Multi-bunch Emittance Preservation in a Linear Collider

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Abstract

Almost all 2 × 250 GeV linear collider schemes make use of a bunch train with more than 50 bunches. Stability requirements of the bunch train put serious constraints on the alignment tolerances of the accelerating sections in a large scale future linear collider. A computer code, called L, has been developed to study the beam dynamics in linear colliders. The code is applied to the multi-bunch beam break-up instability driven by dipole modes. Results are presented for the S-Band (SBLC) and TESLA linear collider schemes. The multi-bunch emittance defined from the centroids of each bunch can be preserved if the acceleration sections are well aligned and the parasitic dipole modes are damped. The alignment tolerances are given with respect to the Q-values of the dipole modes. Furthermore the sensitivity to injection jitter is investigated.

1 INTRODUCTION

Cumulative multi-bunch beam break-up (BBU) instabilities were first observed at SLAC [1]. This type of instability has to be considered for any large scale future linear collider which is operated in a multi-bunch mode. Multi-bunch operation is very attractive since the luminosity, $\mathcal{L}$, depends linearly on the total beam power:

$$\mathcal{L} = \frac{P_{beam}}{E_{c.m.}} \frac{N}{4\pi\, \sigma_x^*\, \sigma_y^*}, \qquad P_{beam} = n_{bunch}\, f_{rep}\, E_{c.m.}\, N$$

($E_{c.m.} = 0.5$ TeV is the center of mass energy, N the bunch population, f_{rep} the repetition frequency, and n_{bunch} the number of bunches.) The main linear collider parameters used for computer simulations are summarized in table 1.

The BBU instability, driven by dipole modes, puts constraints on the alignment tolerances of the acceleration sections. The effect on the luminosity can be estimated from the situation shown in Fig. 1.

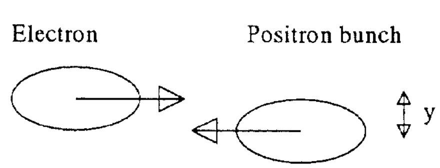

Figure 1: Bunches colliding with an offset y

An electron and a positron bunch collide with a vertical offset $y = y_{e^-} - y_{e^+}$. The Luminosity of the collision is reduced by the following factor:

$$\mathcal{L}_y = \mathcal{L}_0\, \exp(-\frac{y^2}{4{\sigma_y^*}^2})$$

(σ_y^* is the vertical beam size.) Assuming that the positions of the bunch centroids y_{e^-} and y_{e^+} obey a Gaussian distribution along the bunch train, the total luminosity reduction factor is given by:

$$\langle \exp(-\frac{y^2}{4{\sigma_y^*}^2}) \rangle_{y_{e^-}, y_{e^+}} = \frac{1}{\sqrt{B+1}}$$

(the brackets $\langle\rangle$ indicate the average over the bunch trains.) $B := \sigma_{multi}^2 / {\sigma_y^*}^2$ is defined as a blow-up factor, which characterized the multi-bunch quality in units of the single bunch beam size. σ_{multi} is the rms offset of the bunch train. A reduction of the luminosity of 10 % corresponds to blow-up factor of $B = 0.23$.

The bunch train can be characterized in a multi-bunch phase space. Fig. 2 shows the centroids (y', y) of the 125 bunches at the end of the SBLC linac. A multi-bunch

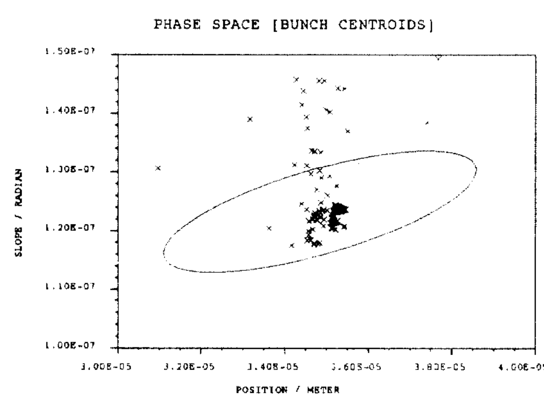

Figure 2: Vertical multi-bunch phase space, (y', y) centroids of the TESLA bunch train. The multi-bunch one sigma ellipse is shown, $Q_{ref} = 1.0\, 10^5$.

emittance (one sigma) is defined from the central moments of the distribution of the bunch centroids.

$$\epsilon_{multi}^2 = \langle (y - \langle y \rangle)^2 \rangle\, \langle (y' - \langle y' \rangle)^2 \rangle - \langle (y - \langle y \rangle)\,(y' - \langle y' \rangle) \rangle^2$$

The blow-up factor B can be written as the ratio of the multi bunch emittance to the single bunch emittance: $B = \epsilon_{multi}/\epsilon_y$. Since the multi-bunch dynamics is investigated separately from any single bunch effect the single bunch

	SBLC	TESLA	
Beam Energy, E	250	250	GeV
Injection energy, E_{inj}	3.15	3.0	GeV
Acceleration gradient, G	17	25	MV/m
Linac focusing function, $\langle\beta_0\rangle$	12	48	m
Scaling of beta function	$\beta = \beta_0 \sqrt{E/E_{inj}}$	$\beta = \beta_0$	
Phase advance per FODO cell, ϕ	90	90	°
Rf frequency, f_{acc}	2.998	1.3	GHz
Cavity structure length, l_{acc}	6.0	1.04	m
Number of structures, n_{st}	2440	10000	
Number of particles per bunch, N	$2.9\ 10^{10}$	$5.14\ 10^{10}$	
Invariant single bunch emittance			
horizontal $\gamma\epsilon_x$	$10.0\ 10^{-6}$	$20.0\ 10^{-6}$	m rad
vertical $\gamma\epsilon_y$	$0.5\ 10^{-6}$	$1.0\ 10^{-6}$	m rad
Number of bunches per pulse n_b	125	800	
Bunch spacing t_b	16	1000	ns
free rf buckets n_{fb}	48	1300	

Table 1: Linear Collider parameters

TESLA		
f	$\hat{W}$	Q/Q_{ref}
GHz	$V/(C\ m^2)$	
1.709	$17.04\ 10^{12}$	1.2
1.736	$22.15\ 10^{12}$	ref : 1.0
1.763	$2.55\ 10^{12}$	1.0
1.837	$0.45\ 10^{12}$	6.5
1.853	$0.44\ 10^{12}$	7.2
1.865	$9.56\ 10^{12}$	10.5
1.874	$12.91\ 10^{12}$	16.7
1.880	$2.87\ 10^{12}$	0.3
1.884	$7.49\ 10^{12}$	46.0
1.887	$0.23\ 10^{12}$	93.5
		$Q_{ref} = 7200$

Table 2: Dipole modes

emittance ϵ_{single} is calculated from the initial invariant emittance given in table 1. No blow-up corresponds to a blow-up factor of 0.

In order to preserve the multi-bunch emittance several methods can be used:

- Damping of the dipole modes,
- Mutual detuning of the dipole mode frequencies,
- Moving the structures with respect to the HOM signals,
- Fast kickers to adjust the bunch positions of each bunch.

For the tracking calculations damping of the modes and mutual detuning from structure to structure is considered. The signals from the higher order mode (HOM) dampers and fast kickers can be used to relax the alignment tolerances. The goal is to achieve structure alignment tolerances of 1 mm for TESLA and 100 μm for the SBLC.

2 DIPOLE WAKE FIELDS

The BBU instability is driven by dipole modes. The parameters of these modes are obtained by numerical calculations with the computer code URMEL [2] and ORTHO using mode matching techniques [3]. Consider two point charges traversing a cylindrical symmetric structure at positions y_1 and y_2. In Cartesian coordinates the transverse wake potential is given by:

$$\vec{W}_\perp(y_2, s) = (x_1 \vec{e_x} + y_1 \vec{e_y})\, W(s)$$
$$W(s) = \sum_{modes} \hat{W}_m \sin(\omega_m s/c) \exp(-\alpha_m s/c)$$

with

$$\hat{W}_m = 2\, \frac{k_m(a)}{a^2}\, \frac{c}{\omega_m}\, \frac{1}{l_{acc}} \qquad \alpha_m = \frac{\omega_m}{2\, Q_m}.$$

$k_m(a)$ is the loss parameter at the transverse position a and ω_m the revolution frequency of the dipole mode m. A damping term has been added to include wall losses. Q_m is the Q - value of the dipole mode m. Actually 180 dipole modes are used for the tracking calculations for the SBLC. Figure 3 shows the wake amplitudes $\hat{W}_m$ versus the dipole mode frequency. The parameters for the dipole modes of the TESLA cavity are given in table 2 [5], which have been confirmed by measurements [6].

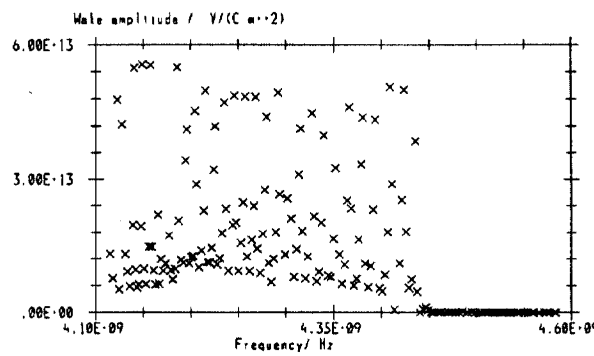

Figure 3: Amplitude of the wake potential $\hat{W}_m$ of the $m = 1 \ldots 180$ SBLC dipole modes versus their frequencies.

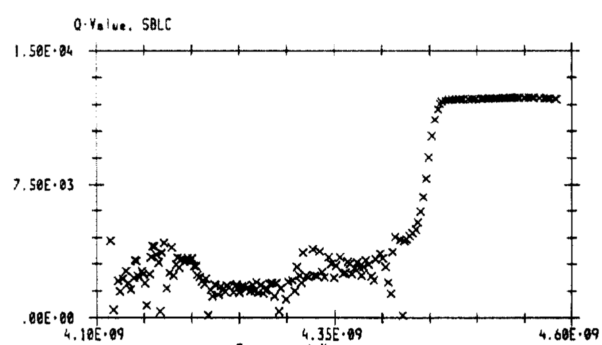

Figure 4: Q-values of the SBLC dipole modes versus their frequencies [4].

3 TRACKING CALCULATIONS

The effects of the dipole modes on the bunch train consisting out of 125 (SBLC) or 800 (TESLA) bunches is studied in this section. The parameters from table 1 are used. The TESLA lattice is a constant β lattice with superconducting quadrupole magnets, while the SBLC is scaled with the square root of the energy. A thin lens approximation for the quadrupoles is used. It is further assumed that the quadrupoles are perfectly aligned along the linac.

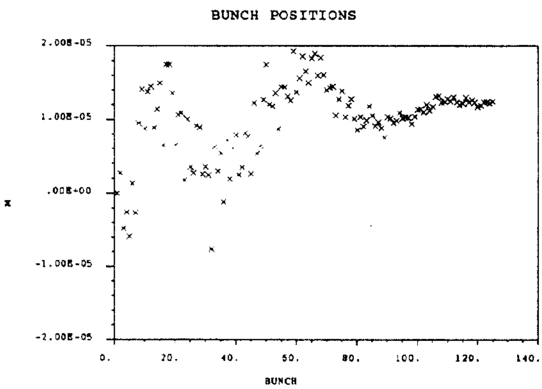

Figure 5: Position of the bunches at the end of the SBLC linac versus the bunch number. The dipole modes a damped Q =profile.

In each acceleration section the n-th bunch is kicked due to the dipole modes excited by the $n-1$ bunches which passed the section before the n-th bunch with offsets y_m. The transverse coordinate y' is changed by the amount

$$\Delta y'_n = \frac{e}{E_n} l_{acc} V'_n, \qquad V'_n = q \sum_{j=1}^{n-1} W\left((n-j)t_b\right) y_j$$

(t_b bunch spacing, E_n energy of the n-th bunch, V'_n accumulated voltage per length in the dipole mode). Any excitation of dipole modes is due to the misalignment of acceleration sections or an injection error of the bunch train. The offsets of the acceleration sections are randomly chosen. The results are given as mean values over ten random seeds (Table 4).

	SBLC	TESLA
injection	30 μm	90 μm
250 GeV	10 μm	10 μm

Table 3: Vertical beam size at injection and at the end of main linac (before the final focus).

For the SBLC simulation 10 classes of cavities with a total frequency spread of 40 MHz are used, while for TESLA a natural Gaussian frequency spread of 1 MHz has been assumed. "Q = profile" for the SBLC is a set of Q-values calculated from an equivalent circuit model [4] with 3 × 3 damped cells in a 6 m long structure (Fig. 4). In table 4 not only the size of multi-bunch ellipse is given but also the variation of the center of ellipse over ten random seeds. The center of the ellipse can always be corrected if the offsets are stable from pulse to pulse. The area of the multi-bunch ellipse scales with the square of the cavity offset while the center of the ellipse depends linearly on the cavity offset. Fig. 5 shows SBLC bunch train. Fast kickers and structure movements can be used to improve this tracking result. The injection tolerances are given as a mean over different structure distribution along the linac.

SBLC	B vert. blow-up	$\langle y \rangle$ /μ m
100μm rms cavity offset		
Q=10000	108 ± 57	± 40
Q=5000	4.0 ± 1.6	± 31
Q=2000	0.1 ± 0.05	± 15
Q=profile	0.33± 0.21	± 21
100μm injection offset		
Q=2000	0.28± 0.06	-
Q=profile	0.55± 0.11	-
TESLA	B vert. blow-up	$\langle y \rangle$ /μ m
1000μm rms cavity offset		
Q_{ref}=7200	0.0036 ± 0.0021	± 7.4
Q_{ref}=1.0 10^5	0.5762 ± 0.37	± 23
1000μm injection offset		
Q_{ref}=7200	0.0002 ± 0.0001	-
Q_{ref}=1.0 10^5	0.027 ± 0.016	-

Table 4: Results from tracking calculations for different damping of the dipole modes.

4 CONCLUSION

The cumulative multi-bunch beam break-up (BBU) instability in the SBLC Collider can be controlled if the dipole modes are damped and if different classes of sections with mutually detuned dipole modes are used. The initial alignment tolerances are about 80 μm if most modes are damped down to $Q = 2000$ and a total frequency spread of 10 % is used. This could be improved with fast kickers or structure movements according to HOM signals. TESLA does not have any problem with multi-bunch instabilities if the strongest mode is damped to $Q \approx 10^4$. The rms alignment tolerance for the cavities is 1 mm (full Gaussian distribution). The required alignment stability from pulse to pulse is 10 μm for the SBLC and 100 μm for TESLA.

5 REFERENCES

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