Transient Beam Loading Compensation in Traveling Wave Linear Accelerators

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ABSTRACT

For normal conducting linear colliders (compare [1]) the transient beam loading in the accelerating structures is typically of the order of 20-30 %. This results in a multi-bunch energy spread of the same magnitude if no remedy is taken into account. On the other hand, in a linear collider the transient energy spread has to be controlled down to a few tenth of a percent. Two possible methods, assuming two different setups, e.g. klystron plus structure and klystron plus SLED cavity plus structure, are investigated. A description of the whole rf system and the resulting energy spread will be presented especially for the case of the S-Band linear collider study [2].

1 Introduction

In a traveling wave structure the build-up of the accelerating voltage as a function of time only depends on the attenuation of the structure, the frequency and the quality factor of the structure. Once the rf pulse reaches the end of the section the accelerating voltage is constant unless the beam is switched on and the resulting transient beam loading voltage builds up over the second filling time. Schematically this is shown in Fig. 1.

First order compensation of the beam loading can be done by injecting the beam before the rf pulse has filled the section. This has been investigated earlier [3] and for beam pulse currents under consideration for linear colliders this method reduces the multi-bunch energy spread to about half the value being achieved before. The principle is shown in Fig. 2 for one klystron station. The optimum injection time is determined by the loaded and the unloaded voltage and can be calculated from the following formula:

$$t_{inj} = -\frac{\omega}{2Q} \cdot (ln(1 - \frac{U_{max} - U_{ind}}{U_{max}} \cdot (1 - e^{-2\tau}))) \quad (1)$$

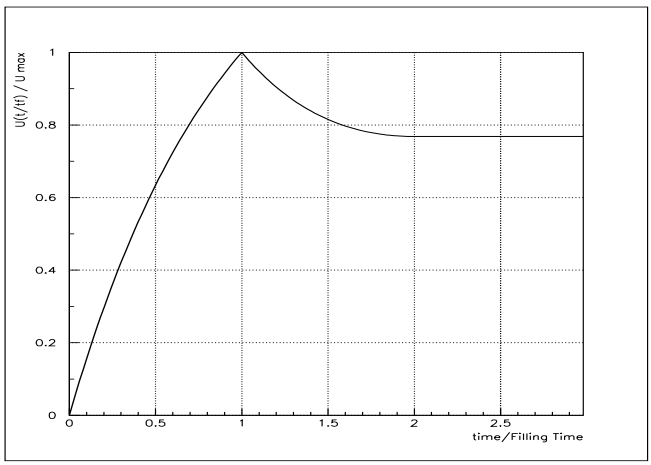

Figure 1: Accelerating voltage as function of time with beam (switched on after the first filling time).

where $\tau$is the attenuation (in neper)

In a linear collider with approximately 1300 klystrons per linac this scheme could be further developed and has been used earlier as well [4, 5, 6]. The switch on time of the rf pulse relative to the injection of the bunch train is varied over a number of klystrons to average the transient beam loading over many sections of the linear accelerator. From the beam dynamics point of view the most significant disadvantage is, that single bunches in the first part of the beam pulse (over the first filling time) locally can have large energy deviations of the order of a few percent, although the bunch to bunch energy spread is compensated down to a few tenth of a percent towards the end of the linac. These comparatively large energy deviations always appear at least over a number of betatron wavelength and can deteriorate the emittance of these bunches due to chromatic effects. From the technical point of view, drive pulses

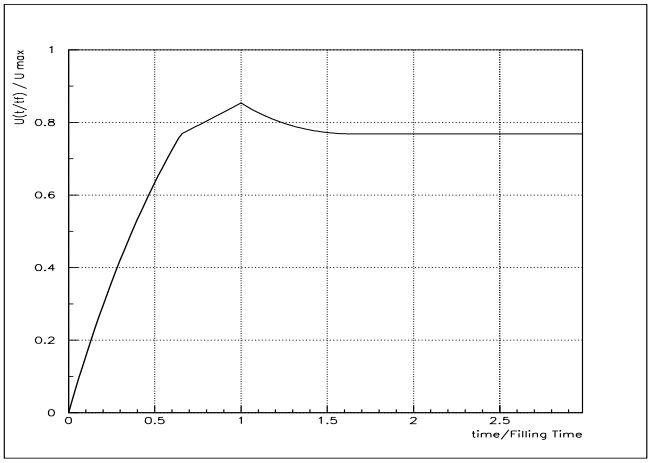

Figure 2: Accelerating voltage as a function of time with beam injected before the section is completely filled with rf.

staggered in time for the different klystrons have to be prepared which either requires an excessive number of low power amplifiers or will lead to even larger energy deviations because less control is available per betatron wavelength. Therefore two other methods for two different set-ups of a possible rf system in a linear collider have been investigated in detail.

2 The RF-System Set-Up

For the S-Band linear collider two different set-ups to power the accelerating structures are discussed. Either two six meter long accelerating structures are directly powered by one klystron or four six meter long structures are powered by one klystron plus one SLED cavity. In both cases a loaded gradient of approximately 17 MV/m is achieved, although using the SLED system, the design beam pulse is only 500 nsec as compared to 2000 nsec for the first case. On the other hand the pulse current is slightly higher with SLED in order not to loose a full factor of four in beam power.

2.1 Energy Compensation with the SLED System

In Fig. 3 the principle operation of the SLED cavity is shown with the respective field (power $\rightarrow$ field squared), cavity charging and accelerating voltage as a function of time. This behavior has been calculated elsewhere in detail and proven by measurements at many accelerator laboratories around the world [7, 8]. Such an rf system set-up is typically operated with short bunch trains ($\approx$ 10-50 nsec). For a linear collider much longer bunch trains with higher charge and therefore stronger beam loading have to be accelerated to fulfill the luminosity goals. In such a scheme the end of the bunch train al-

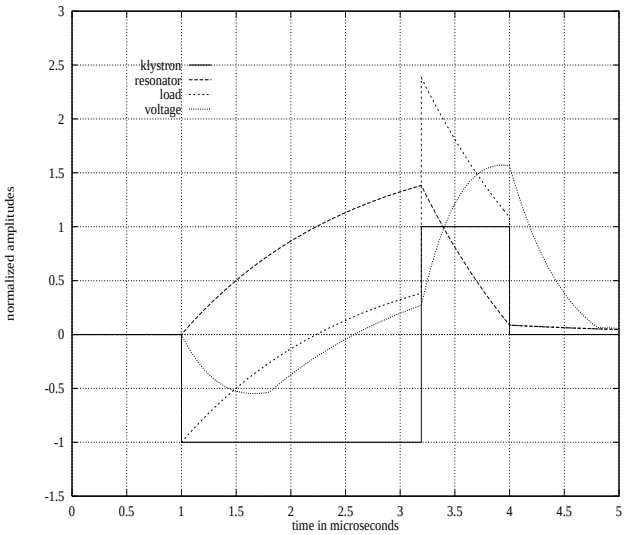

Figure 3: Principle of operation with a SLED cavity showing the field from the klystron, in the SLED cavity, at the entrance of the accelerating section and finally the accelerating voltage as a function of time.

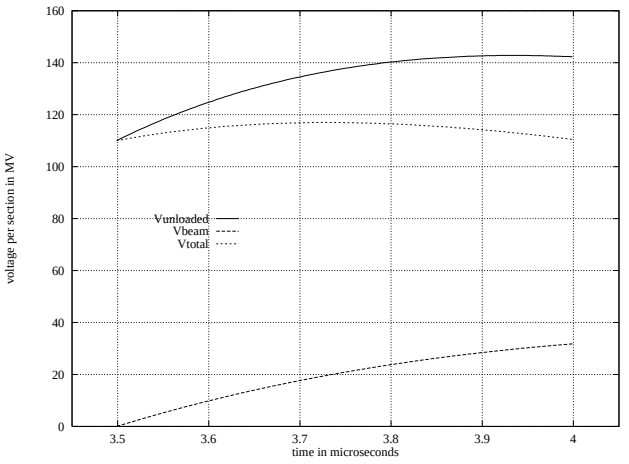

Figure 4: Accelerating voltage as a function of time without and with beam and optimum compensation.

ways has to fit the end of the rf pulse (compare Fig. 3). In general, for a given pulse train length which has to be significantly shorter than the decay time of the SLED cavity, there is always a specific current per pulse in order to achieve the same energy at the beginning and the end of the current pulse while in the middle the energy is higher by several percent. In Fig. 4 which is comparable to Fig. 3, the beam loading and the resulting energy spread (accelerating voltage plus beam loading is shown. The energy spread remains to be of the order of 10 % for a beam current of $\approx$ 500 mA.

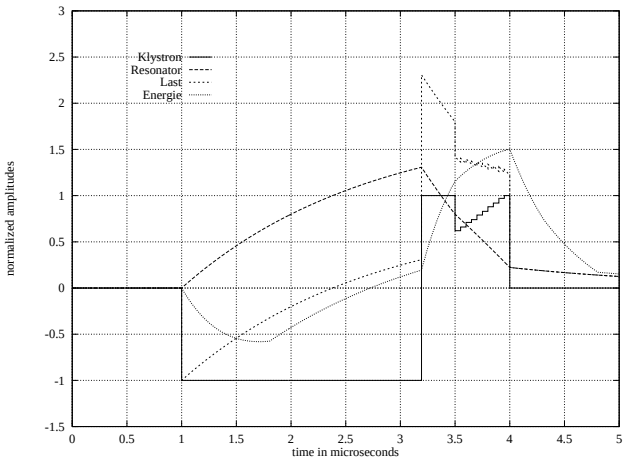

Figure 5: Amplitude modulation for optimum compensation of the transient beam loading. The amplitude is reduced after injection and linearly step by step ramped back to the maximum value.

Solutions to further reduce the energy spread have been discussed and published already [9, 10]. Either amplitude or phase modulation of the klystron pulse after the beam is injected, can be applied to reduce the multi-bunch energy spread to a value even below that of the single bunch energy spread. This result is presented in Fig. 5 using amplitude modulation, where the klystron amplitude is reduced by $\approx 30\,\%$ and linearly step by step ramped back to the maximum value towards the end of the pulse. The resulting energy spread is shown in Fig. 6. The parameters being used for this simulation are given in Table 1.

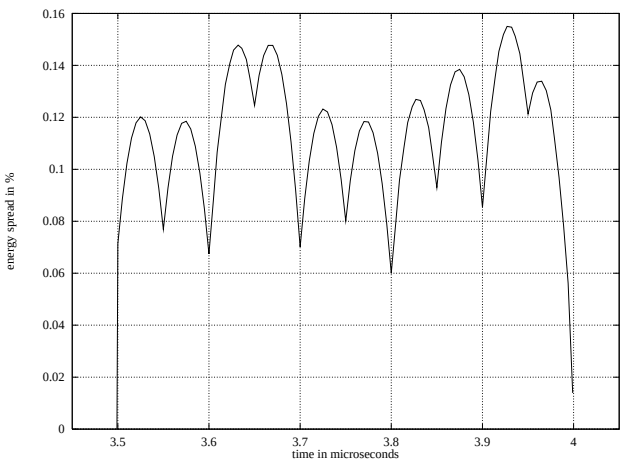

Figure 6: Bunch to bunch energy spread for almost optimum compensation of the beam loading by amplitude modulation.

In a set-up where no SLED cavity is used and the beam pulse is comparable or longer than the filling time of the section, the amplitude ramp would start at the beginning of the rf pulse. A linear amplitude ramp perfectly compensates the beam loading of a constant current pulse in a constant gradient section with constant shunt impedance per unit length. This can be seen in Fig. 7. The rf amplitude (normalized to the maximum amplitude) and the rf phase (normalized to π) are given in the upper graph, while the lower shows the unloaded and loaded accelerating gradient with a beam pulse switched on after one filling time. In the calculation presented, the amplitude starts at 23 % of the maximum value.

section parameter		
section length	m	6
attenuation	neper	0.55
group velocity variation	% of c	4.1–1.3
filling time	nsec	790
shunt imped. variation	MΩ/m	45–61
number of cells		180
klystron parameters		
peak power per input	MW/pulse	150
pulse length	μsec	3
repetition rate	Hz	50
number of sect. per klystron		4
SLED Cavity Parameters		
unloaded Q		180 000
Coupling Coeff.		11.2
beam parameters		
number of e^- per bunch		$1.5{\cdot}10^{10}$
bunch to bunch dist.	nsec	5
number of bunches		100

Table 1: Parameters from the S-Band Linear Collider study used for the simulation.

In general, continuous amplitude modulation has the disadvantage of operating the klystron not saturated. The problems following will not be discussed in detail here, but it should be mentioned that enhanced amplitude and phase jitter have a negative impact on the performance during the ramp. For a detailed study assumptions on the flatness of the amplitude have to be made or measurements using an actual test set-up are required.

2.2 Energy Compensation with to Anti-Phased Klystrons

In a standard accelerator set-up a klystron directly powers one or more accelerating sections. Filling the section with rf and injecting the beam leads to an energy distribution already shown in Fig. 1. For the parameters used in the S-Band linear collider study this would lead

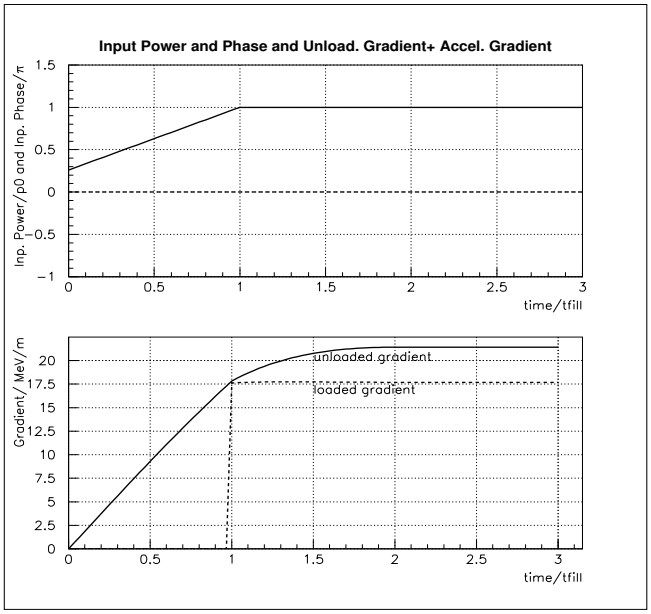

Figure 7: Unloaded and loaded gradient with with a beam pulse long compared to one filling time and rf amplitude modulation to compensate the beam loading.

to an energy spread of approximately 23 %.

A second method for compensating the transient beam loading will be investigated here. Similar methods have been used before, although not to compensate the transient beam loading within one beam pulse.

The idea is to go off crest in two succeeding klystron stations towards a phase angle (klystron n: $+\phi$ and klystron n+1: -ϕ) which will compensate the beam loading at every station and compensates the single bunch energy spread over two stations. Following this strategy, the single bunch energy spread is increased at station n but already compensated at station n+1. Whether this can have influence on the single bunch emittance growth has to be investigated in detail by tracking programs, but from first estimates there seems to be no effect because energy spread growth and compensation happens within two stations which is short compared to the betatron wavelength. In Fig. 8 the single bunch charge distribution (up to 3 σ) and the longitudinal wakefield is shown. In order to compensate the single bunch energy spread the optimum phase is approximately ϕ_0=9° leading to an energy spread of less than 0.3 %. The accelerating wave as well as the sum of the accelerating voltage and the longitudinal wakefield are presented in fig. 9. The maximum value of the longitudinal wakefield is 2.7×10^5 V/m at the design population of 1.1×10^{10} per bunch.

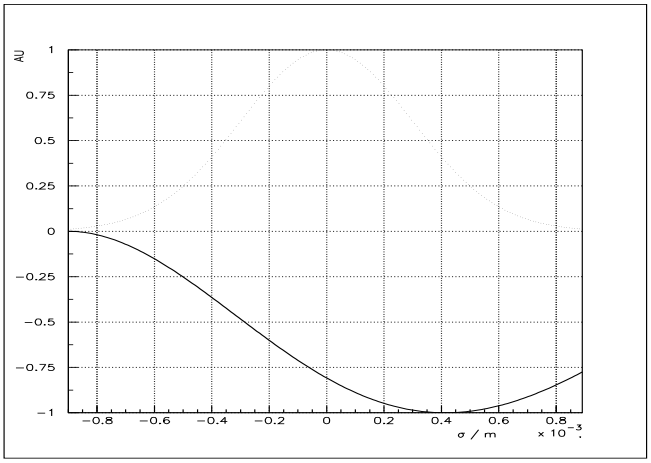

Figure 8: Longitudinal wakefield and single bunch charge distribution.

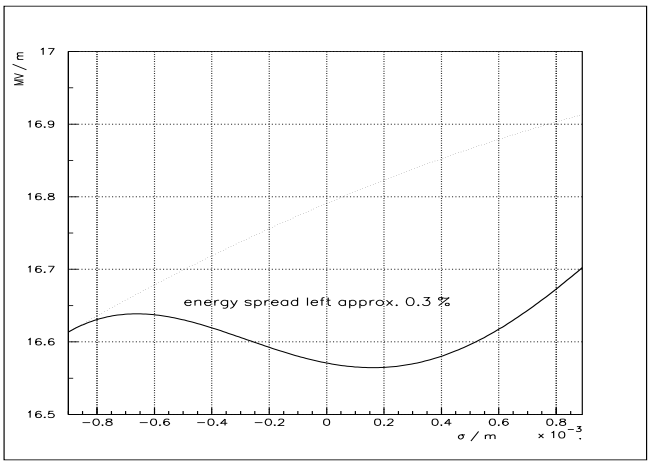

Figure 9: Longitudinal wakefield and Accelerating field at 17 MV/m.

From the beam induced voltage the additional average phase angle required to compensate for the transient loading, can be estimated easily. To first order this is simply given by:

$$cos(\phi_{off}) = \frac{U_{max} - U_{ind}}{U_{max}} \qquad (2)$$

For station n ϕ_{off} has to be added (9°+ϕ_{off}) while for station n+1 ϕ_{off} has to be subtracted (9°-ϕ_{off}). Summing up this leads to a compensated single bunch energy spread comparable to bunches accelerated at the final phase and gradient. Following the first bunch in the train, the integrated phase has to be ramped from ϕ_{off} to ϕ_0 to compensate for the increase of the beam loading voltage. For the first bunch for a bunch accelerated at steady state conditions the resulting single bunch energy

spread is shown in Fig. 11. The principle idea is sketched in Fig. 10, where the additional phase offset for single bunch energy compensation is exaggerated. Of course the same principle would work if artificial energy spread would have to be created for BNS damping. Technically the method can be applied by introducing a phase ramp of the order of ϕ_{off}. While the phase of the electric field stored in the section is still at an average phase angle of $\phi_0 \pm \phi_{off}$, the phase ramp starts traveling through the section over the filling time, comparable to the filling of the section with beam induced field.

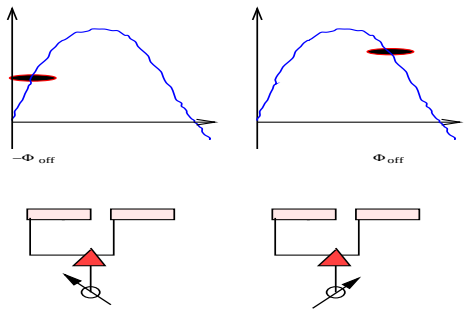

Figure 10: Transient beam loading compensation with simultaneous compensation of the single bunch energy spread.

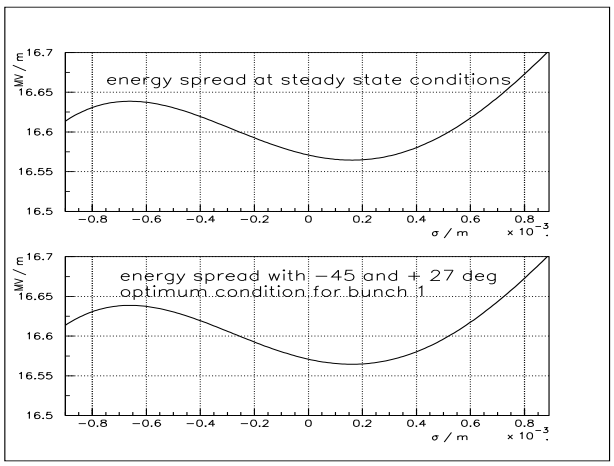

Figure 11: Resulting energy spread after phase step in front of the accelerating section.

In Fig. 12, the rf amplitude (normalized to the maximum amplitude) and the rf phase (normalized to π) are given in the upper graph, while the lower shows the unloaded and loaded accelerating gradient with a beam pulse switched on after one filling time. The detuning angle at the beginning of the rf pulse is 56°, while the average angle given by equation 2 is approximately 35°. Here the klystron amplitude is always at the maximum and the klystron operates saturated.

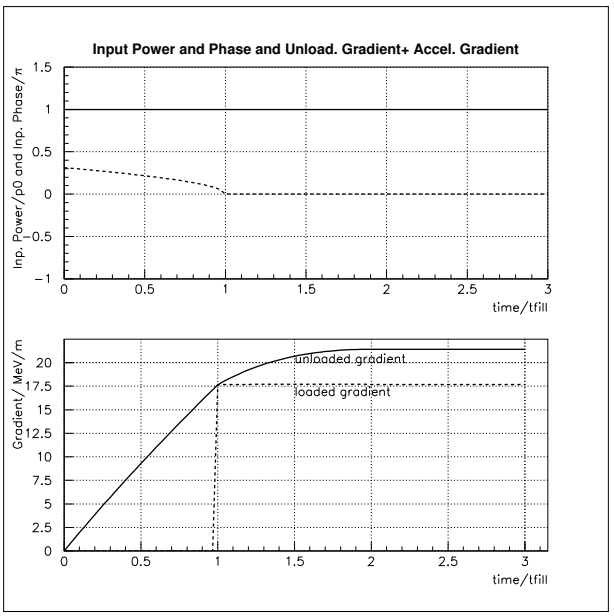

Figure 12: Resulting energy spread after phase ramp in front of the accelerating section.

3 Technical Impacts

For both methods proposed to compensate the transient beam loading, it is obvious that control for the drive power or the drive phase of the klystrons is required. For example, the SBLC klystrons produced so far are saturated with approximately 400 watt at the input cavity [11]. From the results presented here it is obvious as well, that the drive signal is either the same for all klystrons (compare method 1 used with SLED cavities) or two classes of klystrons (with $\pm\phi_{off}$) with equal drive signals are existing. Therefore one common drive line for one linac (or two drive lines for one linac) could in principle be used and the control problem with the operation and drive for more than thousand klystrons per linac could be reduced by orders of magnitude. This subject is discussed in greater detail in a second paper [12]. A technical solution and limitations will be discussed as well.

4 Conclusion

The conceptual layout for two different methods to compensate the transient beam loading in traveling wave linear accelerators is presented. Both methods are capable of reducing the multi-bunch energy spread over either

one or two klystron stations. Due to the fact that this is typically small compared to the betatron wavelength in a linear collider, single bunch emittance growth due to a locally enlarged energy spread and residual dispersion is almost negligible. This is a significant advantage compared to other methods proposed earlier, where the multi-bunch energy spread could only be corrected over a few or many klystron stations (distance comparable or larger than one betatron wavelength).

5 Acknowledgment

Especially we would like to thank R. Brinkmann who triggered the idea on energy compensation by phase modulation during a discussion. The authors are also indebted to many colleagues from the S-Band linear collider study group at DESY who contributed to these ideas.

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