Beam Dynamics Studies for the SBLC

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Abstract

In linear accelerators, wake field effects and dispersion from orbit distortions can lead to considerable emittance dilution. Since the transverse wake fields and the dispersion depend on the orbit in the accelerating structures and quadrupoles, there are constraints on the resolution of the beam position monitors and on alignment tolerances.

The tracking code L, which is affiliated to the family of MAFIA codes, has been developed to simulate both single and multi-bunch dynamics in linear accelerators. By use of this code, the impact of misalignments on the combined single and multi-bunch behaviour of the beam is investigated for the S-band accelerator as envisioned in the SBLC study. Further, the performance of a full machine tuning scheme including beam loading compensation, orbit correction, structure adjustment and emittance correction is examined. From the results, limits for the alignment tolerances are deduced.

I. General Considerations

The SBLC 2×250 GeV linear collider design study considers a bunch train with an average beam power of 7.25 MW (per train), and an invariant (single bunch) emittance of $\gamma\epsilon_x \ / \ \gamma\epsilon_y = 10.0 \ / \ 0.5 \ \times \ 10^{-6}$ m. To achieve a luminosity of $3.75 \times 10^{33} \, (\mathrm{cm}^2 \, s)^{-1}$ (with pinch) it is important to preserve not only the single bunch emittance but also to avoid any cumulative beam break-up along the bunch train. It is assumed that 125 bunches with a spacing of 16 ns from bunch to bunch and a bunch population of $N = 2.9 \times 10^{10}$ are injected with an energy of 3.15 GeV into the main linac where they are accelerated to 250 GeV by 2517 S-band structures (each 6 m long, with a loaded gradient of 17 MV/m) [1]. The main parameters of SBLC study are summarized in table I.

General Parameters		
energy (center of mass)	GeV	**500**
luminosity (including pinch)	$(\mathrm{cm}^2\mathrm{s})^{-1}$	$3.75 \cdot 10^{33}$
nominal luminosity	$(\mathrm{cm}^2\mathrm{s})^{-1}$	$2.2 \cdot 10^{33}$
active length (two linacs)	km	30.2
repetition rate	Hz	50
particles per bunch		$2.9 \cdot 10^{10}$
bunches per pulse		125
bunch length (rms)	mm	0.5
bunch spacing	ns	16
normalized vert. emittance $\gamma\epsilon_y$	m	$0.5 \cdot 10^{-6}$
normalized horiz. emittance $\gamma\epsilon_x$	m	$10 \cdot 10^{-6}$
injection energy	GeV	3.15
Accelerating Structure		
loaded gradient	MV/m	17
unloaded gradient	MV/m	21
RF frequency	GHz	3.0
average shunt impedance	MΩ/m	55
iris size a/λ		0.16 - 0.11
structure length	m	6
number of structures / linac		2517
HOM		
frequency	GHz	4.1 - 4.6
number of HOM used in simul.		180
Lattice		
type		FODO
phase advance / cell	°	90
scaling		$\beta \sim \sqrt{E}$
number betatron oscillations		73

Table I
Main parameters of the SBLC design study.

The primary sources of emittance growth are wake field effects and dispersive errors caused by small misalignments of the accelerating structures, the lattice quadrupoles and the beam position monitors (BPM's). To avoid single bunch emittance growth and multi-bunch beam break-up the following diagnostics and cures are considered for the SBLC:

- Beam based alignment techniques
- Higher order mode (HOM) dampers at each accelerating structure, lossy cells
- Accelerating structure movers
- Nondispersive trajectory bumps, tuned by emittance measurements
- Active stabilization of quadrupoles
- Fast kickers.

[1] An overhead of 4 % is assumed

HOM dampers are necessary to damp the dipole modes, which drive the cumulative multi-bunch beam break-up. Furthermore, the accelerating structures can be moved with active structure movers, using the signals from HOM-couplers as a reference. The usefulness of the HOM signals as a diagnostic tool will be investigated at the DESY S-band test facility. The accelerating structure movers can also, like trajectory bumps, be operated in connection with emittance measurements. Once the multi-bunch beam break-up is cured by HOM dampers and structure movers, the single bunch effects determine the alignment tolerances.

II. Longitudinal Dynamics

Transient wake fields cause an energy spread in each bunch, while strong beam loading effects lead to different energies of the bunches in the train. The single bunch energy spread due to the longitudinal wakes amounts to 2.6 % (peak to peak) if not compensated. This spread can be adjusted to a level required for crab crossing by placing the bunch off-crest with respect to the RF. The acceptance of the final focus is $\pm 1.8\%$ [1]. An energy spread can even advantageously be used for BNS damping. The required BNS energy spread is 0.9 % as calculated from computer simulations.

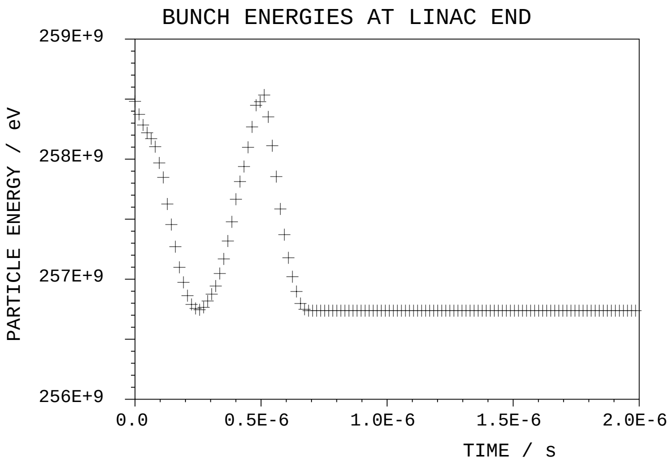

Figure 1. Compensation of the multi-bunch energy spread with staggered timing, results from computer simulations

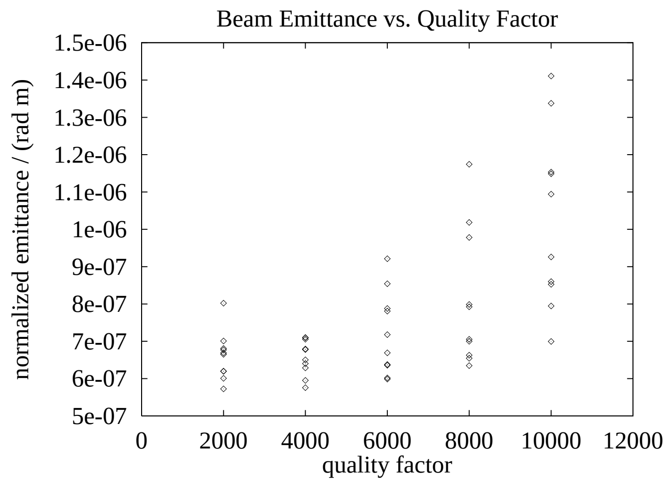

Figure 2. Normalized beam emittance at the end of the linac versus quality factor of the dipole modes. The acc. structures are moved with 30 μm rms to the beam.

A more severe problem is the beam loading leading to a energy spread of 18 % (peak to peak) over the bunch train if not compensated. With staggered timing of the RF-pulses [6] the multi-bunch energy spread can be reduced significantly. This technique exploits the fact that one can produce different profiles of the energy gain in one structure over a bunch train by turning on the RF-power at different times before arrival of the bunch train at the structure. The turn-on times of each klystron are then chosen to minimize the peak to peak energy spread after the structures fed by that klystron. Furthermore it will be investigated at the DESY S-band test facility whether a control of the klystron power over the 2.8 μs long pulse can successfully be used to compensate the beam loading effects. Fig. 1 shows the energies of the 125 bunches at the end of the linac using only the staggered timing of the RF-pulses. The first 50 bunches are affected by the transient beam loading. The residual bunch to bunch energy spread can be reduced to about 1% (peak to peak).

III. Transverse Dynamics

For simulation of the beam dynamics, the bunches are longitudinally divided into slices with charge q_i, phase space moments $\sigma_{11\,i}$,..., and centroids y_i. The projected emittance of the bunch train is given by: $\epsilon_y = \sqrt{\sigma_{yy}\,\sigma_{y'y'} - \sigma_{yy'}{}^2}$ with the phase space moments defined by:

$$\sigma_{yy} = \frac{1}{q_{train}} \sum_{i \in I} q_i \, \left(\sigma_{11\,i} + (y_i - \langle y \rangle)^2 \right), \qquad \sigma_{y'y'} = \ldots$$

The moments of the whole bunch train are calculated as a sum over all slices of all bunches (I = {slices, bunches}) according to the above formula. The bracket $\langle y \rangle$ indicates the average of the bunch centroids over the index set I.

For simulation of the long range dipole wake driving the cumulative multi-bunch beam break-up we used the dipole modes calculated by [5]. It has been assumed that there exist 10 classes of accelerating structures with mutually detuned dipole modes (~ 3.6 MHz frequency shift from class to class). Each structure itself is a plain constant gradient structure.

Tolerances are given for an emittance dilution of $\Delta\epsilon_y/\epsilon_y \approx$ 30 % if all effects are considered. The full dynamics of a bunch train (i.e. single and multi-bunch) has been studied by computer simulations [2]. With an initial misalignment of the accelerating structures and quadrupoles of $100\mu\mathrm{m}$ with respect to the machine axis and of the BPM's with respect to the quadrupole centers, it was assumed that the linac was adjusted for luminosity operation along the following steps:

1. Set the klystron ignition times according to staggered timing.
2. Carry out beam based orbit correction using the WF-algorithm outlined in [4].
3. Adjust the axes of the accelerating structures to the beam trajectory with a precision of $30\mu\mathrm{m}$ with active structure movers. As he signal from the HOM's would be used as a reference, this measure will require the installation of at least two pairs of HOM-couplers per accelerating structure.
4. Fine-tune the beam emittance with non-dispersive bumps [4].

With these assumptions, the total growth of the projected emittance was simulated for quality factors of the dipole modes ranging from $Q = 2000$ to $Q = 10000$ and a constant BPM resolution of 5μm For $Q = 4000$ a emittance growth of $\Delta\epsilon_y/\epsilon_y =$ 31 % $\pm$ 10 % is found from 10 random seeds. Fig. 2 shows the complete result of this simulation.

Further, we looked at the impact of the BPM resolution on the achieved emittance. For this purpose, we simulated the beam dynamics in a machine that was adjusted according to the procedure outlined above with resolution of the BPM's ranging from $\sigma_{res} = 1\mu\mathrm{m}$ to $\sigma_{res} = 32\mu\mathrm{m}$. The quality factor of the dipole modes was kept constant at $Q = 2000$. The result of this simulation is shown in Fig. 3. At a BPM resolution of $4\mu\mathrm{m}$ the emittance dilution at operation with 125 bunches becomes $(30 \pm 13)\%$.

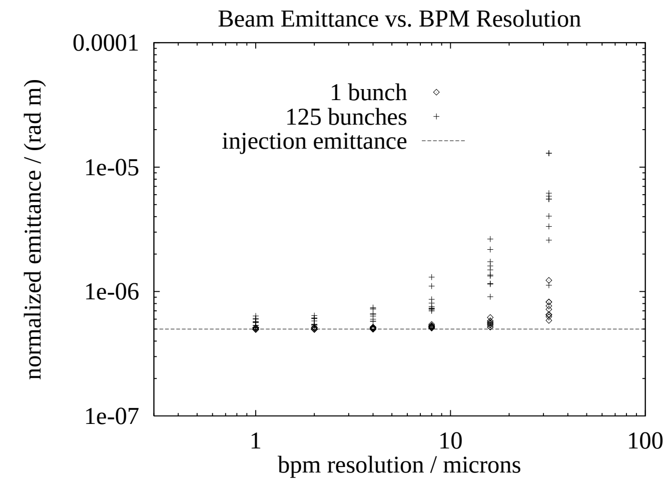

Figure 3. Normalized beam emittance at the end of the linac at single and multi-bunch operation versus BPM resolution. The dipole modes have a constant quality factor of $Q = 2000$. The acc. structures are moved with 30 μm rms to the beam.

IV. Tolerances and conclusion

Including “all” effects, i.e. transient beam loading, single and multi-bunch wake fields, dispersion and chromatic effects the following rms tolerances for an emittance growth of about 30 % $\pm$ 10 % are found from computer simulations:

- Injection jitter	$\sim 10\ \mu\mathrm{m}$
- Quadrupoles	
prealignment	$\sim 100\ \mu\mathrm{m}$
BPM resolution	$\sim 3 - 4\ \mu\mathrm{m}$
jitter	$\sim 75\ \mathrm{nm}$
- Accelerating structures	
prealignment	$\sim 100\ \mu\mathrm{m}$
with movers	$\sim 30\ \mu\mathrm{m}$ with respect to the orbit
- Dipole modes	
detuning	~ 10 different structure with $\Delta f_{total} \sim 36$ MHz
damping	$Q \sim 2000 \ldots 4000$ 2 HOM dampers + lossy cells
- Charge jitter	$\leq 5\%$ for single bunches
- Klystron phase errors	$\sim 4^\circ$

The damping of HOM dipole modes is achieved by two pairs of dampers per acc. structure and additional “lossy” cells [3], i.e. the iris region is coated which a lossy material. The accelerating mode is only slightly influence by this type of lossy cells since the quality factor is mainly determined by the fields near the outer cavity walls.

From the computer simulation, which have been done so far, it can be concluded that the effective multi- and single emittance can essentially be preserved if the above mentioned tolerances can be obtained. At the DESY S-band test facility the accelerating structures movers and the HOM signals will be investigated in order to demonstrate that it is feasible to obtain an rms offset of 30 μm between the structures and the beam. Furthermore, it still has to be demonstrated that it is possible to build accelerating structures with a sufficient straightness.

The dipole modes used in our simulations were calculated with a simplified geometry of the acc. structures. Hence, the modes have to be verified. Also, higher passbands could contribute significantly to the multi-bunch beam break-up [3].

The instrumention and control requirements for application of the sophisticated orbit correction techniquess have not yet been considered. The various feedback loops for a linear collider, which may have many interdependencies, are not yet studied for the SBLC design study.

References

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