wires are $4\,\mu$m diameter.

The BMS provides for fine tune at the IP and adjustment of phase from the collimators to the final focus. Measurements made in the TDS give information for adjustment of these quads. Beam can be checked at the IP image points that occur at the begining of the CCS and within the CCS at the beginning of the FT. The vertical image of the 15 nm spot has a magnification of $46\times$ to give a spot of 700 nm. This will require laser wire or gradient undulator (see below) instruments. The sextupoles in the CCS have to be turned off for this measurement at the image point in the FT in order not to dilute the spot size by large chromatic aberrations. The CCS " -I" optics sections must be checked by a BPM-corrector null method to assure the proper optics.

Final tuning of the IP spot size requires movement of the sextupole pairs in a variety of combinations. The crucial vertical spot size measurement must be carried out with a laser interferometer (Shintake monitor [1]). The required resolution is about a factor of five better than what has already been demonstrated at the FFTB [2]. The horizontal spot is better measured with a laser wire [3]. These monitor laser beams pass through the electron beam 30-80 cm from the IP point and the low-β^* point must be shifted in z to this location. This is accomplished by the sextupole adjusters in the CCS.

The Shintake monitor has limited dynamic range of spot size that it can accurately measure for any specific laser wavelength. At a laser wave length of 262 nm spot sizes from 10 to 45 nm can be measured with 10% accuracy. On the other hand the laser wire spot can not be made smaller than $\approx$ 380 nm diameter using the an ArF excimer laser. This comes close to the beam size of 335 nm horizontally.

The profile scans using laser beams must detect the scattered Comptons which come out straight ahead with an opening angle of $1/\gamma$. For systems within the IP detector, the Comptons must be detected dowmstream of the IP.

The Shintake monitor has the potential for bunch length measurement as well. But as both it and the horizontal laser wire are deeply embedded in the detector, other less invasive instruments or instruments at other locations may be more practical for measurements that do not have to be done at the IP.

Other monitors are planned for the IP region (see also Chapter 2):

- Beam-Beam deflection monitor
- Fast luminosity monitor
- Precision energy measurement
- Polarization measurement

These monitors are noninvasive and can be used during standard operation.

The steering from the beam-beam force is used to monitor the offset of the two colliding beams. A kick angle of 75 microradians per vertical sigma offset is expected. A BPM 2 m downstream of the IP would see typically 150 μm offset per beam sigma separation. Individual bunch measurements are possible. The signal can be used for beam steering feedback (see Section 4.8.3).

A fast luminosity monitor can be used to detect beam detuning at the IP to do noninvasive fine adjustments and beam scans. Radiative Bhabha pairs detected about 9 m from the collision point could provide the appropriate monitor information.

Precision absolute energy measurements will be made of the beams in the extraction lines after the IP. The measurement uses displacement synchrotron light fans from bend magnets to measure the bend angle of the beam in a spectrometer magnet. A resolution of 10^{-4} is expected. However beams must not be colliding if precise before collision beam energy is to be measured.

The polarimeter uses laser beam scattering and detects Compton scattering asymetry. It is likely to be located before or after the IP.

Beam Steering – Initial Setup and Drift

Static tolarances of BDS magnet alignment indicate that typically y alignment tolarances of 0.5 to 10 μm are needed for many of the magnets if less than 2% luminosity decrease (with collision beam steering) is to result from an individual magnet. A model for uncorrelated rms motions of the magnets in x and y predicts that rms motions of 139 nm in y and 295 nm in x will yield 2% luminosity reduction (again with collision beam steering) (Section 4.7.3).

The simulation program Merlin has been used to check possible noninvasive tuning proceedures to correct the deterioration of the beam size by linear optics aberrations (Section 4.7.6). It was found that simple one-to-one steering of the BDS elements using the BPM's and magnet movers every minute was sufficient to restore the luminosity to almost its full value. A drop in peak (after retuning) lumimosity of 5% occured after about 5 days indicating that an invasive retune would be necessary on this time scale.

	where	typical beam size [μm]	resolution required [μm]	freq. of adjustment	bunch structure	invasive y,n
POSITION x, y						
bpm	linac	120-14 x,27-3 y	2 y	25 min.	pulse avg.	n
	BDS	360-13 x,75-0.9 y	2 y	1 min.	pulse avg.	n
(disp. tuning)				5 days	pulse avg.	y
slow feedback	IP	0.335 x,0.016 y	10 y	0.4 sec.	pulse avg.	n
fast feedback	IP		10 y	0.1μs	pulse avg.	n
BEAM SIZE						
carbon wire	TDS	20 x, 6 y	1 x, y, u	5 days	one bunch	y
laser wire	IP image	13 x,0.9 y	0.3 y	demand	bunch by b.	y
	IP$\pm$0.8m	0.335 x	0.3 x	5 days	pulse	y
Shintake mon.	IP$\pm$0.8m	0.016 y	0.01	5 days	average	y
BEAM ENERGY						
bpm	CS or CCS	180 x	3 x	0.4 sec.	bunch-by-b.	n
synch. light	extr. line			exp. demand	bunch-by-b.	n
ENERGY SPREAD						
wire	CS or CCS	40 x	5 x		one bunch	y
BUNCH LENGTH						
streak camera,	before	300 z	100 z	demand	one bunch	n
interferometer	linac			demand	or avg.	n
BUNCH CHARGE						
toroid/wall current	linac, BDS		1%	observe	bunch-by-b.	n

Table 4.8.1: *Overview of beam diagnostic requirements and tools. Additional instrumentation for luminosity and beam polarization measurement (not shown in the table) is foreseen in the IR.*

4.8.1.1 The Beam Position Monitor System

Introduction As described in section 4.3, measurement of the beam position with respect to the quadrupole plays an important role in the design of a linear collider. Single and multi bunch beam blow up generated by uncontrolled orbit distortions has to be minimized. To preserve the small emittance generated in the damping ring in the SBLC an accuracy of a few micrometer relative to the magnetic axis of the quadrupoles is necessary. At the same time any movement of the quadrupoles in the main linac of less than a few micrometer has to be controlled. For example the expected movements of the quadrupoles induced by temperature variations will be in the region of 10 - 20 μm per degree C°. The reach the equilibrium temperature in the linac tunnel will need a few days or weeks of continuous operation during which fast and accurate orbit correction is particularly important. Taking into account the different thermal time constants of the different components individual movements have to be expected.

Beam Properties and Design Criteria A number of design criteria are comparable with existing beam position measurement systems in the circular accelerators. Only a moderate dynamic range for the intensity is required and just a few millimeters of sensitive range where the specified accuracy has to be guaranteed are necessary (see table 4.8.2).

Particle per bunch	2×10^9 to 5×10^{10}
Number of bunches per burst	1 to 330 bunches
Bunch to bunch distance	6 nsec to single bunch
Burst length	2 μsec. max
Repetition rate	Single pulse to 50 Hz
Monitor resolution	$\pm 2\,\mu$m
Monitor alignment	$\pm 5\,\mu$m
Operation range	± 2 mm
Operation mode	single and multi bunch
Readout frequency	up to 50 Hz

Table 4.8.2: *Design specifications for the beam position monitor system for the SBLC*

The Type of Pick Up and the Signal Processing The pick-ups of existing beam position monitor systems can basically be divided into three different types: buttons, loops and cavities.

A button monitor is a pick-up which is usually (in storage rings) smaller than or comparable to compared to the bunch length, just a few mm diameter circular plate, embedded inside the vacuum chamber. This pick-up couples primarily capacitive to the beam and transmits the signal via one RF feed-through to the outside electronics. Combinations of two or more pick up signals result in a beam position measurement.

One of the first designs was made for PETRA, a 2.2 km long e^+e^- storage ring at DESY, in 1976 [4]. Most of the circular lepton accelerators with a short bunch length like PEP, TRISTAN, LEP, DORIS, ESRF and HERA-e ring etc. make use of the advantages of this kind of pick up, such as the simple mechanics and the high electronic stability.

Loops are pick ups which have different dimension in the longitudinal and transverse direction with respect to the beam, e.g. like a wire with two feed-throughs at the ends. A loop couples primarily inductive to the beam. If the impedance is matched to both ends we call this monitor a strip line or a directional coupler. Two operation modes are given depending on the length of the antenna. First, the antenna is long and second, the antenna is short relative to the bunch length in the beam. Due to the longitudinal dimension of the loops the coupling factor for longer bunches is higher in comparison to buttons. Therefore the loops are mostly under operation in proton machines like, for example, in the HERA P-ring. At the FFTB [1] loops are also in use for a high resolution beam position monitor.

More recently, a number of proposals and also first results using cavities as high resolution beam position monitors, have been presented [5]. The beam passes through a cavity with a dipole mode frequency of several GHz. Two pick-ups are located on opposite sites of the cavity. The beam position is detected using the difference signal of the two pick ups. One of the advantages of a cavity based monitor is the intrinsic frequency filter, and if used in a resonant mode, excited in resonance by a multi-bunch train, the amplified signal produced by the beam.

Processing the signals, the beam position detected with two opposite antennas to first order is simply given by:

$$X = C \cdot \frac{(\mathrm{P}_1 - \mathrm{P}_2)}{(\mathrm{P}_1 + \mathrm{P}_2)}$$

C is the so called monitor constant which is a geometric factor. This factor is usually related to the vacuum chamber cross section.

With the diameter of the SBLC vacuum chamber of ≈ 25 mm, C will be of the order of 10 to 15 mm for loop or button monitors. Therefore the stability of the pick up and the resolution of the signal processing has to be 10^{-4} to fulfill the required accuracy in beam position measurement of $\pm 2\,\mu$m .

The SBLC bunch timing from single bunch up to 330 bunches in one burst of two microseconds length is one of the critical issues in designing the pick up and the signal processing. Two principle schemes, either narrow or wide band signal processing are typically used in today's operating accelerators.

A narrow band layout with state-of-the-art filters, amplifiers, mixers or analog combiners delivers directly the difference and sum information of two pick up signals as described in the above formula. Schematically this is shown in the upper part of Figure 4.8.1. The resolution and the accuracy is limited by the non-linearities of the components, the signal-to-noise ratio and a number of other smaller errors.

For single bunch detection a broadband signal processing has some advantages like the higher power of the signals or the redundant information, because each individual pick up signal can be digitized independently. But the resolution and accuracy is

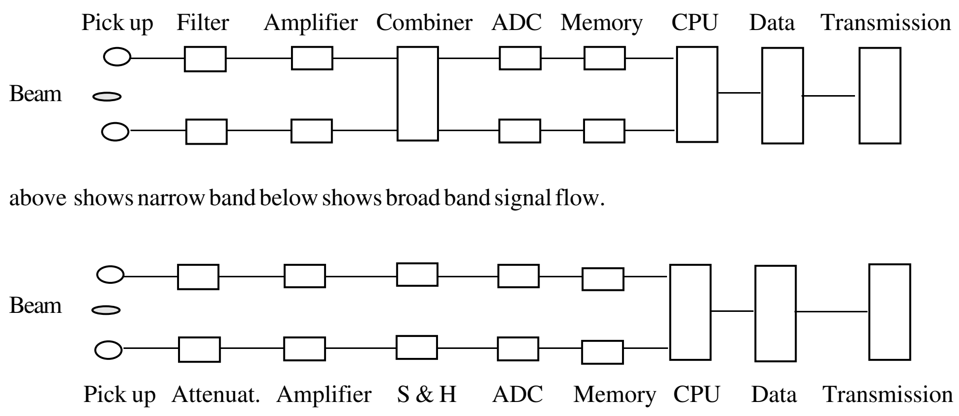

Figure 4.8.1: *Sketch of the two principal transmission schemes for either narrow band (upper part) or broadband (lower part) signal processing of BPM signals.*

limited by properties of the ADC (see lower part of Fig. 4.8.1). A Strip Line Monitor is designed and under operation at the S-Band Test Facility [6] and a sketch is presented in Fig. 4.8.2. Mechanical pre-alignment in principal is possible and has been done for these bpm's down to approximately 20 μm [8].

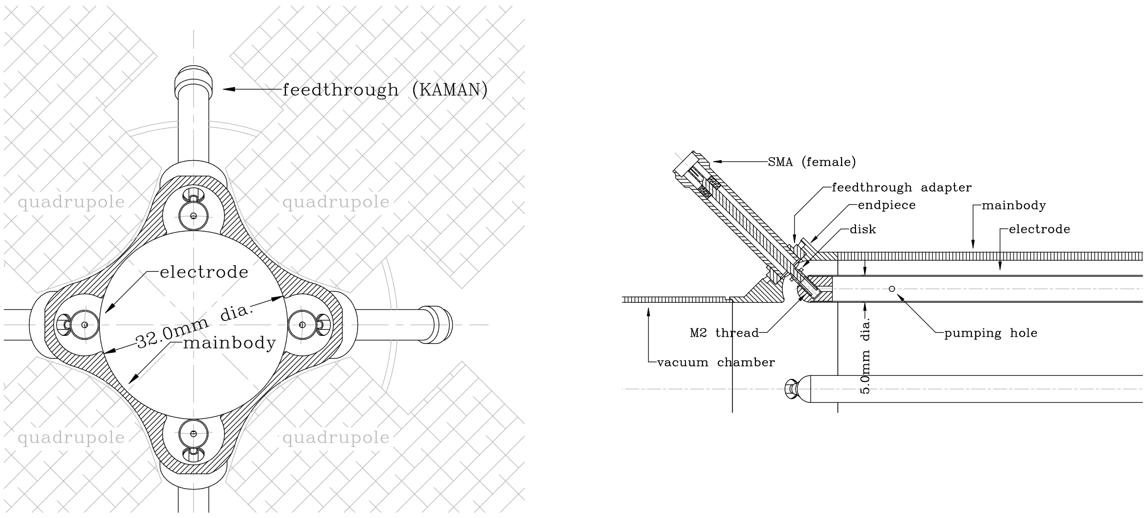

Figure 4.8.2: *SBLC stripline beam position pickup (cross- and longitudinal-section)*

With today's technology for high frequency electronic components both concepts, the narrow and the broad band signal processing, will fulfill the requirements of the S-Band Linac beam position monitor system. The choice for buttons or loops instead of cavities seems natural due to the wide operation range from single- bunch to multi-bunch with a bunch spacing of 6 ns and 330 bunches per burst.

Calibration The most important information to be extracted from the beam monitor system is the beam position relative to the magnetic quadrupole axis in the horizontal and vertical plane. With the necessary accuracy of less than $\pm 5\mu$m relative to the quadrupole axis a calibration of the monitors without the beam is extremely complicated, expensive, ineffective and not advisable.

The alternative, in-situ calibration of each beam position monitor to its associated quadrupole with the beam, offers all advantages we need. It is a well known procedure to change the current of a quadrupole and measure the change of the beam position with all the monitors downstream in the linac. This procedure is simple, repeatable at any time and can be done in a fast, proper and fully automated way.

With the use of the so called Beam Based Alignment - shown for example at SLAC with the FFTB [1] and at DESY with the HERA e-ring [7] - any other monitor calibration is not necessary. The accuracy is much higher as compared to standard alignment techniques, because the number of involved monitors is large and limited only by the resolution of the monitor being investigated without any other significant error contributing.

Controls With the foreseen orbit read out frequency up to 50 Hz this procedure can be fast compared to any thermal or diffusive ground motion time constant. Assuming, for example, 5 seconds for a one monitor calibration, with approximately 600 monitors in each linac in total only one hour will be required. Once the accelerator is set-up this procedure can be performed in parallel at different sections.

Each beam position monitor will be equipped with a local memory management where all pick up information can be stored in parallel. With the worst case of four pick up signals from each bunch in one burst of 330 bunches we get 4 * 330 Words (of two bytes each) per pulse. A local micro computer at each monitor will calculate from this the 330 horizontal and vertical positions in a few milliseconds.

The distributed beam position control system transmits the beam position averaged over one burst to the machine control system within the 20 msec given by the linac repetition rate.

Summary The typical demands from the SBLC beam position system are challenging but feasible with todays available electronics and control. With the expectable improvements of the industrial standard analog and digital electronics in the future the more extended features seem to be possible in a few years.

Finally with today's data transmission technology in controls - used for example at the new PETRA Control System - the entire orbit information from both linacs is transmittable at real time (50 Hz repetition rate) to the central machine control system.

From this point of view the beam operation should be possible on a controlled pulse-to-pulse basis with an accuracy of less than $\pm 5\,\mu$m for each beam position value along the 30 kilometer long accelerator.

4.8.1.2 Bunch Length Measurement

The rms bunch length for the SBLC design is 300 μm (1 ps). For the FEL operation, the rms bunch length is 0.025 mm (80 fs) (see chapter 5).

For bunch length measurements in this regime, different kinds of radiation emitted by the particle beam can be used. This can be transition radiation, synchrotron radiation or Čerenkov radiation. Transition radiation has the advantage that it can easily be produced by moving a thin metal target into the beam. However, at high current the target can be destroyed. This can be avoided either by doing measurements at low current only or by using diffraction radiation [9]. Alternatively, synchrotron radiation produced non-destructively by magnetic elements can be used [10].

Short radiation pulses can be measured in the time domain using streak cameras. A streak camera consists of a photocathode which converts light pulses into electron pulses. These are then deflected and displayed longitudinally on a phosphor screen (Fig. 4.8.3). These systems offer the unique possibility of single bunch observation in real time. The time resolution, widely assumed to be limited to 1 ps and longer, has been improved significantly by the manufacturers. Fast streak cameras are now commercially available with a resolution of down to 180 fs. This might be even improved in the future.

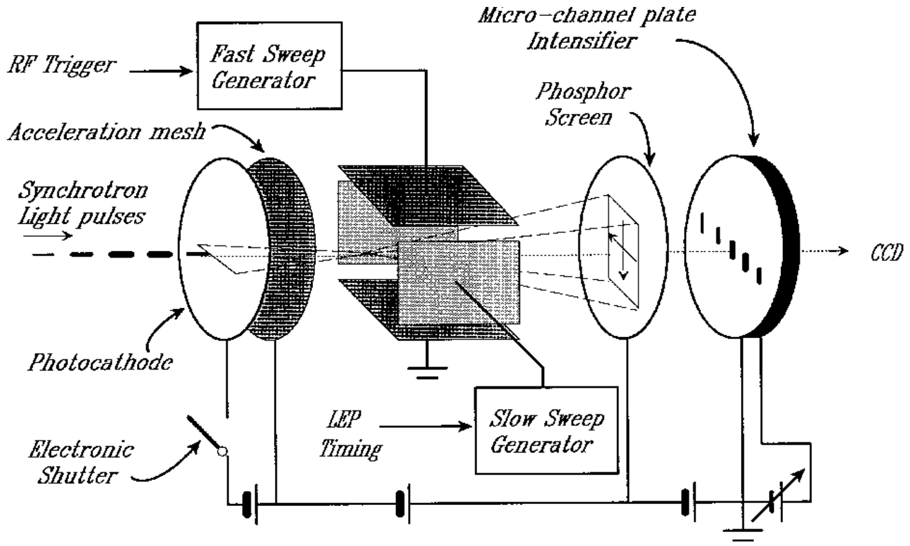

Figure 4.8.3: *Streak camera for measurements in the time domain as used at LEP.*

Alternatively, measurements in the frequency domain can yield information about the bunch length. This method works better the shorter the bunch length is. At wavelengths of the order of the bunch length and longer, coherent transition or synchrotron radiation is produced as the bunch acts as one single particle. The coherent part of the spectrum is much more intense than the incoherent part. It can be shown that the coherent radiation spectrum is just the Fourier transform of the longitudinal charge distribution. Hence, measuring this part of the spectrum means measuring the bunch length.

From picosecond bunches, coherent radiation is produced in the millimeter wavelength range. For the observation of mm wavelength radiation, a photo-acoustic detector can be used. It works at room temperature and has a flat response from 0.1 mm wavelength up to 1 cm. For shorter bunch lengths, the onset of the coherence effect shifts to the far infrared where pyroelectric and bolometric detectors are available at low cost.

Two different types of spectrometers have been developed for use at the TESLA Test Facility and as prototypes for the linear collider. A series of high pass filters for mm waves serves, together with the broadband detector, as a simple spectrometer. This spectrometer has been successfully used for bunch length measurements at the CLIC test facility [11].

A polarizing Michelson interferometer (Martin-Puplett interferometer) can measure the autocorrelation function of the radiation pulses. The power spectrum can then be obtained as the Fourier transform of the autocorrelation function. The interferometer uses wire grids as beam splitter and roof mirror reflectors (Fig. 4.8.4). It has an intrinsic flat characteristic over the whole wavelength range of interest.

As a third option, the use of a new spectrometer based on superconductivity is being examined. A setup developed at the Forschungszentrum Jülich is being evaluated with respect to its possible application for bunch length measurements [12].

4.8.2 Beam Size Monitoring

An important class of diagnostics are the transverse beam size monitors which are required primarilly for the measurement of the beam emittance. Two modes of operation are expected:

1. problem diagnosis, commissioning and boot-strapping, i.e. non-luminosity operation possibly with single bunch per pulse, and

2. continuous or semi-continuous monitoring of the beam during nominal luminosity operation.

For the former case, either Optical Transition Radiation (OTR) screens or SLC-type wire scanners[13] using 4 μm or 7 μm carbon filaments are expected to be the standard diagnostic.

Carbon filament wire scanners are used to sample the beam at different positions within the beam profile, and the beam width is then determined by fitting a Gaussian distribution to the data. The technique requires several bunches to perform a single measurement, so the result is an effective beam size of all bunches measured including any position jitter between them. However, the jitter can be measured by high-precision ($\approx 1\mu$m) BPM's so that this contribution to the effective beam size can be unfolded. Two types of signal can be used: i) bremsstrahlung from the wire can be detected some distance directly downstream, or ii) secondarys which are eventually scattered out of

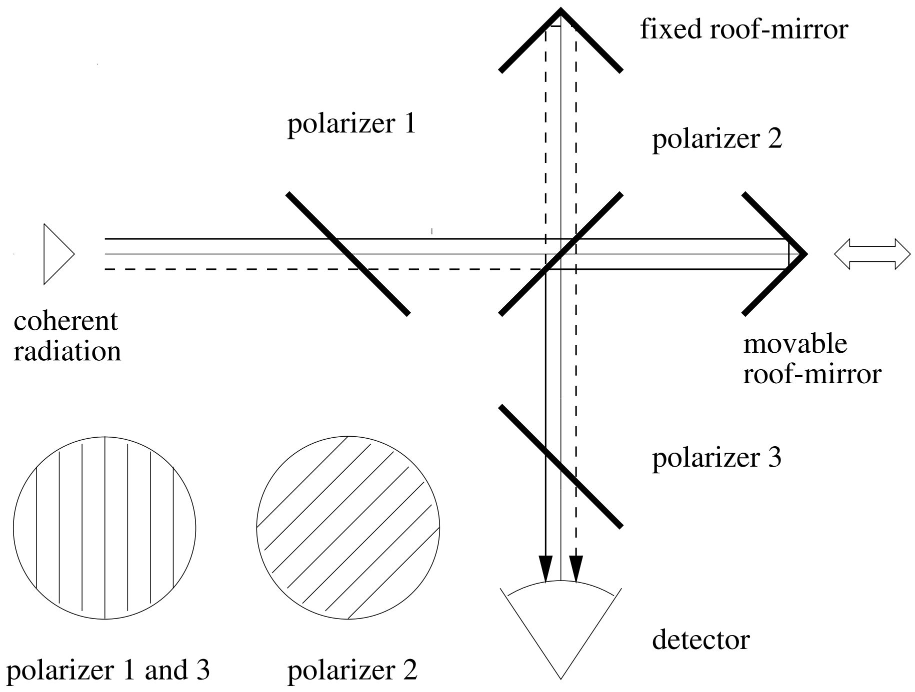

Figure 4.8.4: *Martin-Puplett interferometer for measurements in the frequency domain as to be used at TTFL.*

the beam pipe can be detected. The former requires a downstream dipole in order to position the bremstrahlung deletector on the downstream (photon) axis: such an approach is most applicable in the beam delivery system where bends occur naturally. In the linac and other straight sections, one must rely on the secondaries scattered out of the beampipe for detection. The wire scanners themselves are small compact devices which can easily be incorporated into the machine with the mimimum of impact to the lattice.

At the full SBLC bunch population of 1.1×10^{10}, the charge density of a single bunch should be sufficiently low that a 4 μm Carbon wire should survive single bunch operation at the nominal repetition rate of 5Hz. The temperature rise in the wire caused by a single bunch (with charge N_e) passage can be estimated from the energy loss dE/dx = 4 MeV/cm, the heat capacity $c_p = 1.18\,\mathrm{J/(g\,K)}$ and the specific density $\rho = 2\mathrm{g/cm^3}$ of Carbon:

$$\Delta T \approx 0.44 \cdot 10^{-3}\mathrm{K} \times \frac{N_e[10^{10}]}{\sigma_x \sigma_y [\mathrm{cm}^2]} \tag{4.8.1}$$

In the TDS we have $\sigma_x\sigma_y \approx 120\,\mu\mathrm{m}^2$ and for N_e=$1.1{\cdot}10^{10}$ we get ΔT=400 K, which seems tolerable. However, the wire will only survive a few bunches of the nominal bunch train in multi-bunch mode, and so Carbon wire devices cannot be used for monitoring the beam size during luminosity production. Even in single-bunch operation, it is still possible that the wires will fail, and so it is prudent to have each scanner equipped with 5 to 10 separate wires.

The resolution of a beam size measurement with a wire is expected to be better than the wire diameter. The sytematic error for a 4μm wire and 6μm beam size is about 5%.

The OTR device In the measurement of transverse beam charge distribution, OTR present a number of advantages: it is fully linear with the beam charge, without any saturation effect, it is emitted by a surface crossing and thus does not show any depth effect. Its temporal emission in the subpicosecond range allows the selection of a single bunch. The main practical limits to OTR use at high energies, when the low emittance allows small beam dimensions, are the diffraction limit that, due to the angular distribution and the polarization properties, is larger than for standard point optical sources and for 500 nm wavelength is roughly $10\,\mu$m, and the fact that it is derived by an intercepting device, so that the screen can be destroied by the high energy density lost in the material by well collimated beams. For an aluminum foil, which is the preferred material for its high and uniform reflectivity over the whole optical spectrum, the temperature rise caused by a microbunch of $1.1{\cdot}10^{10}$ electrons is $.07\,^\circ\mathrm{C}/R^2$ in which R is the radius (in mm) of a flat circular beam distribution, and assuming a rather conservative value of $2\,\mathrm{MeV/cm^2}$ as the single particle energy deposition (energy independent). Limiting the temperature rise to $300\,^\circ$C, we obtain a minimum beam radius of $6\,\mu$m (that corresponds to a rms value of about $3\,\mu$m). It will be important to study different materials to find the best compromise between emission efficency and thermal and mechanical properties.

For multi-bunch operation, there are three possibilities:

1. laser wire scanner
2. pulse snatching scheme (off-axis monitoring).
3. gradient undulator

In principle a laser wire acts in the same manner as a Carbon-wire scanner. A laser wire can be focused to a sub-micron spot, which is then scanned through the beam. The situation is also similar to the Carbon-wire approach with respect to signal detection: either the Compton scattered photons are detected directly downstream (again requiring a downstream dipole), or the back-scattered electrons (which are eventually sweeped out of the machine) are used. For SBLC, it is feasible that a long pulse-train laser can be used to sweep through the entire bunch train in a single shot, thus allowing a fast effective beam size measurement of a single bunch train. Such an approach is necessary for the laser monitors close to the interaction point, where it is neccessary to mitigate the effects of the final doublet vibratration on the (particle) beam. In a short-pulse mode, the laser wire can be used to sample single bunches in the bunch train, sampling on successive trains the same bunch location. This mode of operation is

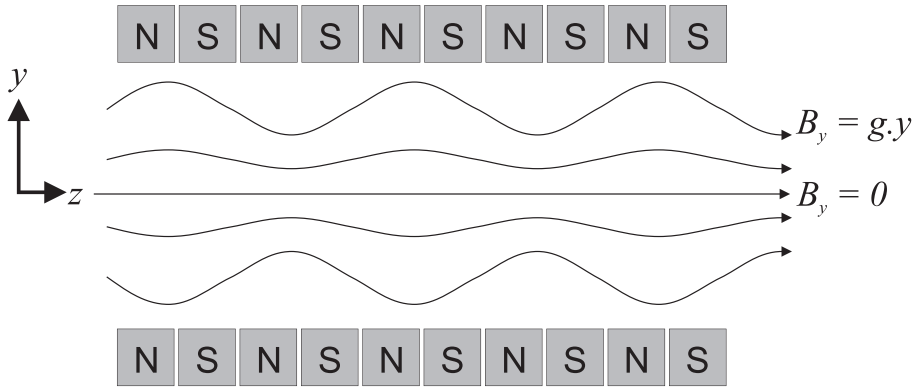

Figure 4.8.5: *Principle of the X-ray Gradient Undulator. The vertical undulator field is proportional to the vertical offset (y), being zero on the nominal axis (y = 0). Thus particles on-axis do no radiated, while particles off-axis do. The total power radiated by a centered beam is therefore proportional to* σ_y^2 *[14].*

directly analagous to the single-pulse Carbon-wire operation. As of writing, laser-wire technology is still in its infancy, although such a device now exists and operates at the SLC [3]. However, much work still remains to be done (especially for the back-scattered electron mode). It is advantageous (and prudent) to always place a carbon-wire device and a laser-wire device together, so that one can be used to calibrate and troubleshoot the other.

A more conservative approach (but slightly more invasive) is to use fast kickers to "steel" a single bunch from a bunch train and send it to an off-axis scanner. Here again Carbon-wire devices can be used (as well as any other fluorescent or OTR screen technique). The approach probably requires more tunnel space than the laser-wire option.

Of the three methods proposed, only the X-ray gradient undulator[14] offers a single-shot single bunch measurement of the beamsize. A gradient undulator is an undulator whose pole-pieces are displaced one-half period as shown in figure 4.8.5. The undulator field has now a linear gradient in the vertical direction. As a result, vertically off-axis particles radiate, while particles on-axis do not. The total power output from the undulator is directly proportional to the square of the beam height. Theoretical studies have shown that at the exit of the linac (250 GeV) in excess of 10^5 60 MeV photons can be expected for a 1 m device with a 1 cm undulator period, and a field gradient of 4.8 T/cm. The main disadvantage of the device is that it requires a dipole downstream in order to place the X-ray detector on the axis of the undulator (again making the device more suitable for the beam delivery section). If the device is to be used in the linac, then small chicanes will be required, and a length penalty will be incurred. It should be noted, however, that the gradient undulator is a conceptual device, and work is currently in progress to evaluate its performance and limitations.

4.8.3 The Interaction Region Feedback

Fast ground motion will cause independent orbit movements in the two linacs of a linear collider such, that the beams may miss each other at the interaction point (IP). But even at rather large vertical beam-beam separations at the IP, beams will deflect each other through their electro-magnetic fields. By measuring the position of a beam, which has just passed the IP and compare in it the position of a first pilot bunch -which does not have a partner in the opposing beam- with that of the following bunches in the same bunch train, the opposing beam can be steered with ultra fast kicker magnets for optimum collision at the IP. A feed-back system based on this principle will make the necessary steering corrections within a time short compared to the duration of the bunch train.

Fast beam steering at the interaction point, which relies on the beam-beam effect of colliding bunches, is a powerful tool to relax nanometer tolerances for final focus quadrupoles in linear colliders. Even betatron amplitude growth excited by vibrating quadrupoles further upstream in the linac, which is not filamented by the time the beam reaches the IP, can be corrected with fast beam steering. From Tracking calculations we expect only 30% filamentation over the entire length of the linac 4.3. One stringent requirement for a feedback, which corrects the bunch train offset in the IP is, that the beam pulse is long compared to the overall processing time of the detected signal from the beam position measurement (BPM) to the kicker magnet. Parameters which influence this delay are the distance of the beam position monitor to the IP, the processing time of the feedback loop and the required magnetic field strength compared to the available peak power of the amplifier (see Figure 4.8.6). The amplitude of pulse to pulse ground motion which can be expected from measurements done in the HERA tunnel, which is a tunnel under the city of Hamburg with an colliding beam facility [15, 16] is approximately 70 nm rms for Frequencies below 1 Hz which is roughly six times the design vertical beam size. In order to limit the Luminosity reduction to 5%, the jitter at the IP should be smaller than 30% of the beam size, which is 5 nm in our case. A list of the main interaction region parameters is extracted from the complete list and given in Table 4.8.3. One possibility to achieve this tolerance is to design a passive support system that keeps the final doublets at a given position over a time scale much larger than the repetition rate of the accelerator. This is certainly a challenging task for the technical design of the quadrupole supports which are part of the experiment of a linear collider. Vibrations from the linac quadrupoles are not correctable by this method with reasonable effort. For the S-Band Linear Collider study two feedback loops are foreseen to relax this tolerance well beyond the measured value of 100 nm which was mentioned before. One loop relies on a direct measurement of the quadrupole vibration in combination with a mechanical (or correction magnet) feedback. Such a loop has been tested already and a suppression of a factor of 4 in amplitude for the rms value at 2 Hz has been proven which is described in more detail in section 4.8.4. This feedback loops have mainly been developed to correct the linac quadrupole vibration.The second loop will be described in more detail in the following text.

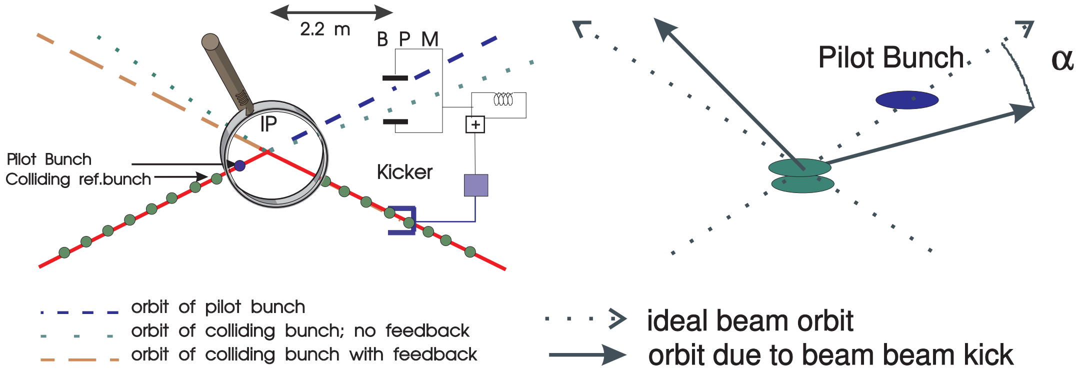

Figure 4.8.6: *Sketch of the interaction region layout and the location of the beam position monitor and the kicker magnet. The pilot bunch is the first electron bunch in the train with no interacting counter part.*

Ne per bunch		$1.1{*}10^{10}$
vert. beam size (no pinch)	nm	15
horiz. beam size (no pinch)	nm	335
Disruption (vertical)		7.1
Disruption (horizontal)		0.32
β_y at IP	mm	0.45
β_x at IP	mm	11.0
bunch length	mm	0.3
crossing angle	mrad	6
bunch train length	msec	2
bunch to bunch distance	nsec	6
distance: BPM to IP	m	≈ 2

Table 4.8.3: *Interaction region parameters for the 500 GeV S-band Linear Collider Study*

For a round beam the beam-beam force of two colliding bunches is proportional to the separation of the two bunches over approximately one σ. Operating with an aspect ratio($=\sigma_x/\sigma_y$) of 20 (or more), as it is foreseen in Linear Colliders to reduce the beamstrahlung, produces an almost linear beam - beam force over approximately $10\,\sigma_y$. According to the beam-beam simulations using the parameters from 4.8.3, the kick angle a per σ_y separation of the two colliding beams is given to within a good approximation by:

$$\alpha(\mathrm{mrad}) = \frac{\Delta y}{\sigma_y} \cdot 0.057 \cdot (\mathrm{mrad}) \tag{4.8.2}$$

Let us assume that the BPM next to the IP is located at the position of the first quadrupole of the final doublet, which is 2 meters away. At this position the beam offset in the monitor according to formulae above be 120μm per σ_y separation at the IP, which is easy to measure as compared to the four micrometer resolution being required for the rest of the linac BPM's. A method based on beam-beam deflections to measure precisely the offset of the two colliding beams has been used for single bunch operation in the SLC from pulse to pulse already [17]. On the other hand, a bunch to bunch measurement of the beam position, as being proposed for the TESLA Linear Collider study for both outgoing beams within one pulse can not be used, because of the delay time for signal processing as compared to the overall pulse length and bunch to bunch distance (compare 4.8.3). Therefore a combination of both methods is proposed which uses a pilot bunch in one of the two colliding beam pulses and only a single BPM in combination with a single kicker magnet.

In general, using such a scheme has the significant advantage, that almost no mechanical disturbance with an amplitude larger than a nanometer (vibration, girder resonance etc) can separate the colliding beams on the time scale of one bunch train length ($2\,\mu$sec $\rightarrow$ 500 kHz), once they are colliding.

The location of the beam position monitor and the kicker has to be as close as possible to the IP in order to reduce the processing time of the feedback loop. Because the quadrupole next to the IP will have an integrated BPM the shortest distance is 2.2 meters from the IP. If the delays on cables, the response time of the feedback amplifier and the finite rise time of the kicker are added up, an overall delay of 50 nsec is expected. If we assume in addition that one bunch train will have a pilot bunch, the delay will increase to about 60 nsec. Therefore 3% of the $2\,\mu$sec long beam pulse will not be corrected and, if far enough separated between pulses, will not contribute to Luminosity. In case of SLED operation with a 500 nsec long beam pulse, as foreseen for the energy upgrade to 800 GeV, the potential loss will increase to 12%. A continuous measurement of the beam-beam separation during the pulse will be done to correct even displacements which change along the bunch train.

aperture radius	mm	10
effective length	mm	500
magnetic field (max. possib.)	Tm	1.1x10−4
power amplifier		
pulse duration	msec	2
bandwidth of amplifier	MHz	50
peak power /amplifier	kW	2.5
pulse current	A	±10
rise time	nsec	20
repetition rate	Hz	50

Table 4.8.4: *Design values for the feedback kicker and the broad band amplifier.*

In order to allow orbit corrections at the IP for a value of 150 nm, the required kick is only $0.07\,\mu$mrad, if a distance from the kicker to the IP as close as the BPM position is assumed. For the 250 GeV beam a magnetic field of 6×10^{-5} T is sufficient. The kicker will be a strip line type kicker fed by two broad band amplifiers which can excite a maximum magnetic field of 1.1×10^{-4}. The parameters are given in 4.8.4. The power amplifiers deliver a peak power of 2.5 kW each and have a bandwidth of more than 50 MHz to power each strip.

The Beam Position Monitor In order to measure the beam position of the pilot bunch with respect to the colliding bunches an analog delay will be used to subtract the two signals from the pilot bunch and the first colliding bunch directly. In addition the bunch intensity must be determined as well because the beam-beam kick is proportional to the bunch charge in the opposite beam. The resolution of the beam position measurement is $5\,\mu$m [18] which is 4% of the effect of a one σ_y separation and the bunch intensity measurement should be of the same order.

4.8.4 Active stabilization of mechanical quadrupole vibrations

To compensate ground motion induced quadrupole jitter at frequencies beyond approximately 2 Hz, an active mechanical stabilization system has been developed [19]. It consists of an inexpensive geophone measuring the motion of each single quadrupole and a piezo actuator to compensate the detected magnet motion. For simplicity reasons as well as cost limitation, the mechanical design is based on a single piezoelectric actuator tilting the quadrupole around its transverse horizontal axis thus keeping its center at rest, as schematically shown in Fig. 4.8.7. The opposite end of the magnet

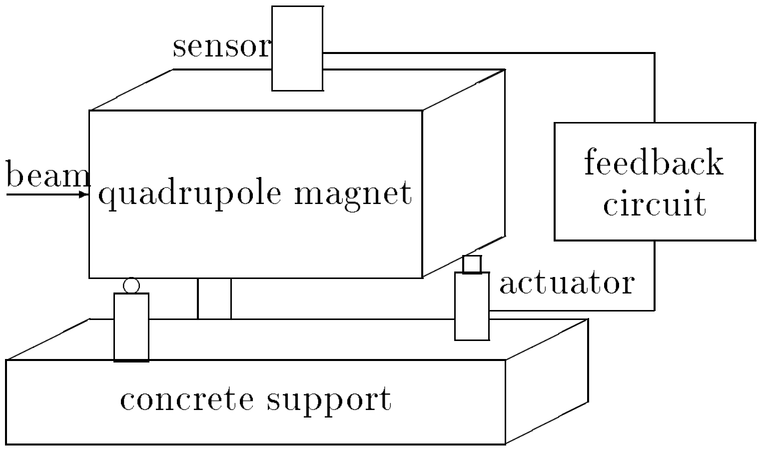

Figure 4.8.7: *Schematic view of the active stabilization system.*

is placed on two massive ball-ended feet to reduce dry friction. To fix the magnet's horizontal position, two horizontal "arms" with sufficient vertical compliance but high stiffness in the horizontal directions have been placed on one side of the quadrupole. The sensor is mounted on top of the magnet just above its center.
The internal noise of the geophones provided by KEBE [20] has been determined at 1.1 ± 0.3 nm in the frequency band beyond 2 Hz, which is well below the quadrupole jitter tolerance.
The whole system is placed on a very stiff concrete support with high internal damping

to avoid amplification of ground motion due to mechanical resonances. As experimentally confirmed, it has no mechanical eigenmodes in the frequency range up to 300 Hz. The triangular cross section ensures the transfer of horizontal ground motion without amplification.

The complete active quadrupole support is shown in Fig. 4.8.8.

For this first prototype of the active stabilization system, the feedback circuit has been

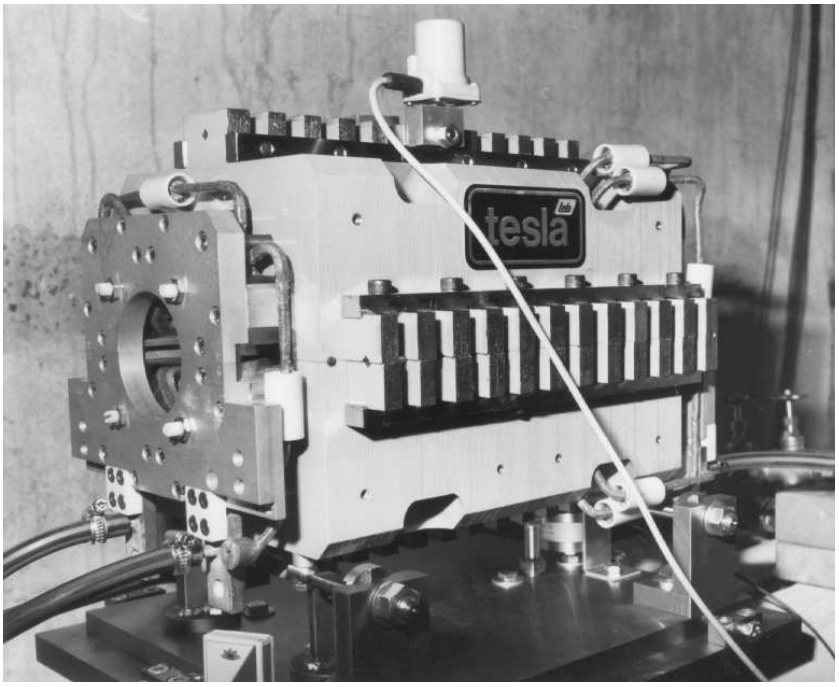

Figure 4.8.8: *Active stabilization system, consisting of a KEBE geophone on top of the magnet and a piezo actuator below it to tilt the quadrupole around its horizontal transverse axis. A match-box in the front indicates the size.*

realized on a PC with 16 bit A/D board. Compared to an analog system, this has several advantages. First of all, filters with extremely low time constants of many seconds can be realized, limited only by the numerical accuracy of the processor. Furthermore, the feedback algorithm can be easily changed, and even some built-in intelligence can be implemented.

The algorithm consists of a 100 sec highpass filter to cut offsets of the input signal, a 100 sec lowpass filter used as integrator to get the displacement from the velocity signal, and several digital filters, as schematically shown in fig. 4.8.9. An 8 Hz first order lowpass filter is used to suppress the 143 Hz resonance below 0 dB in order to achieve stability of the feedback system. To compensate the gain loss connected with this low cutoff frequency, a 7 Hz to 30 Hz first order bandpass filter is connected in parallel to the output of this lowpass filter, resulting in additional gain in this frequency band without any global but only some local phase shift. The gain factors G_1 and G_2 are chosen as 2.9 and 1.5, respectively, which is close to the stability limit of the feedback system. Though this results in increased amplitudes at 0.8 Hz and between 30 and 70 Hz, this is experimentally confirmed to be the best compromise between a high attenuation factor in the frequency band from 2 Hz to 30 Hz and this amplification, resulting in the smallest rms value for frequencies higher than 2 Hz. Of course, this result depends on the ground motion spectrum and might therefore slightly change in the real linear collider environment.

As was observed during the tests, the feedback system tends to perform low frequency

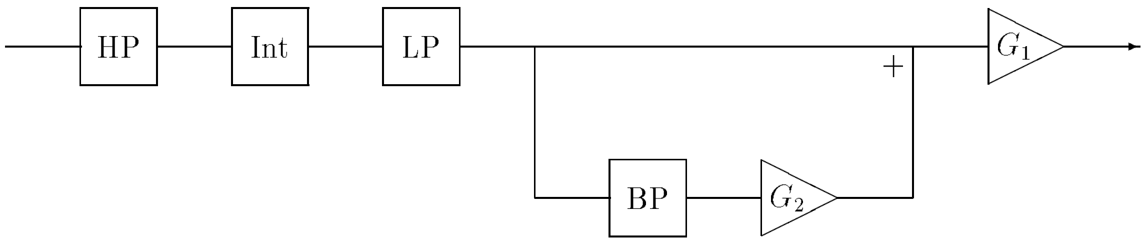

Figure 4.8.9: *Schematic view of the feedback algorithm, consisting of an integrator (Int) and several digital filters (lowpass LP, highpass HP, bandpass BP).*

oszillations over the total 16 bit range of the DAC after having accidentally reached its range limit due to some unusually high ground motion amplitudes. To stabilize the system again, it is necessary to decrease the gain. Therefore, the gain factor G_2 is reduced by 20 % each time the output value of the DAC reaches ± 15 bit and then increased again by an increment of $2 \cdot 10^{-4}$ in each cycle, resulting in a high reliability of the system even under extreme conditions.

The complete system has been set up in DESY hall 2, an experimental hall close to the DESY synchrotrons which has been chosen for the installation of the S-band test linac. Since there are two accelerators, several transformers and some other technical equipment operated nearby, it may be considered as an example of an operating Linear Collider environment. Therefore, the results obtained in this place should be comparable to those to be expected in the future accelerator.

To determine the performance of the system, a second KEBE sensor was placed on the floor just below the magnet. The signals of the feedback sensor as well as this second one were simultaneously sampled at 400 Hz to exclude artefacts in the results due to the statistical behaviour of ground motion. Sets of 1024 data points each were integrated to obtain the displacement from the velocity signal, multiplied by a Hanning window and Fourier-transformed in order to determine the power spectra Φ_{xx} and Φ_{yy} of the two signals. Here, the subscript x denotes the motion signal obtained on the ground, while y corresponds to the signal measured on top of the magnet. From these power spectra, the rms values σ_x and σ_y of the displacement in the frequency band f_0

to infinity can be calculated as

$$\sigma(f > f_0) = \sqrt{\int_{\omega_0=2\pi f_0}^{\infty} \Phi(\omega) d\omega}. \tag{4.8.3}$$

To ensure the reliability of this method, signals of both sensors were processed with the feedback system switched off. In this case, the transfer function is expected to be unity. Because the internal noise level of the two identical sensors is negligible compared to typical ground motion amplitudes, the correlation function γ can be estimated to be identically unity. With this assumption, the transfer function H reduces to

$$H(f) = \frac{Y(f)}{X(f)}, \tag{4.8.4}$$

and therefore, its modulus can be calculated from the square root of the ratio of both power spectra:

$$|H(f)| = \sqrt{\frac{\Phi_{yy}}{\Phi_{xx}}}. \tag{4.8.5}$$

The measured feedback gain calculated as the square root of the ratio of these two power spectra is shown in Fig. 4.8.10, together with the theoretically expected curve. As this figure shows, both curves are in nearly perfect agreement.

Fig. 4.8.11 presents the rms value σ of simultaneously measured ground and magnet

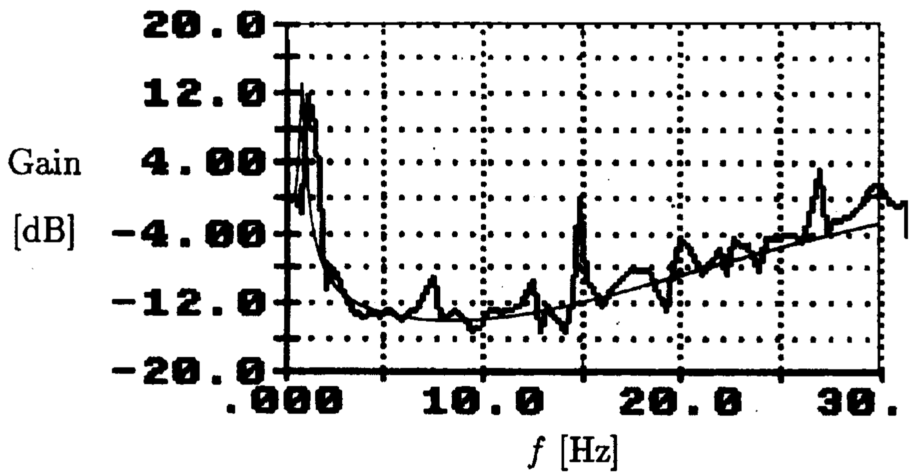

Figure 4.8.10: *Measured feedback gain (thick line) in the frequency band from 0 to 30 Hz, calculated from the square root of the ratio of the two power spectra simultaneously measured on the ground and on top of the magnet. The smooth thinner curve shows the theoretical transfer function.*

motion as a function of the lower cut-off frequency f_0, as has been calculated from the power spectra Φ_{xx} and Φ_{yy}. Although a vertical ground motion rms value of 100 nm at

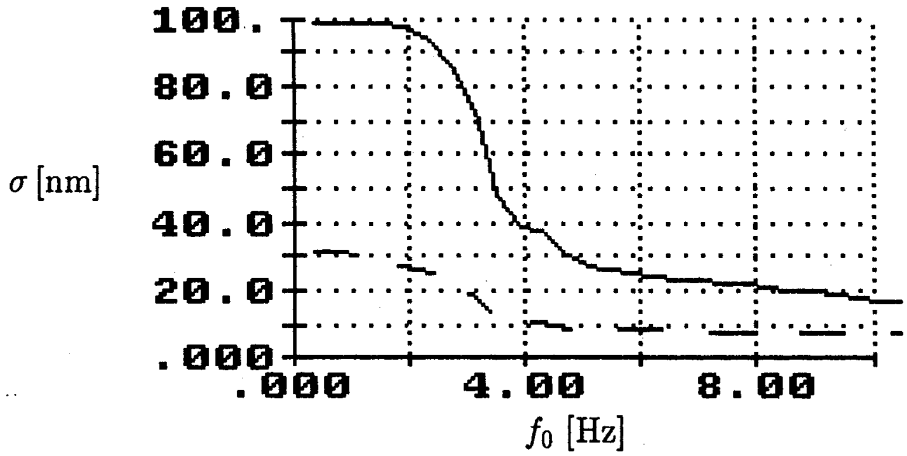

Figure 4.8.11: *rms value of ground (solid) and magnet motion (dashed) with the feedback system switched on in the frequency band f_0 to infinity as function of the lower frequency f_0, f_0 ranging from 0 to 10 Hz.*

$f_0 = 2\,\text{Hz}$ is considered a noisy environment, the active stabilization system is capable to damp magnet motion to an rms value of about 26 nm in this frequency band. Taking into account the very low internal noise of the sensors, one can expect even lower values in less noisy environments. Therefore, this system might be even applicable in some parts of the final focus system where no klystrons and modulators operated at 50 Hz are present.

While the design water flow is 120 l/h, all data were taken at an increased flow of 220 l/h. It turned out that the influence of cooling water is almost negligible. The only difference in both power spectra is a small enhancement around 100 Hz which practically does not contribute to the magnet motion rms value.

To investigate the effect of ground motion on beam dynamics in the SBLC main linac, a simulation algorithm has been developed [21]. Adapting it to power spectra and coherence functions measured at DESY [22], the beam jitter at the end of the main linac was simulated. Here, a beam-based orbit correction system was assumed which applies a kicker signal measured at the nth bunch train to the $(n+1)$th bunch train in order to prevent slow beam motion.

Without active stabilization of mechanical quadrupole vibrations, the vertical rms beam jitter is about $\sigma_y = 1.3\,\mu\text{m}$, while with active stabilization it is reduced to $0.45\,\mu\text{m}$. Together with a vertical beam size being $\sigma_{\text{beam}} = 9.1\,\mu\text{m}$, the luminosity reduction due to beam jitter can be calculated as

$$\mathcal{L} = \mathcal{L}_0 \cdot \exp\left(-2\frac{\sigma_y^2}{4\sigma_{\text{beam}}^2}\right). \qquad (4.8.6)$$

Using equation (4.8.6), the obtained luminosity degradation is about 1 % without and 0.1 % with active stabilization of quadrupoles. Therefore, active stabilization of mechanical quadrupole vibrations might not be necessary in the SBLC main linac, but it may be considered as an option to increase the luminosity. Additionally, a similar system is planned to be used in the final focus system.

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