4.3 Beam Dynamics

4.3.1 Introduction

The main linac has to provide a beam not only of very high energy but also of very high quality (i.e. high intensity, low emittance, small energy spread). The requirements on the quality of the beam are defined by the demands of the high energy physics experiments at the interaction point. This section will study essentially the emittance preservation of a multi bunch train on its way through the main linac. The generation of a low emittance beam is described in section 4.5, while the collimation of the beam and the final focus system can be found in section 4.7.

The transverse quality of the beam can be degraded by misalignments and vibrations of the main linac components, i.e. accelerating structures and focusing magnets. The misalignment and the resolution of the beam position monitors (BPM) are also very important since this determines the possibilities to control the beam quality by various correction methods. The chromatic effects of the focusing system and the transverse wake effects in the accelerating structures are the physical mechanism of the emittance growth. These effects are studied to determine the alignment and vibration tolerances of the main linac components.

The bunch length is practically frozen in the main linac since the bunch is injected at an energy of 3.15 GeV and is rapidly accelerated to even higher energies. The longitudinal quality of the beam is defined by the energy spread in the bunch. The acceptance of the final focus systems sets a loose upper limit of ± 1.2 % on the tolerable energy spread. A lower energy spread is desirable to minimize chromatic effects and their implications on the transverse quality of the beam, or can arise from high energy physics demands for an extremely narrow energy distribution.

The acceleration of a relatively long bunch train can cause various problems with respect to the stability of the bunch train. A current pulse with 333 bunches and a population of $1.1 \cdot 10^{10}$ Electrons per bunch can excite strong resonant transverse electro-magnetic fields, which can cause cumulative beam break-up, a severe instability first observed at SLAC [1]. Therefore it is an absolute necessity to damp and detune this higher order parasitic modes in the accelerating structure, as described in section 4.2.1. The required amount of damping (Q-values of the modes) are investigated from a beam dynamics view point by computer simulations.

The use of a multi-bunch scheme introduces another complication due to strong transient beam loading which amounts to roughly 20 % energy deviation (peak-to-peak) over the first part of the bunch train if no correction method is applied. The inter-bunch energy spread can be reduced by the control of the amplitude or phase of the rf-pulse to a level of 10^{-3}, see section 4.2.9.

4.3.2 Beam Optics

The beam is focused by quadrupole magnets which are arranged in a FODO lattice. This lattice is characterized by the phase advance per cell and the beta function which is scaled with the energy along the main linac. Since the normalized emittance of $\gamma\,\epsilon_y = 0.25 \cdot 10^{-6}$ m in the vertical plane, envisaged for the SBLC, is a factor 20-30 smaller than in existing linacs, i.e. the SLC at SLAC [2], the preservation of the emittance is even in the absence of wakefields in the accelerator structures a critical issue. For the SBLC a constant phase advance of $\mu = 90°$ and a scaling of the beta function with the square root of the energy has been adopted:

$$\mu = 90°, \qquad \beta \sim \sqrt{E}.$$

As explained below, a correlated energy spread in the bunch provides a reduction of emittance growth from coherent betatron oscillations by cancelling chromatic with wakefield effects (so-called BNS-damping). With the above choice for the scaling of the beta function, this energy spread is constant along the linac. Generally, the choice of the lattice parameters takes into account a balancing of transverse wakefield and chromatic effects.

	cells	structures		$\bar{\beta}$/m	ΔE/GeV	E /GeV
1	48	$\times 2 =$	96	13.3	9.8	13.1
2	36	$\times 4 =$	144	26.6	15.0	28.1
3	36	$\times 6 =$	216	40.0	22.4	50.5
4	32	$\times 8 =$	256	53.3	26.6	77.1
5	32	$\times 10 =$	320	66.6	33.2	110.3
6	32	$\times 12 =$	384	80.0	39.9	150.2
7	32	$\times 14 =$	448	93.3	46.5	196.7
8	32	$\times 16 =$	512	106.6	53.2	250.0
Σ	280		2376			

Table 4.3.1: *FODO lattice for the SBLC main linac. The linac is divided into eight sections. The beta function is scaled approximately with the square root of the energy.*

Actually, the main linac is divided into 8 section with a constant beta function FODO lattice in each section. The first section is built from FODO cells with one 6 m long accelerator section between the quadrupole magnets, while the eights section has eight 6 m long accelerator sections between the quads. Table 4.3.1 summaries the lattice of the main linac. The number of FODO cells and accelerator sections is given without any overhead for energy management. The energy gains (ΔE) and energies (E) are calculated assuming a loaded gradient of 17.3 MeV/m and an injection energy of 3.15 GeV. The beta function $\bar{\beta}$ is the mean of the beta function in the focusing and defocusing quadrupoles assuming a filling factor of 90 %, i.e. a cell length of about 13.3 m in the first section of the linac. The required qaudrupole strengths, apertures and lengths are discussed in section 4.2.10.

The emittance growth of the bunch train is studied by a tracking code, called L [3], with uses the environment of the program MAFIA [4]. For these simulations a thin

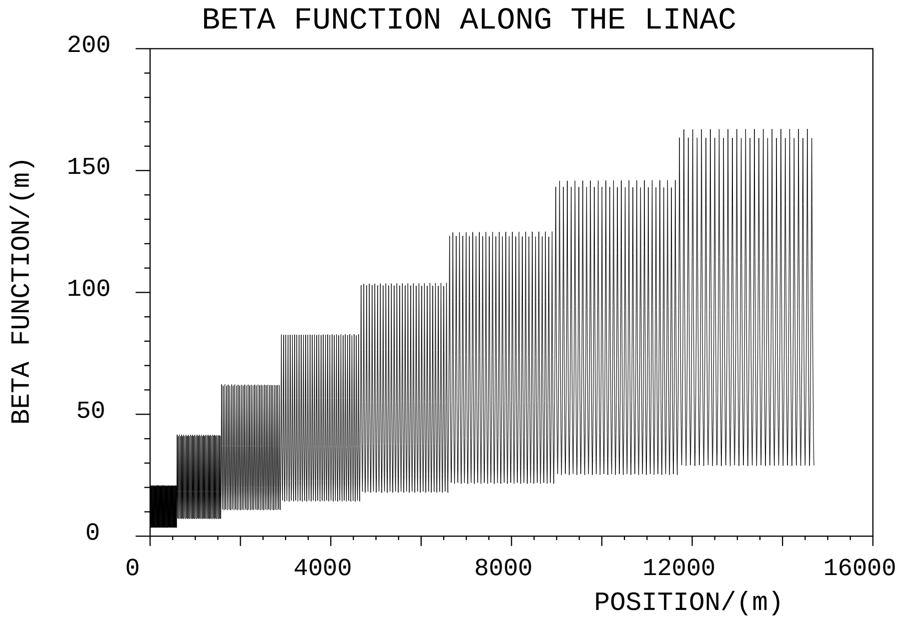

Figure 4.3.1: *Beta function along the SBLC main linac.*

lens FODO lattice is used with ideal telescopic system between the eight sections to match the beta function. Fig. 4.3.1 shows the beta function along the SBLC main linac. One can clearly identify the eight sections of the main linac and the scaling of the beta function with energy.

4.3.3 Wake Fields and Beam Loading

The accelerating structures of the main linac are (normal conducting) traveling wave structures operated in the $2\pi/3$ - mode at a frequency of 2.998 GHz. Each 6 m long section is a 180 cell structure made from "cups" (see Fig. 4.3.2). The cell and iris diameters decrease along the structure in the direction of the beam to achieve a constant accelerating gradient. The power dissipation is constant along the structure. An important characteristic parameter of a constant gradient structure is the attenuation constant τ, which is defined from the ratio of output and input power of the structure and determines dP/dz, the rf power dissipated per unit length:

$$\frac{P_{out}}{P_{in}} = \exp(-2\,\tau), \qquad \frac{dP}{dz} = -P_{in}\,\frac{1-\exp(-2\,\tau)}{l_{sec}}$$

($l_{sec} = 6$ m is the length of an accelerating structure). The attenuation τ, the frequency and the Q-value of accelerating mode directly determine the group velocity of the wave and therefore the iris diameter. The choice of the attenuation $\tau = 0.55$ is a trade off between unwanted effects due to transient beam loading and wakefields and on the other side the required rf-power.

Wakefields are electromagnetic fields due to the interaction of the bunch with the environment, i.e. the accelerating structures. One can distinguish between **short range**

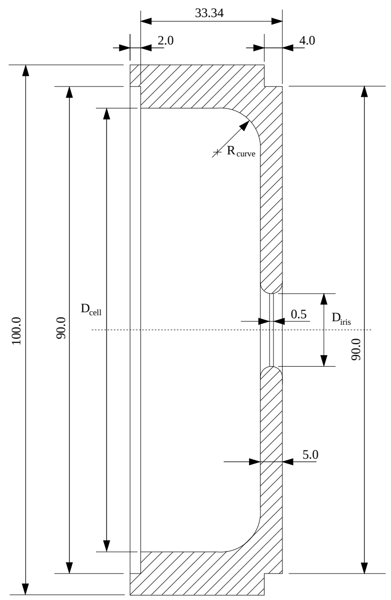

Figure 4.3.2: *One "cup" of a 6 m long accelerating structure. The structure is made from 180 cups (and one end plate) with slightly different cell and iris diameters (D_{cell}, D_{iris}).*

wakefields, which have implications for a single bunch and **long range wakefields**, which could drive instabilities affecting the whole bunch train.

The short range wakefields are numerically calculated by the computer code MAFIA [4] for a 15 cell accelerating structure, which represents the properties of the real 6 m long structure sufficiently [5]. Fig. 4.3.3 shows the longitudinal (short range monopole) wake potential as a function of the position in the bunch. The bunch charge distribution is shown in arbitrary units.

The longitudinal wake fields directly contribute to the energy distribution in one bunch (see Fig. 4.3.4). The change of the energy distribution after one accelerating structure is:

$$\Delta E(s) = G\, l_{sec}\, \cos(\varphi_0 + 2\pi\, f_0\, s/c) \;+ N\, e\, W_{||}(s)$$

(G is the accelerating gradient, l_{sec} the length of the accelerating structure, φ_0, f_0 the rf phase and rf frequency). The wake potential multiplied by the bunch charge $N\,e$ is added to the contribution from the accelerating mode which depends on the rf-phase along the bunch.

Transverse (dipole) wakefields are excited if the beam traverses an accelerating structure off axis. The fields excited by the head of the bunch will kick the tail of the bunch even more off axis. The whole bunch may develop a banana shape tail. This can strongly degenerate the emittance of the beam. Fig. 4.3.5 shows the transverse dipole wake potential as calculated with MAFIA [4, 5]. The head of the bunch is on the left side of the figure.

Long range wakefields are a severe concern with respect to instabilities. Dipole modes are trapped in the accelerating structure over several cells. The frequency of the 180 dipole modes of the lowest passband is in the range from 4.1 GHz to 4.6 GHz.

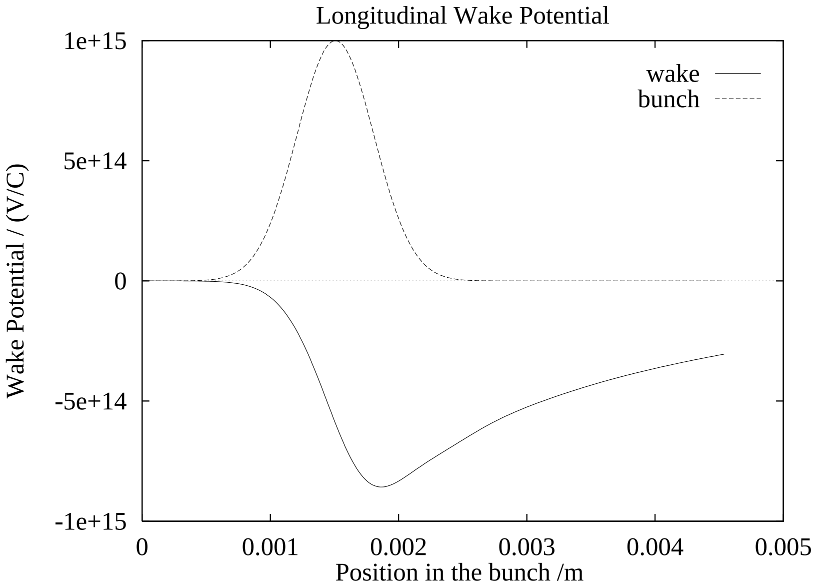

Figure 4.3.3: *Longitudinal mono-pole wake-potential for a 6 m accelerating structure. The Gaussian bunch ($\sigma = 300\mu m$) is shown in arbitrary units. The wake potential is scaled from a MAFIA calculation performed for a 15 cell structure [5].*

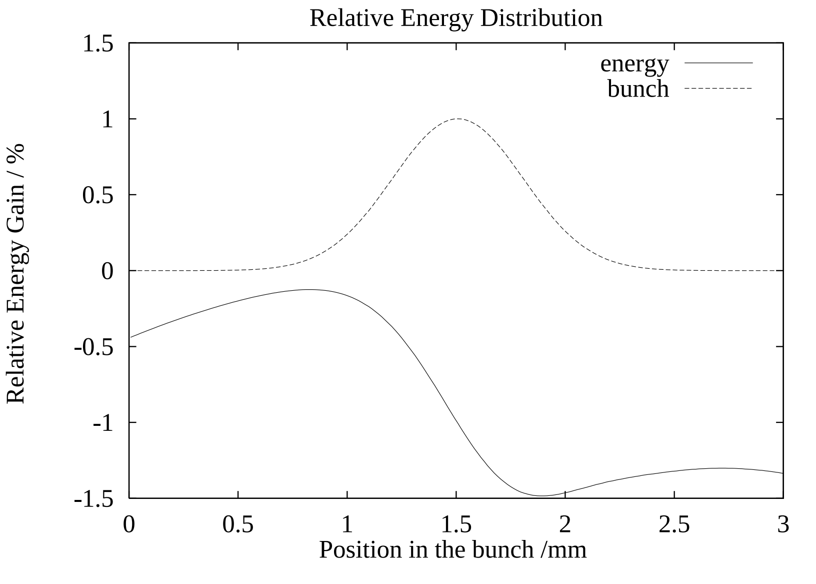

Figure 4.3.4: *Energy spread in the bunch caused by the longitudinal wake field. The bunch center is at z =1.5 mm. The peak-to-peak and rms energy spread amount to 1.8 % and 0.35 %, respectively.*

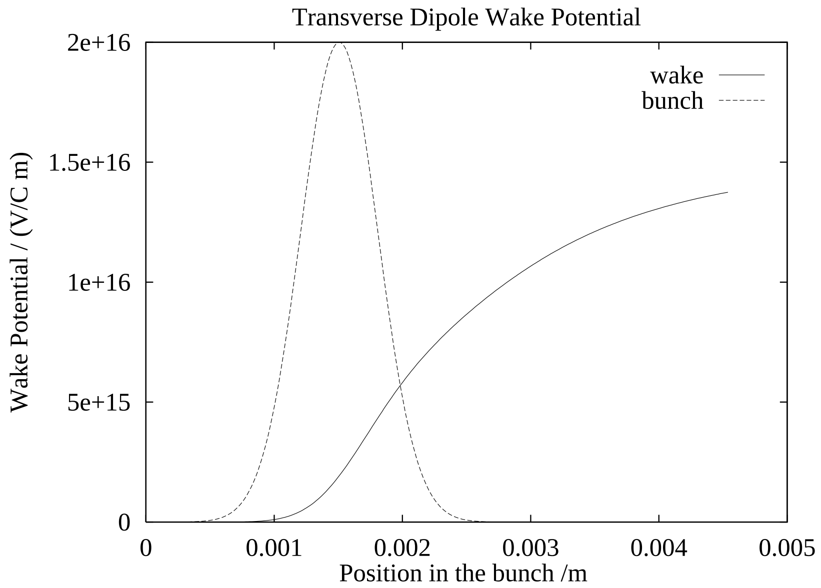

Figure 4.3.5: *Transverse dipole wake-potential for a 6 m accelerating section. The Gaussian bunch ($\sigma = 300\mu m$) is shown in arbitrary units. The wake potential is scaled from a MAFIA calculation performed for a 15 cell structure [5].*

Each mode is characterized by the frequency, the Q-value and the longitudinal loss parameter $k_{\|}^{(1)}$. The transverse dipole wake potential can be calculated according to the Panofsky-Wenzel-Theorem [6]:

$$W_{\perp}^{(1)}(s) = \sum_{\text{modes}} 2\,\frac{k_{\|}^{(1)}(a)}{a^2}\,\frac{c}{2\pi f}\sin(2\pi f\; s/c)\,\exp(-\,(2\pi f/2Q)\,s/c)$$

The loss parameter is computed for a reference offset a of the beam. The kick Δy_n on the bunch n due to the fields generated by bunch m depends linearly on the offset y_m of the bunch m from the axis of the accelerating structure: $\Delta y_n \sim W_{\perp}^{(1)}(s_{n,m})\; y_m$ ($s_{n,m}$ is the distance between bunch n and m).

Using a mode matching technique the modes of the lowest dipole passband have been calculated [7] for a simplified geometry with subsections of six homogeneous cells. The envelope of the long range dipole wake potential is shown in Fig. 4.3.6. These modes are used for the tracking calculations. If no damping method is used then all modes will have Q-values of at least 10000. Instabilities can be reduced if the modes are damped. In the following section it is discussed in detail how the emittance of the multi-bunch train depends on the Q-values of the dipole modes.

More recent calculations [8] indicate that the long range wake due to the *lowest* passband is overestimated with this set of modes while contributions from higher passbands are missing. There are several modes in the 6th passband (frequency about 9.3 GHz) with large loss parameters. Fig. 4.3.7 shows the envelope of the long range dipole wake potential of the first and sixth passbands for a smoothly tapered 6 m long accelerating structure. A detailed discussion of the subject can be found in section 4.2.1.

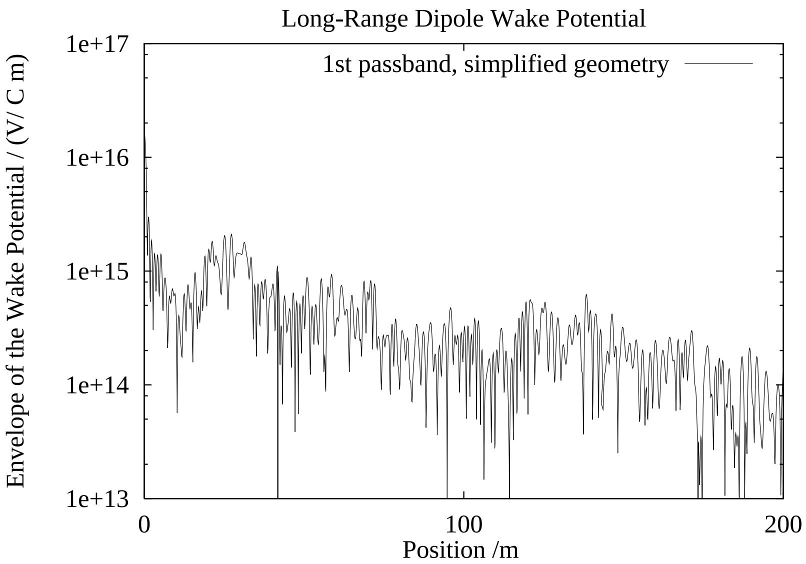

Figure 4.3.6: *Envelope of the long range dipole wake potential of a 6 m accelerating section, using 180 modes from the first passband calculated by [7]. it is assumed that all modes are damped to Q-values of 3000.*

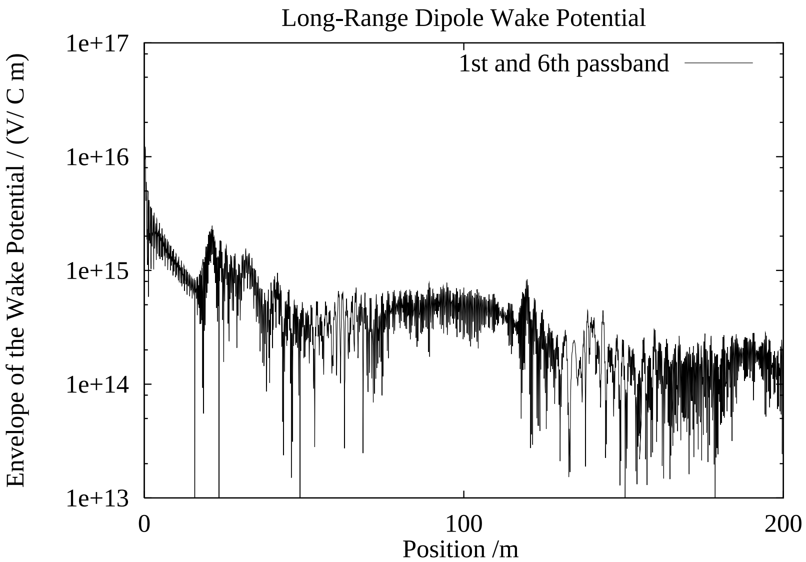

Figure 4.3.7: *Envelope of the long range dipole wake potential of a 6 m accelerating section, using all modes from the first and sixth passbands calculated by [8]. It is assumed that the modes of the first passband are damped to Q-values of 3000, while the modes of the sixth passband are damped to Q-values of 8000.*

Another long range effect is the bunch-to-bunch energy difference due to **transient beam loading**. One filling time ($t_{fill} = 0.789\mu s$) is needed to build up the accelerating field in the structure. Then the bunch train is injected. After a second filling time a steady state is reached. If no compensation method is used this leads to a bunch to bunch energy difference of about 20 % over the first third of the bunch train. It is assumed in the following that this energy spread is corrected quasi-locally by the methods described in section 4.2.9.

4.3.4 Emittance Preservation

The primary sources of emittance growth are wake field effects and dispersive errors caused by small misalignments and vibrations of the main accelerator components. To avoid a significant degradation of the beam quality, i.e. essentially to preserve the transverse emittance, the following cures are considered:

- Beam based quadrupole/BPM alignment,
- Beam based accelerating structure alignment,
- Damping of higher order modes (HOM),
- Active stabilization of quadrupoles.

It is assumed that the starting point of any beam based alignment technique is a good survey of all accelerator components. All presented results of the study are based on a *prealignment precision* of 100 μm of accelerating structures and quadrupole magnets. This precision has to be obtained with respect to a "straight line" over a distant of about 500 m, (i.e. one betatron wave length at the end of the linac). The beam position monitors (BPMs) have also to be aligned with respect to the magnetic axis of the quadrupoles with a precision of 100 μm. Even more important is a high resolution of the BPMs to measure difference orbits with a precision of 5 μm.

A common orbit correction technique is a so called "one-to-one" correction using the readings of nearby BPMs to determine the settings of the corrector magnets. Since the position of the BPMs with respect to the quadrupoles is only known with a precision of 100 μm this correction method is not sufficient to preserve the very low vertical emittance of the bunches. More sophisticated beam based alignment techniques have been developed at SLAC [12]. A steering technique called "DF" (Dispersion Free) can be used if the emittance dilutions are primary caused by dispersive effects in the quadrupole magnets. The strength of the quadrupole magnets is varied to determine the dispersion from difference orbits. An improved so-called "WF" (Wake-Free) version of these methods [12] uses even more difference orbits. The strengths of the focusing and defocusing quadrupole magnets are differently varied in order to avoid any enhancement of wake field effects.

The alignment of the accelerating structures can be improved by active movers at each structure which adjust the structure with respect to HOM coupler signals. Two pairs of HOMs couplers mounted at each 6 m long accelerating structure are sufficient to determine the offset and tilt of the structure with respect to the bunch train. It is assumed that with this method an alignment of the accelerating structures of 50 μm (rms) can be achieved.

The dependence of the emittance growth on the various alignment tolerances and parameters of the HOMs is investigated by computer simulations [9, 10]. The (projected) emittance of the bunch train is computed from the moments of the particle distributions in phase space. Each bunch is divided into several slices with a centroid (y_n, y'_n) and an individual phase space distribution with moments $\sigma_{yy}^{(n)}$, etc. The vertical emittance of the bunch train is given by:

$$\epsilon_y = \sqrt{\sigma_{yy}\,\sigma_{y'y'} - \sigma_{yy'}^2}$$

The second order moments $\sigma_{yy}, \sigma_{y'y'}, \sigma_{yy'}$ of the positions (y) and slopes (y') are calculated according to

$$\sigma_{yy} = \frac{1}{\sum_n q_n} \sum_n q_n \left((y_n - < y >)^2 + \sigma_{yy}^{(n)} \right),$$

and analog for σ_{yy} and $\sigma_{yy'}$. The sum includes all bunches and all slices with charge q_n. The emittance is calculated with respect to mean value $< y >$ of the slice centroids in the bunch train.

4.3.4.1 Multi Bunch Effects

First, the multi-bunch effects are studied separately, i.e. essentially the cumulative multi-bunch beam break-up instability. The beam quality of the bunch train is characterized by the relative centroid emittance, i.e. the moment σ_{yy} is calculated only from the centroids $(y_n,\ y'_n)$ of each bunch. The vertical single bunch emittance $\epsilon_y = 0.25 \cdot 10^{-6}\,\mathrm{m}/\gamma$ ($\epsilon_y = 5.1 \cdot 10^{-13}$ m at 250 GeV) is used as a reference.

It is assumed that the transient beam loading is compensated by the above mentioned local methods (control of the rf-amplitude). These results are compared with simulation where the beam loading is switched off during the tracking of the bunch train. Fig. 4.3.8 shows the results for different Q-values of the dipole modes [10]. The Q-values of the *undamped* HOM's are larger than 10000. An rms accelerating structure misalignment of 100 μm has been assumed. The quadrupoles are perfectly aligned for this computer simulation. Each data point corresponds to one random seed of the simulation. If the beam loading is taken into account but assumed to be locally compensated to $\Delta E/E \approx 6 \cdot 10^{-4}$ then the relative emittance growth is (8.8 ± 8.0) % for a Q-value of 2000 and (352 ± 160) % for a Q-value of 10000 for all the dipole modes.

Therefore, the dipole modes have to be damped to Q-vales between 2000 and 4000. This can be achieved by coating of the iris of each cell of the accelerating structure with lossy material. Additionally, HOM couplers are used which serve also as beam position monitors and provide the signal for the accelerator structure movers.

Furthermore, it is beneficial to use slightly, with respect to HOMs, detuned accelerating structures to disturb any coherence from one accelerating structure to the next one. The results show in Fig. 4.3.8 are obtained for 10 classes of accelerating structures with a total detuning range of 36 MHz. This detuning of the dipole modes can be done by a variation of the radius R_{curve} of the cups (see Fig. 4.3.2).

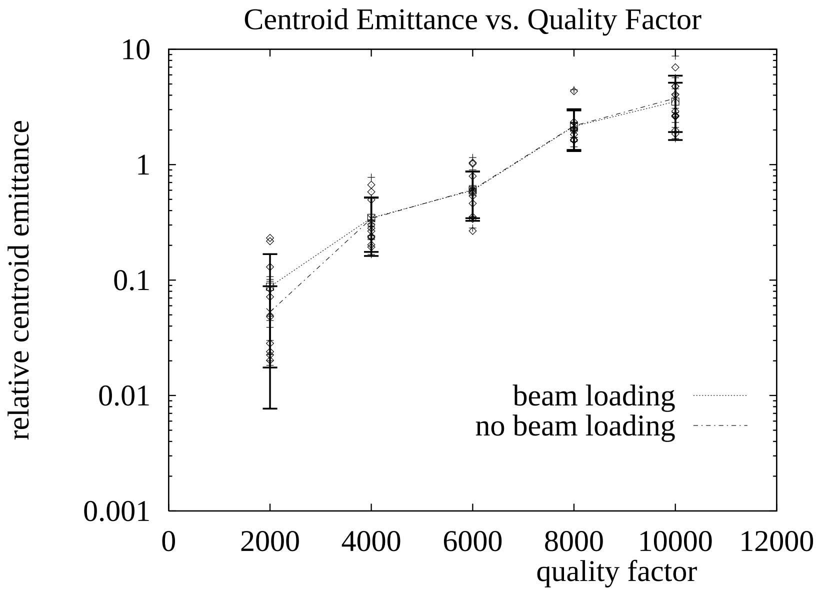

Figure 4.3.8: *Multi-bunch centroid emittance growth due to misaligned accelerating structures as a function of the Q-value of the dipole modes. An rms accelerating structure misalignment of 100 μm has been assumed. The vertical single bunch emittance is used as a reference.*

4.3.4.2 Single and Multi Bunch Effects

Once that the cumulative multi bunch beam break-up is controlled by appropriate damping of the dipole modes the single bunch dynamics determines the alignment tolerances of the main accelerator components. Since multi bunch effects still contribute to emittance growth due to a residual bunch-to-bunch energy difference and the long range wakefield effects of the HOMs, single and multi bunch effects are studied together. The emittance of the whole bunch train is again measured in units of the initial vertical single bunch emittance. Fig. 4.3.9 shows the results obtained by computer simulations [10]. The following correction techniques have been used:

- Local compensation of the bunch-to-bunch energy difference,
- Beam based WF steering,
- Accelerating structure adjustment by means of movers.

The orbit correction with the WF algorithm is applied during a single bunch operation mode with a reduced bunch population of $2.0 \cdot 10^9$. This corrects the dispersion effects due to the quadrupole misalignment (100μm rms after the survey) and defines the required BPM resolution of 5μm. The short range transverse wakefield effects are reduced by a beam based realignment of the accelerating structures with movers with an rms accuracy of 50μm. Transverse short range wakefields effects are reduced by a method called **BNS damping** according to the inventors of the method [11]. The effect of transverse wakefields can be partly canceled by chromatic effects due to a correlated energy spread in the bunch. For the SBLC parameters this energy spread is

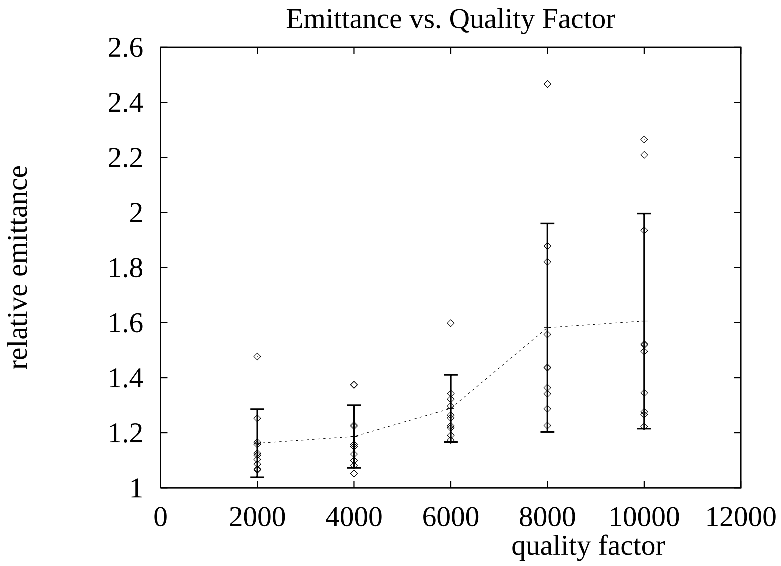

Figure 4.3.9: *Emittance growth due to misaligned accelerating structures and quadrupole magnets as a function of the Q-value of the dipole modes. Single and multi bunch effects are included. Beam based orbit corrections techniques and an adjustments of the accelerating structures by means of movers has been applied. Each data point corresponds to a random seed.*

just produced by the longitudinal short range wakefields, i.e. the optimal BNS rf-phase is just on the crest of the wave [10]. It is not necessary to add an additional energy spread to the bunch. Under these conditions the emittance growth is

$$\frac{\Delta\epsilon_y}{\epsilon_y} \leq 20\,\% \pm 10\,\% \qquad \text{for} \quad Q \leq 4000\,,$$

as shown in Fig. 4.3.9.

The influence of single bunch charge fluctuation and longitudinal jitter on the emittance preservation has been studied in [10, 9]. Provided that the total charge of the bunch train is constant a rms charge fluctuation from bunch to bunch up to 10 % has no significant impact on the emittance growth. Longitudinal jitter of the bunches is not important as long the jitter amplitude is smaller than the rms bunch length of $\sigma_z = 300\,\mu$m. If the charge fluctuation and longitudinal jitter amplitudes stay in this limits then the influence on the energy spread is also not relevant.

4.3.5 Orbit Stability

The beam quality is sufficiently preserved for luminosity operation if beam based alignment techniques are successfully applied. The WF algorithm is based on at least three orbit measurements: one with the nominal strength of all quadrupoles and two with a reduced strength of the focusing and defocusing quadrupoles respectively. Usually it is assumed that the misalignment of the quadrupoles is unknown but constant during the application of the algorithm. But this approximation is only valid for short time scales and small distances since slow diffusive ground motion processes will change the displacement of the accelerator components with time. This sets an upper limit on the time available for performing the WF-steering procedure.

The orbit drift induced induced by the quadrupole motion also has an effect on the emittance dilution. Therefore orbit correction in the linac has to be applied periodically after certain time intervals.

Additionally, fast (i.e. pulse-to-pulse) quadrupole vibrations due to ground motion or environmental noise will reduce the luminosity because of transverse separation of the beams at the IP if their amplitudes are too large. A mechanical feedback system has been developed [13] which can stabilize the quadrupoles to an accuracy of 20 nm (see section 4.8.4). In addition, a fast orbit feedback at the IP can be used within a bunchtrain (see section 4.8.3). As is discussed in section 4.8.4, the expected vibration amplitudes are not a serious problem, but the above mentioned feedback systems can become more important if a luminosity upgrade with smaller vertical emittance is considered.

4.3.5.1 Effect of Diffusive Ground Motion

Diffusive ground motion processes will vary the displacement of two points in the accelerator with time. The so called "ATL-rule" seems to apply to a wide range of ground motion processes. This rule states that the relative displacement Δy of two points separated by the distant L is expected to be

$$< \Delta y^2 >= A \cdot T \cdot L$$

after a time T (see also the subsection on ground motion in section 4.7). The coefficient A depends on the site and ranges from 10^{-8} $\mu\text{m}^2/\text{m s}$ in quiet places to 10^{-4} $\mu\text{m}^2/\text{m s}$ in very noisy places. This study assumes a coefficient $A = 10^{-5}$ $\mu\text{m}^2/\text{m s}$, which is a safe choice compared with the value of $A = 4 \pm 2 \cdot 10^{-6}$ $\mu\text{m}^2/\text{m s}$ measured for the HERA accelerator at DESY [14].

The question how fast the orbit measurements for the WF steering have to be performed to avoid degradation due to ground motion was first studied in [10]. The simulation assumes perfectly aligned accelerating structures and an rms misalignment of the quadrupoles and BPMs of $100\,\mu\text{m}$. The time interval between the simulated orbit measurements is varied and a ground motion process is applied to the accelerator components according to the ATL-rule. Fig. 4.3.10 shows the centroid emittance of the slices of a single bunch obtained after WF steering as a function of the time interval between simulated orbit measurements. The results found under the assumption for the ground motion is that the time interval between subsequent measurement of orbits should not exceed two minutes, which should not present a problem.

After addressing the problem how fast a beam based alignment has to be performed the question arises how often it is necessary to repeat the procedure. We first investigate how the emittance dilution develops as a result of orbit drift caused by uncorrelated random motion of the quadrupoles. The result is shown in Fig. 4.3.11 for a random misalignment of $1\,\mu\text{m}$ (note that the emittance dilution scales with the square of the

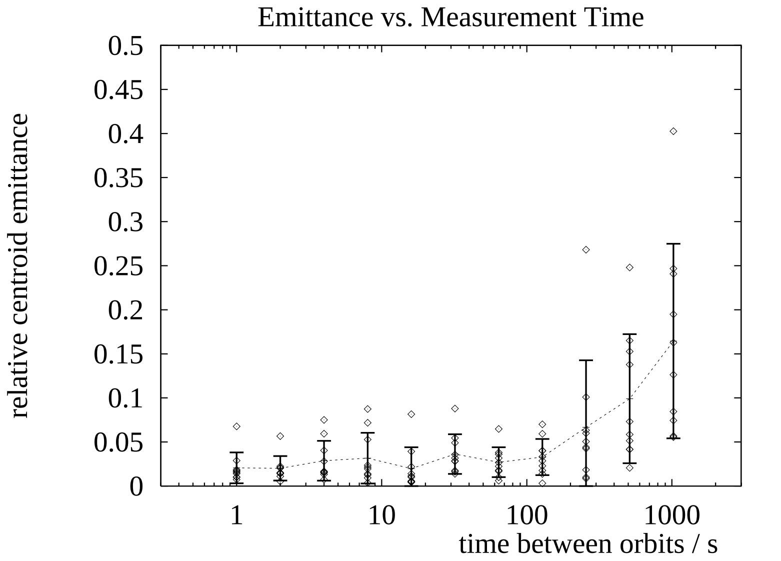

Figure 4.3.10: *Relative single-bunch centroid emittances after WF steering versus the time interval between simulated orbit measurements. In the beginning the quadrupoles and BPMs were randomly misaligned with an rms value of* 100 μm *(each data point corresponds to one random seed). Between simulated orbit measurements a ground motion process was applied according to the ATL-rule.*

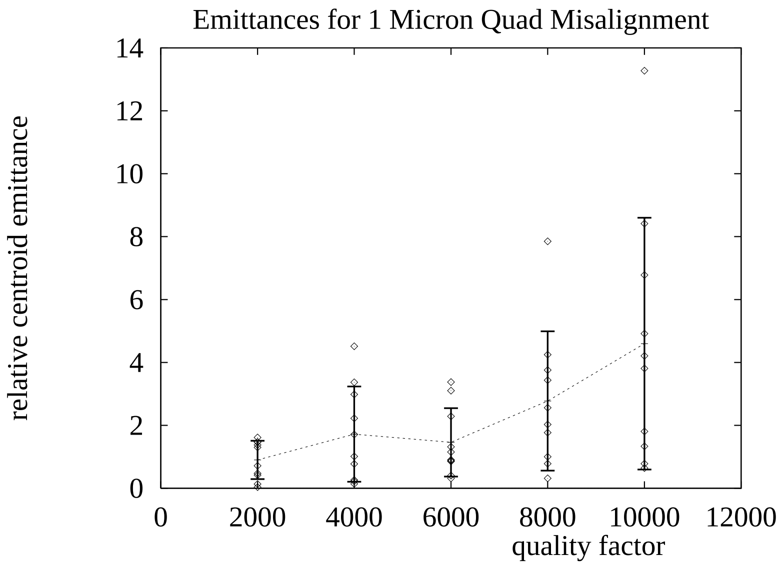

Figure 4.3.11: *Centroid emittance growth due to random quadrupole motion with* 1 μm *rms offset for different Q-values of the HOMs. No orbit correction method has been applied. Each data point corresponds to one random seed. The vertical single bunch emittance is used as the reference.*

rms quadrupole misalignment). With Q-values below 4000, we conclude that orbit correction has to be applied after the quads have moved by 250 nm (rms) in order to limit the emittance dilution to less than 6 %. In terms of the ATL-model for diffusive ground motion, this translates into a time of 25 minutes after which the beam must be re-steered to the "golden" orbit which was found previously with the WF-procedure [10]. A new "golden" orbit with a WF beam based technique has to be established every 11 days. Otherwise, accumulated errors, which are not corrected by a simple one-to-one correction, will lead to an emittance growth of more than 6 %.

4.3.6 Possible Improvements

The methods described in the preceding sections are sufficient to safely achieve the required design emittance at the end of the linac. Additional methods, briefly summarised in the following, can be applied to further reduce emittance growth and to open up the possibility of luminosity upgrade with smaller vertical emittance.

- Empirical orbit steering with either non-dispersive bumps (to reduce wakefield effects) or dispersion bumps (to reduce chromatic dilution) are common practice at the SLC and can be used here as well. Transverse beamsize diagnostic stations will be installed at different points along the accelerator to facilitate empirical optimization for sub-sections of the linac.

- The effect of long-range wakefields from misaligned accelerating structures can be compensated to a large extend by fast kickers which are capable to act on individual bunches. At the end of the linac, each bunch has a slightly different orbit due to the deflection by the HOMs. This pattern (more precisely: the part of it which is reproducable over many pulses) of multi-bunch orbit deviations can be measured and fast (less than 6 ns pulse width) kickers can be used to remove it.

- The alignment of BPMs to the magnetic axis of the quadrupoles can be drastically improved with a beam based technique (by measuring difference orbits after changing the strength of each quadrupole individually). If the alignment thus obtained is sufficiently stable over long periods of time, the repeated application of the WF-method may become unnecessary.

4.3.7 Summary: Tolerances and Emittance Dilution

The beam dynamics of a multi bunch train in the main linac has been studied. To preserve the emittance of the bunch train it is necessary to ensure that several tolerances are kept into partly tight limits. All data given here correspond to a (vertical) emittance dilution of 20% $\pm$ 10% for the whole bunch train. The implications on the following issues are discussed:

- alignment tolerances,
- instrumentation (BPMs),

- accelerator structures.

The quadrupole magnets and accelerator section have to be prealigned to a precision of 100 μm (rms) by a good survey. The reference of the survey is a "straight line" over a distant of a betatron wavelength (i.e. about 500 m). The BPMs are mounted in the quadrupole magnets with the same rms precision of 100 μm. The position of all accelerator section can be changed by movers between the girder and the section. Finally, the accelerator section has to be aligned with respect to the beam with a precision of 50 μm (rms). A good instrumentation is necessary to achieve this goal.

There are two types of beam position monitors, the stripline BPMs in each quadrupole magnet and the HOM-couplers at each accelerator section. The signals of the HOM-couplers are used to set the motors of the movers while the stripline BPMs are used to set the corrector strength of the dipole correctors according to a beam based orbit correction method. The system HOM-coupler/mover has to achieve the above mentioned alignment precision of 50 μm (rms) for the accelerator structures. The BPMs have to measure difference orbits with a high resolution of 5 μm (rms), which includes electronic drifts, etc. . The control system has to ensure that it is at least possible to set all quadrupole magnets and measure the orbits in about 100 s to avoid degradation of the WF steering algorithm due to ground motion. The amplitude of fast quadrupole vibrations determines the orbit stability at the interaction point, but is not expected to have an effect on emittance dilution in the linac.

The long range wake field effects due to dipole modes in the accelerator section can cause cumulative beam break-up of the bunch train. Therefore it is important to damp and detune these HOMs. Ten types of accelerator structures are foreseen which are different with respect to the dipole mode. The total detuning range is 36 MHz for the dipole modes. Coated irises and the HOM-couplers are used to damp all HOMs to Q-values between 2000 and 4000. The straightness of the 6 m long accelerator section has been at least as good as the mover/HOM-coupler alignment system, i.e. 50 μm.

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