CERN - European Laboratory for Particle Physics

CLIC Note 408

CLIC Main Linac Beam-Loading Compensation by Drive Beam Phase Modulation

R. Corsini, J.P Delahaye, I. Syratchev

Abstract

The CLIC final focus momentum acceptance of ± 0.5 % limits the bunch-to-bunch energy variation in the main beam to less than ± 0.1 %, since the estimated single-bunch contribution is ± 0.4 %. On the other hand, a relatively high beam-loading of the main accelerating structures (about 16 %) is unavoidable in order to optimize the RF-to-beam efficiency.
Therefore, a compensation method is needed to reduce the resulting bunch-to-bunch energy spread of the main beam. Up to now, it has been planned to obtain the RF pulse shape needed for compensation by means of a charge ramp in the drive beam pulse. On the other hand, the use of constant-current drive beam pulses would make the design and operation of the drive beam injector considerably simpler. In this paper we present a possible solution adapted to the CLIC two-beam scheme with constant-current pulses, based on phase modulation of the drive beam bunches.

Geneva, Switzerland
August 1999

CLIC main linac beam-loading compensation by drive beam phase modulation

R. Corsini, J.P Delahaye, I. Syratchev
CERN, CH-1211 Geneva 23, Switzerland

ABSTRACT

The CLIC final focus momentum acceptance of ± 0.5 % limits the bunch-to-bunch energy variation in the main beam to less than ± 0.1 %, since the estimated single-bunch contribution is ± 0.4 %. On the other hand, a relatively high beam-loading of the main accelerating structures (about 16 %) is unavoidable in order to optimize the RF-to-beam efficiency.
Therefore, a compensation method is needed to reduce the resulting bunch-to-bunch energy spread of the main beam. Up to now, it has been planned to obtain the RF pulse shape needed for compensation by means of a charge ramp in the drive beam pulse. On the other hand, the use of constant-current drive beam pulses would make the design and operation of the drive beam injector considerably simpler [1]. In this paper we present a possible solution adapted to the CLIC two-beam scheme with constant-current pulses, based on phase modulation of the drive beam bunches.

INTRODUCTION

If no beam loading compensation is used, the CLIC main beam bunch train energy would decrease to about 16 % of its initial value along about 20 ns, corresponding to the accelerating structure filling time, τ_{fill}. After a filling time, a steady-state condition is reached, and the bunch energy stays constant.
The principle of the beam-loading compensation scheme for CLIC [2,3] consists in artificially creating the steady state condition by specially shaping the first 20 ns of the RF pulse (like it is shown in Figure 1). When the first bunch is injected in the structure, it is subject to an accelerating gradient whose dependence from the position inside the structure is exactly equal to the one normally reached in the steady state regime.
The optimum shape of the RF amplitude for the CLIC nominal main beam parameters is very close to a linear ramp during the filling time, followed by a flat-top. The ideal ramp can be expressed as:

$$A(t) = A_0 + (1 - A_0)\frac{t - \tau_0}{\tau_{fill}} + F(t) \quad , \quad \tau_0 < t < \tau_0 + \tau_{fill} \qquad (1)$$

where τ_0 is the ramp starting time and A_0 = 0.68, the expression being normalized to the flat-top amplitude. The nonlinear correction is described by the function *F(t)*. A plot of *F(t)*, obtained by a numerical optimization, is shown in Figure 2.
The linear part of equation (1), according to simulations, would already be sufficient to correct the main beam bunch-to-bunch energy variation to about ± 0.05 %, half of the maximum allowed. Including the non-linear correction, the energy variation is reduced by an order of magnitude, to ± 5 10^{-5}.

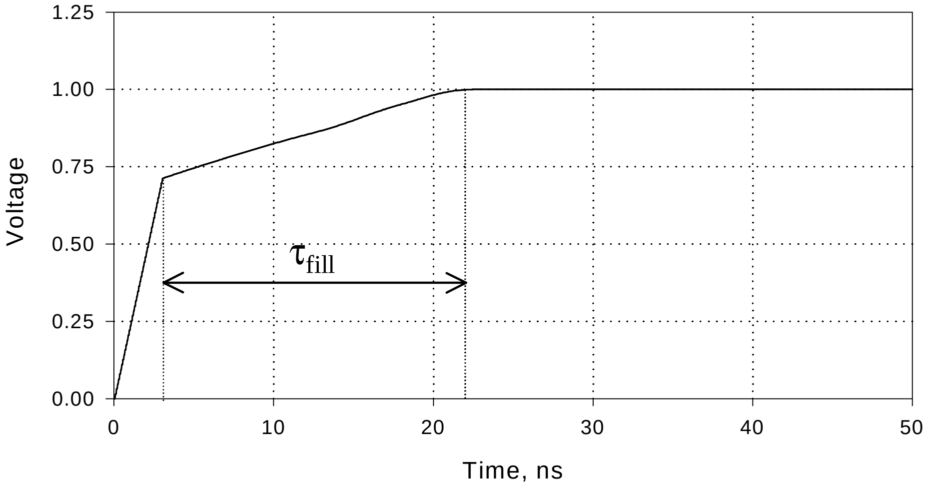

Figure 1: Ideal RF pulse amplitude, normalized to the flat-top value. The part of the RF pulse identified on the picture with τ_{fill} is the one seen by the first main beam bunch, and is described by equation (1).

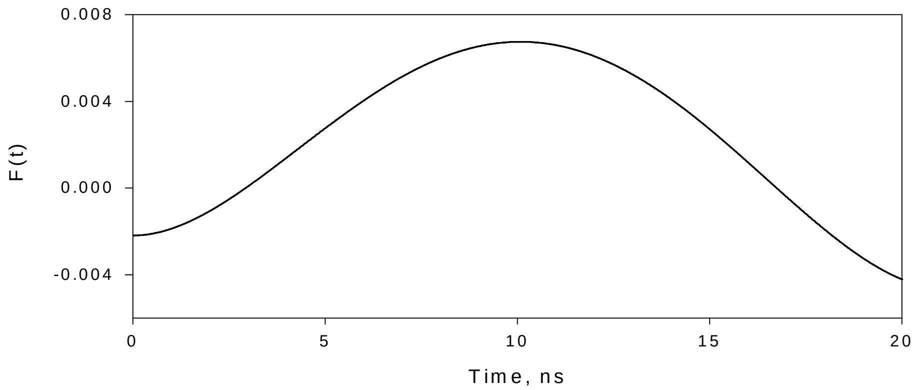

Figure 2: Deviation from linearity in the RF pulse amplitude during τ_{fill} , normalized to the flat-top value, i.e., function *F(t)* in equation (1).

The RF power is produced in CLIC [4] by the interaction of a high-current drive beam with specially designed RF structures, the Power Extraction and Transfer Structures (PETS). Each main beam pulse (e^- or e^+) is accelerated to its final energy by 22 drive beam pulses, each one powering one fraction of the main linac and losing about 90% of its energy in a ~ 640 m long decelerator section. The drive beam pulses are created and accelerated to about 1.2 GeV in the drive beam generation complex, and are 130 ns long, being composed by bunches of 16 nC each, spaced by 2 cm.

In this note is proposed to synthesize the optimum RF ramp by a proper phase modulation of the drive beam bunches along the initial 20 ns of the drive beam pulse, corresponding to a filling time τ_{fill} of the accelerating structure. During this time, consecutive bunches oscillate around the ideal phase, with a de-phasing amplitude $\pm \Delta\phi$ decreasing with time. The RF power production efficiency from the PETS will be proportional to $\cos(\Delta\phi)$, while the average RF phase will stay constant. The desired phase variation can be obtained by introducing an energy oscillation between consecutive bunches, using an accelerating cavity at a frequency 7.5 GHz, corresponding to half the bunch distance. The first drive beam bunch is injected in the energy modulating structure while the RF power is switched off. Since the structure is being emptied, the following bunches will see a decreasing accelerating/decelerating voltage (see Figure 3).

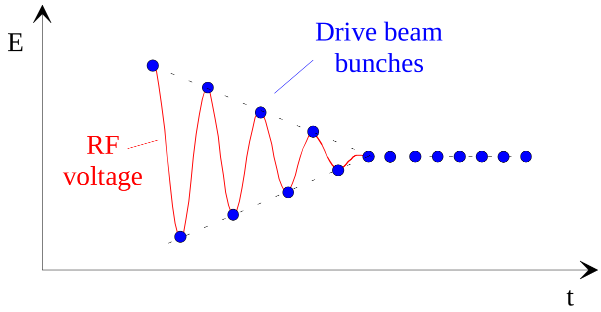

Figure 3: Illustration of the energy modulation process.

The energy modulation is then converted in a phase modulation in the return arcs that inject the different drive beam pulses in the decelerator sections, where the drive beam bunches are also compressed to their final length. A schematic illustration of the mechanism is shown in Figure 4.

In order to relax the requirements on the 7.5 GHz power source, it looks preferable to introduce the energy modulation separately for each of the 2×22 drive beam pulses that power the different sectors. Another advantage of such configuration is that the phase modulation can be tuned independently for the different sectors, allowing for an additional compensation of the final bunch-to-bunch energy spread.

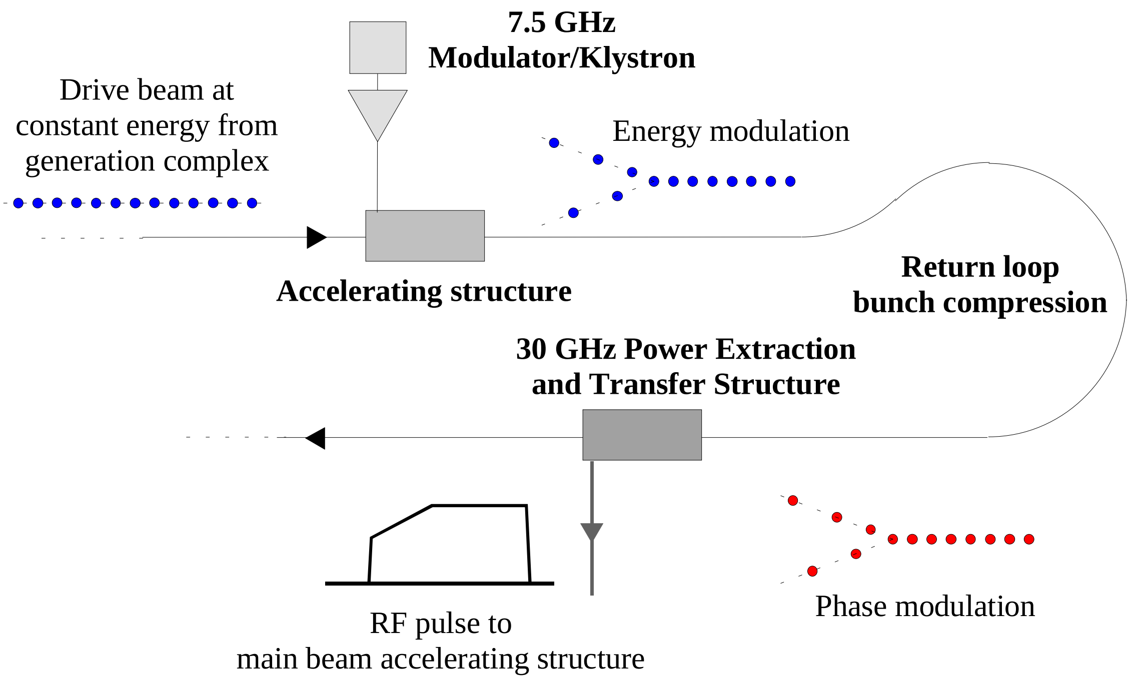

Figure 4: Schematic illustration of the de-phasing mechanism.

OPTIMIZATION OF THE PHASE MODULATION

As mentioned before, the RF amplitude at the PETS output is simply proportional to cos($\Delta\phi$), where $\Delta\phi$ is the phase offset of the drive beam bunches with respect to the PETS frequency. The phase of the output pulse remains constant except during the initial transient, equal to the PETS drain time (time needed to reach the steady state in power production), if the even and odd bunches have $\pm\,\Delta\phi$ phase offsets.
Thus we can express the optimal phase modulation as:

$$|\Delta\phi(t)| = \mathrm{acos}\left[A_L(t)\right] \tag{2}$$

where $A_L(t)$ is the linear approximation of the optimum RF amplitude ramp:

$$A_L(t) = A_0 + (1 - A_0)\frac{t - \tau_0}{\tau_{fill}} \tag{3}$$

In Figure 5 the optimised phase modulation of the drive beam bunches is shown. In figure 6 the RF pulse ramp produced by the drive beam in a PETS, with and without phase modulation, is shown. In the simulation, a group velocity of 0.5 c and a PETS active length of 1 m where chosen.

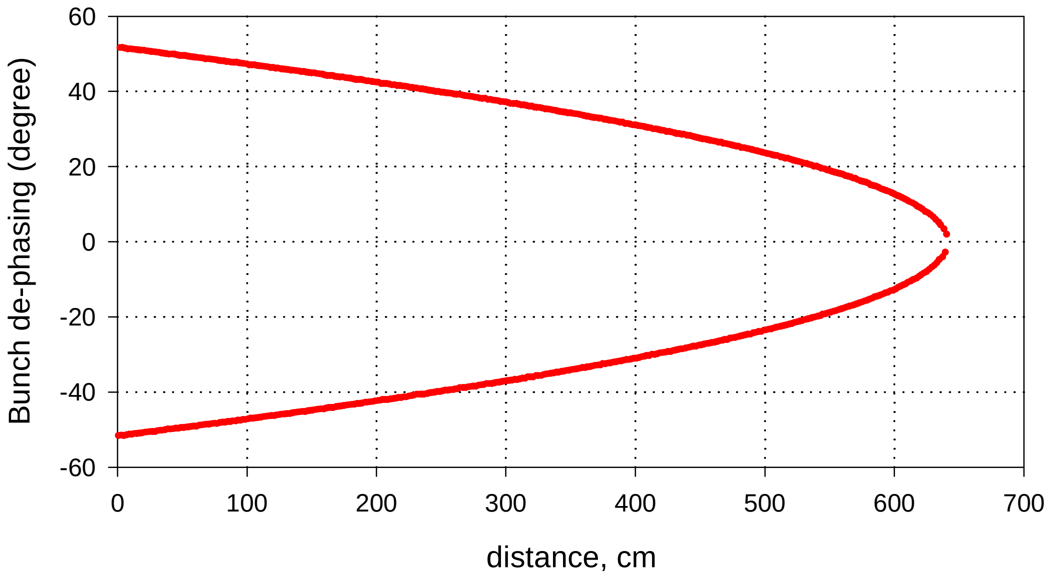

Figure 5: Optimum phase modulation in the drive beam pulse leading edge.

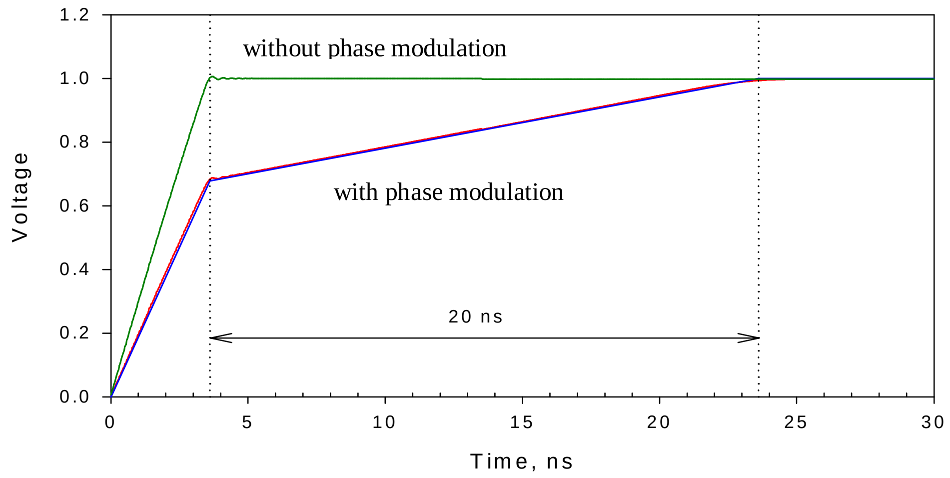

Figure 6: RF amplitude at the PETS output with and without phase modulation. The initial ramping-up, starting from zero, corresponds to the PETS drain time.

LINEAR ENERGY MODULATION

It is assumed in the following that the return arcs introduce a variation in the bunch distance that is linearly proportional to the bunch energy difference; therefore the phase modulation will have the same dependence from time than the energy modulation.

The needed modulation spans only 20 ns over the 130 ns total duration of the drive beam pulse. This can be obtained if the drive beam is injected in the modulating cavity at the same time when the input RF pulse is shut off. Since the cavity is being emptied, the integration by the beam of the RF voltage along it will result in a ramped down energy modulation during a time equal to the cavity filling time. Naturally, one would obtain in such a way a linearly decreasing energy modulation. We will concentrate at first on this simple case; we will show later how a more precise approximation of the ideal phase modulation of figure 4 can be obtained.

The initial value of $\Delta\phi$ can be calculated in first approximation using equations (2) and (3), obtaining $\Delta\phi = 47°$. Taking into account the transient in the PETS (lasting a drain time ~ 3 ns), the more precise value $\Delta\phi = 54°$ can be obtained, corresponding to ± 1.5 mm at the resonant PETS frequency of 30 GHz. The corresponding energy variation can be calculated knowing the matrix element R_{56} of the return arcs, correlating the energy variation $\Delta p/p$ with the path length difference Δl. Since the R_{56} is about 0.15 m (tuned experimentally to optimize the bunch compression [4]), the needed energy variation will be $\Delta p/p$ ~ ± 1%. The integrated RF voltage seen by the first bunch is therefore of the order of 10 MV. Thus we can estimate the RF power that has to be delivered from each 7.5 GHz klystron.

In order to perform accurate simulations of the drive beam energy modulation the parameters of the π/2, 7.5 GHz energy modulating structure where calculated (see Figure 7).

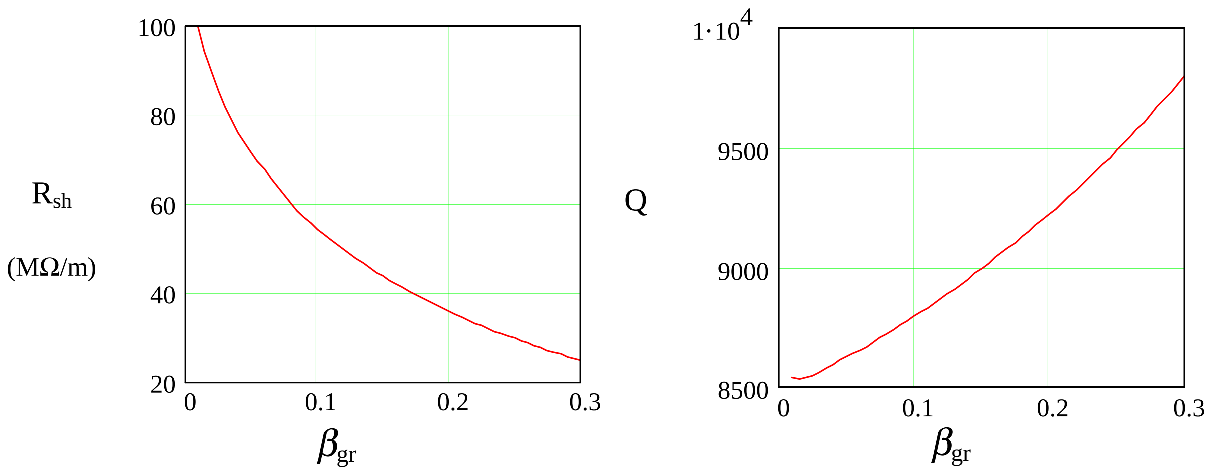

Figure 7: Energy modulating structure shunt impedance and quality factor as a function of group velocity.

In Figure 8 the integrated voltage seen by the first bunch as a function of the input power, calculated for the different structure parameters, is shown. We can conclude that a linear ramp energy deviation can be easily produced with a ~1 meter long 7.5 GHz structure, fed with a pulsed klystron of less than 25 MW power.

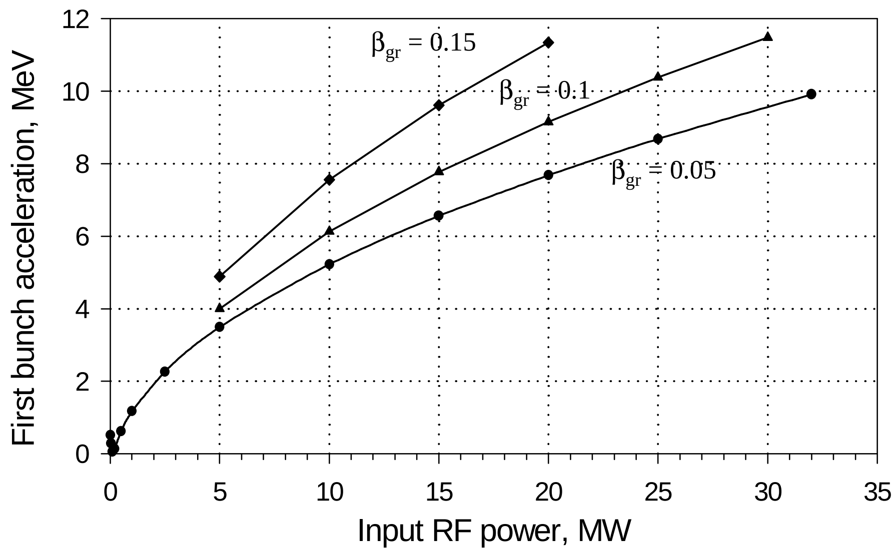

Figure 8: Integrated gradient seen by the first bunch in cavities with different group velocities and lengths, and with 20 ns filling time, as a function of input power.

Potential problems are short and long-range longitudinal wake-fields, which can be important in a high-frequency structure. Potentially, short-range wake-fields could disturb the energy versus time correlation needed in each bunch for optimum bunch compression. The bunches phase extension with respect to 7.5 GHz is also non-negligible, and can have the same effect.

Long-range wakes can alter the desired modulation along the first 20 ns and, even worse, provoke an unwanted modulation of the energy in the flat-top, which has to stay constant. Short-range wake-field have been modelled by scaling to a higher frequency ν and different iris radius a the formula for delta-wakes in the ν_0 = 3 GHz SBLC structure [5], like:

$$W_L(t) = 250\, V/(\mathrm{pC\ m}) \left(\frac{a}{a_0}\right)^2 \left(\frac{\nu}{\nu_0}\right)^2 \exp\left(-0.85\sqrt{z/\mathrm{mm}\ \nu/\nu_0}\right) \quad (4)$$

The influence of short-range wakes is small. More important is the effect of RF curvature due to the bunch phase extension. The two effects are compared in Figure 9. Anyway, these effects does not affect much the bunch compression process, as shown in Figure 10, and can be considered as small corrections to the optimum phase modulation amplitude.

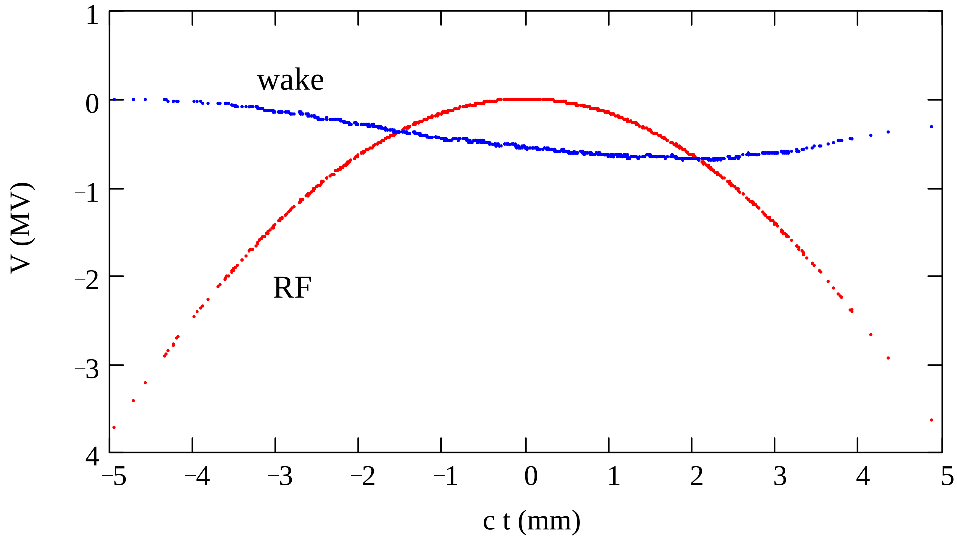

Figure 9: Single-bunch wake voltage and voltage variation along the bunch due to RF phase extension in the 7.5 GHz modulating structure.

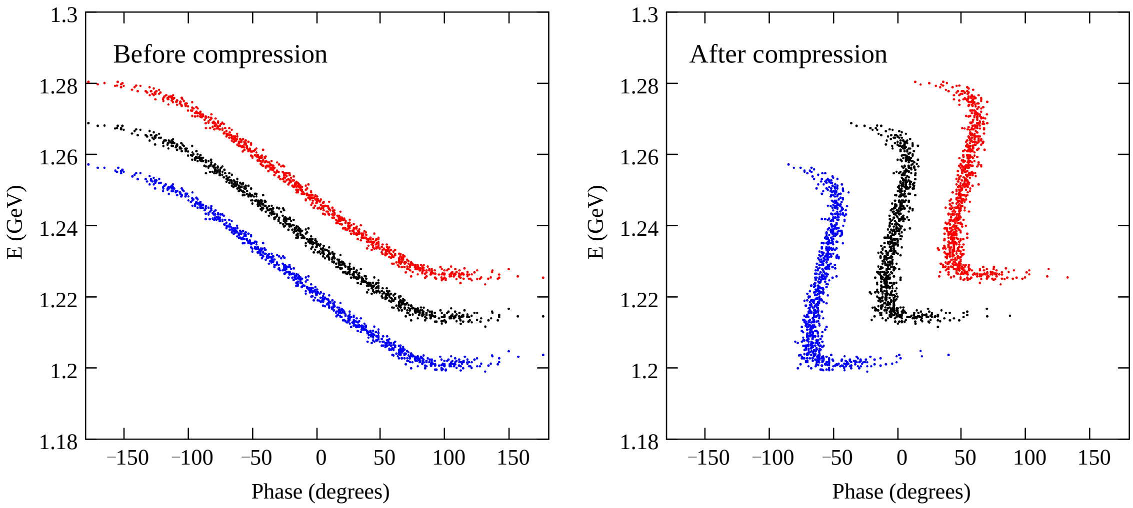

Figure 10: Energy-phase plots for a steady-state, unperturbed drive beam bunch (in the center), and energy and phase modulated bunches, before and after the final compression. The small deformation due to wakes and RF phase extension is not visible.

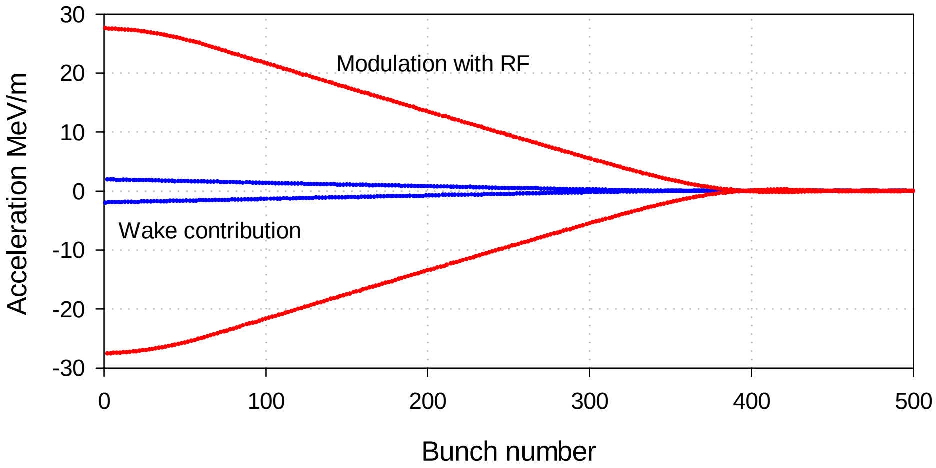

Figure 11: Energy modulation along the drive beam pulse after the structure. The integrated voltage from RF, and the long-range wake-fields contributions are shown separately (β_{gr} = 0.05c). The first bunch is accelerated.

Long-range wake-fields are 180° out of phase for consecutive bunches, therefore the individual bunches contributions do not add up. Steady state is reached after a filling time of the modulating structure, so that the flat-top is not perturbed. Long-range wake-fields represent as well a small correction to the energy modulation. In Figure 11 the energy profile of the drive beam after modulation and the long-range contribution are shown. It can be seen that the energy modulation thus obtained is almost linear. As mentioned before, a linear energy modulation will produce a similar phase modulation. Since the RF amplitude is proportional to $\cos(\Delta\phi)$, the RF ramp obtained is not linear.

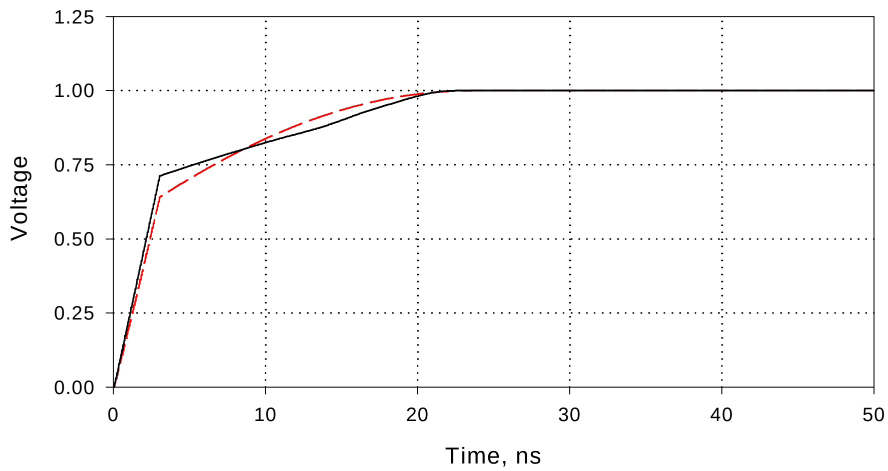

Figure 12: Ideal RF amplitude (solid line), compared with the RF amplitude obtained from the PETS using a linear phase modulation in the drive beam.

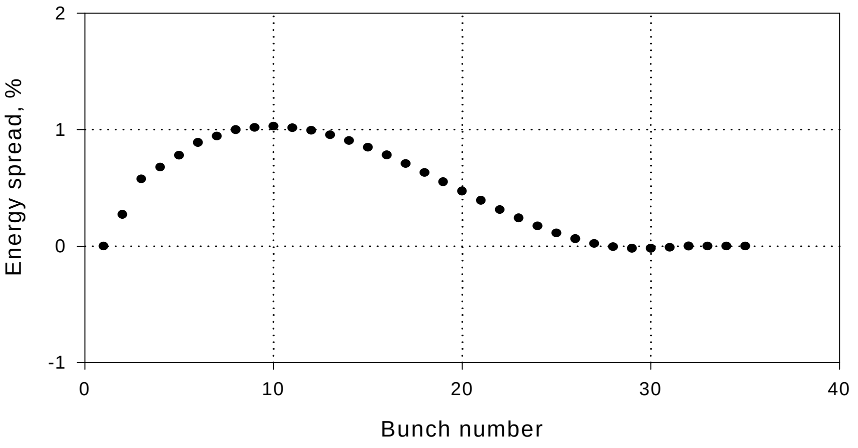

Figure 13: Energy distribution along the main beam pulse, obtained using a linear phase modulation of the drive beam. The energy spread is ± 0.5 %, more than the required ± 0.1 %.

In Figure 12 such ramp is compared with the ideal one, and in Figure 13 the corresponding energy distribution obtained in the main beam is shown. The energy spread obtained with a linear ramp (± 0.5 %) is well above the required limit (± 0.1 %).

OPTIMIZED ENERGY MODULATION

In the previous section we showed how a linearly decreasing energy modulation can be introduced in the drive beam pulse. Unfortunately, the resulting main beam energy spread is too high. It is necessary to produce a phase modulation which is sufficiently close to the optimized one shown in Figure 5 to obtain a main beam energy spread smaller that ± 0.1 %. We studied two possible solutions to this problem.

Special Structure. The basic idea is that, if we can increase the group velocity (so that the RF power evacuate faster) towards the end of the modulating structure, then a non-linear dependence on the energy gain can be achieved. This means that the structure needs to have an extremely non-linear distribution of the group velocity. In this case the voltage gain is defined as:

$$U(t) = \int_{z(t)}^{Lstr} E_z(z')dz' \qquad (5)$$

where *z(t)* can be derived from:

$$t(z) = \int_0^z \frac{1}{\beta(z')c} dz' \qquad (6)$$

Let us consider first that $E_z(z) = const$, then it is possible to calculate a group velocity distribution (shown in Figure 14) that will provide a very fine fit of the ideal energy modulation, like shown in Figure 15.

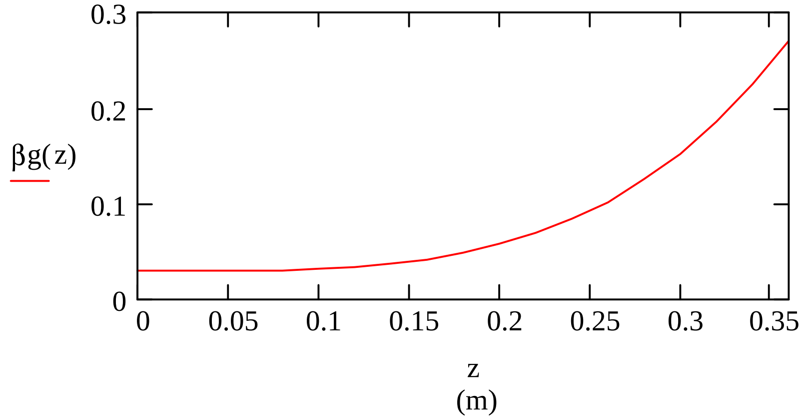

Figure 14: Group velocity distribution needed in the special energy modulating structure to obtain optimized energy modulation, under the condition $E_z(z) = const$.

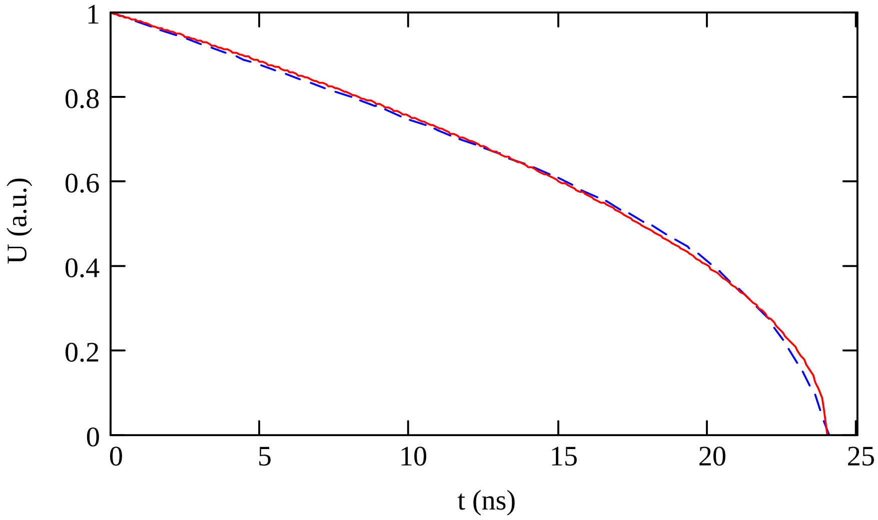

Figure 15. Energy modulation along the drive beam pulse, obtained with the group velocity distribution of figure 13, under the condition $E_z(z) = const$ (solid line), compared with the ideal distribution (dashed line).

Unfortunately, in a standard accelerating structure a change in group velocity implies a change in the shunt impedance *R/Q*. In normal conditions, the accelerating field decreases along the structure as the group velocity increases, thus compensating the non-linear effect we want to introduce (see Figure 16).

Of course one can suppose to use a specially developed structure, in order to obtain a constant field distribution together with a varying group velocity. One possibility would be to introduce damping in the initial part of the structure. Apart from experimental difficulties, such a solution would have the disadvantage of requiring more RF power for a given energy modulation amplitude. Alternatively, the *R/Q* variation along the structure can be adjusted with a special distribution of the phase advances over the cells. This solution makes the structure design very complicated. In conclusion, while it seems possible in principle to use a special structure with variable group velocity and constant gradient, such a structure looks very exotic, and can present sever problems in the practical realisation.

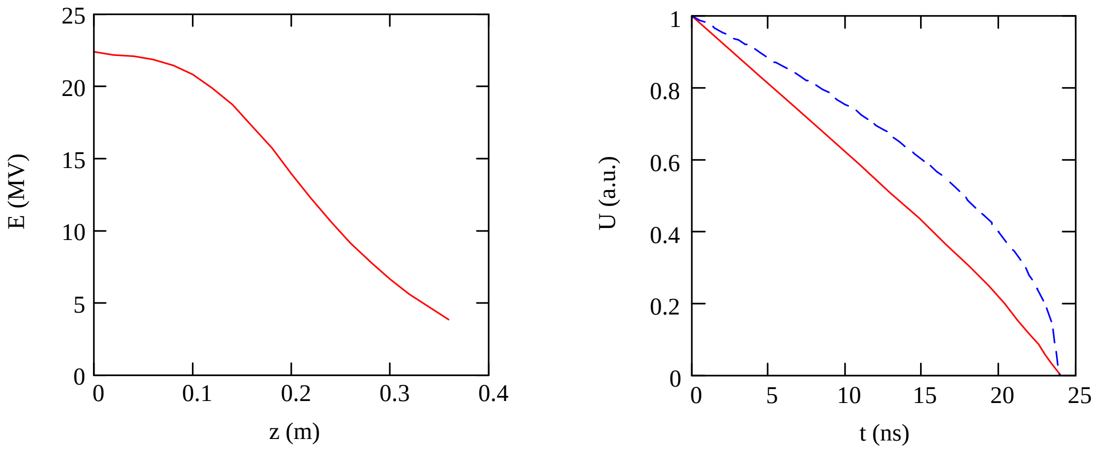

Figure 16: To the left, accelerating gradient distribution along the modulating structure, corresponding to the group velocity distribution of figure 13. To the right, drive beam energy modulation obtained when the gradient distribution is taken into account (solid line), compared with the ideal energy modulation (dashed line).

Structure chain. A more promising solution is based on the idea to synthesize the ideal distribution using a chain of a few structures with different filling times and beam-to-RF delays. Each structure introduces a linearly decreasing energy modulation (like in the simple case discussed in the previous section), but with different amplitudes and over different time scales. The sum of the individual contribution is an approximation of the ideal energy modulation. A schematic layout of the system is shown in Figure 17.

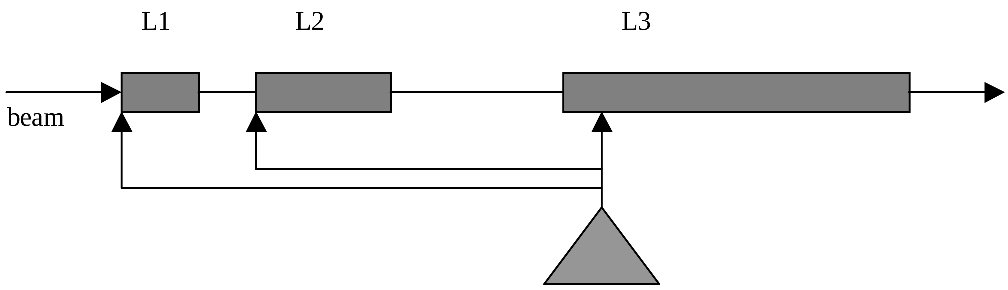

Figure 17: Chain of structures for energy modulation.

In this configuration the resulting energy deviation is the sum of the three cavities contributions. To obtain the best fit, the individual structures energy gain must satisfy the conditions:

$$\begin{cases} U(0) = U_1 + U_2 + U_3 \\ U(t_1) = U_1(1 - \frac{t_1}{t_3}) + U_2 + U_3 \\ U(t_2) = U_1(1 - \frac{t_2}{t_3}) + U_2(1 - \frac{t_2 - t_1}{t_3 - t_1}) + U_3 \end{cases} \quad (7)$$

where U_i are the unknown voltage gains in the individual structures, *U(t)* is the amplitude of the ideal energy modulation as a function of time, t_i are the beam injection times in the different structures; the filling times of the structures are expressed as t_1, $t_2 - t_1$, $t_3 - t_2$.
Following (7), for a given distribution *U(t)* one can choose values of the delay times that gives a very good fit of the ideal energy modulation (see Figure 18).

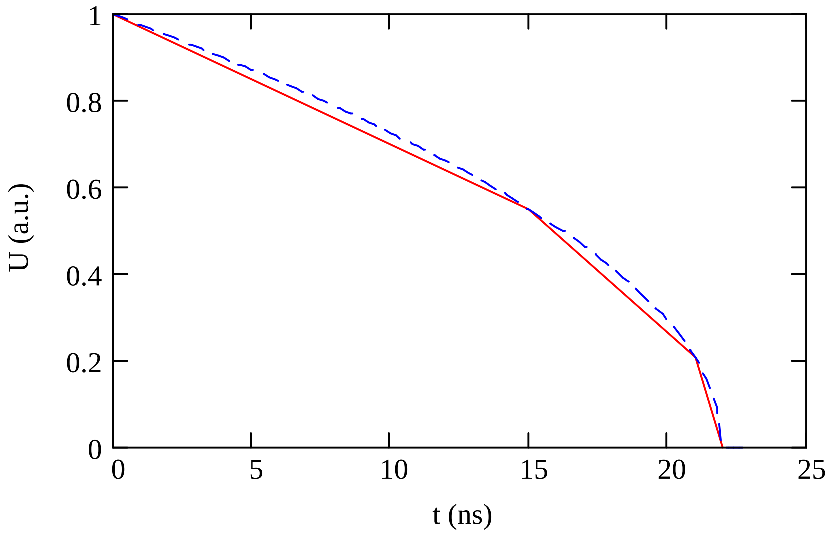

Figure 18: Ideal energy modulation of the drive beam, normalized (dashed line), compared with the fit obtained using a 3-structure chain (solid line), following equation (7).

Using equation (7) as a guideline, the parameters of a 3-structure chain have been fixed, and a full simulation has been made for such a case. In Figures 19 and 20 both the individual contributions and the final drive beam energy modulation are shown.
Finally, in Figure 21 the deviation from the ideal ramp of the RF voltage obtained with the 3-structure chain is plotted.

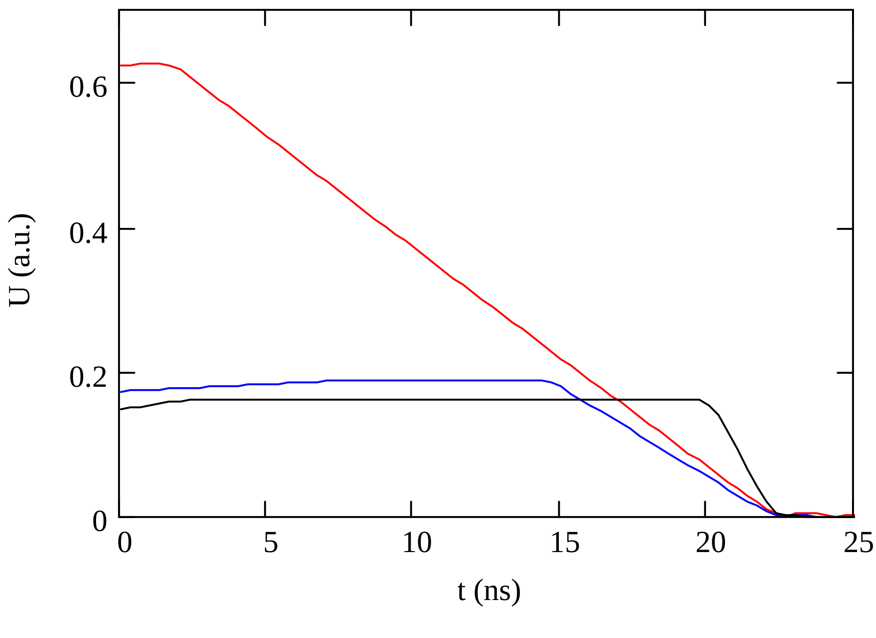

Figure 19: Drive beam energy modulation amplitudes introduced by each of the three cavities composing the chain.

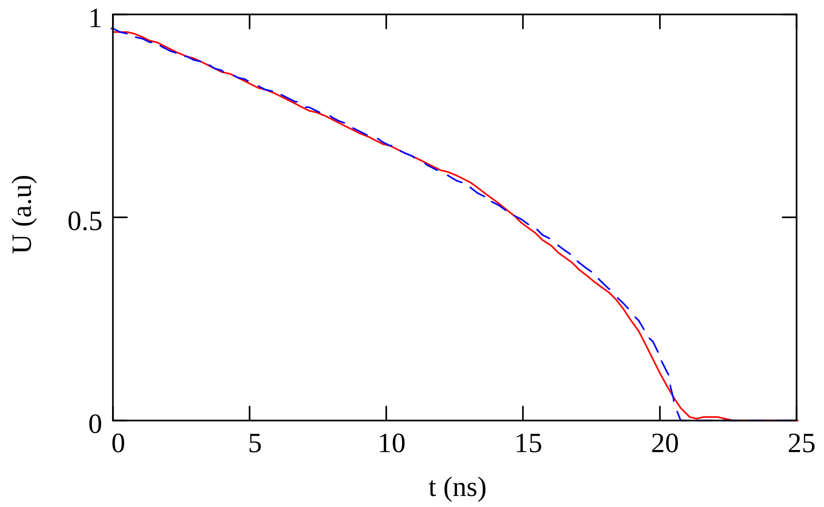

Figure 20: Final drive beam energy modulation amplitude at the exit of the 3-structure chain (solid line), compared with the ideal one (dashed line).

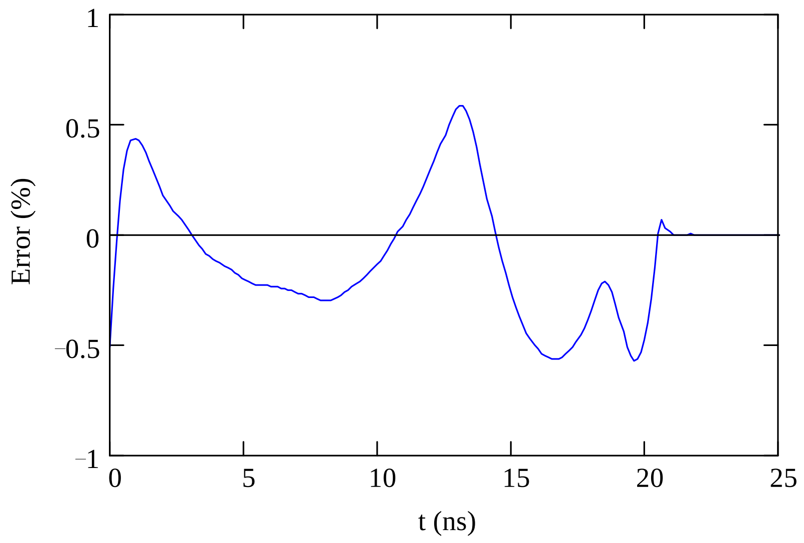

Figure 21: Deviation from ideal ramp (in percentage of the flat top amplitude) of the RF voltage obtained with the 3-structure chain.

In Table 1 the parameters for the 3-structure chain, yielding 10 MV energy deviation for the first bunch, are resumed. The total length of the chain is about 3.8 m. The total RF power (using two identical structures of type 1) is 23 MW.

Table 1

Structure N	L_{str}, m	U_{str}, MV	P_{str}, MW	Delay, ns	Distance,m
1	0.12	1.49	20*	-21	2.72
2	0.4	1.92	9	-15	2.04
3	1.08	6.59	3.8	0	0.

*by using two identical structures the required power can be reduced to 10 MW.

The main beam full energy spread achievable using the 3-structure chain solution has been evaluated through numerical simulations, and is about ± 0.05 %, within the ± 0.1 % acceptable limit. The main beam energy distribution is shown in Figure 22. The level of compensation could be in principle increased by using a larger number of accelerating sections. Alternatively (or on top of it), a further improvement can be expected by a slightly different tuning of the energy modulation in each of the 20 drive beam pulses that provide RF power to each main beam pulse.
The structure chain solution seems to be by far preferable to the special structure solution, since it is much more straightforward, and more flexible. The integrated gradient and the injection time of each structure can in fact be individually tuned in operation, giving some control over the energy modulation profile.

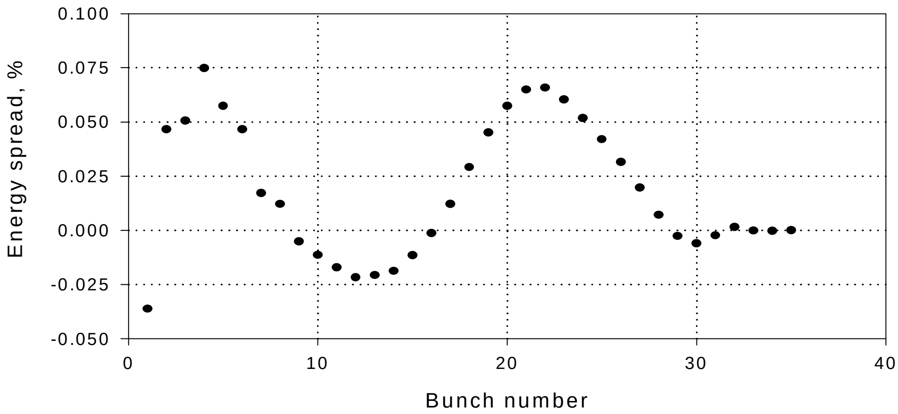

Figure 22: Energy distribution along the main beam pulse, obtained using a linear phase modulation of the drive beam pulse. The energy spread is about ± 0.05 %, well within the ± 0.1 % limit.

CONCLUSIONS

In this report we have presented a possible beam loading compensation scheme for CLIC, adapted to two-beam acceleration and constant current drive beam pulses. Each of the 2 ×20 drive beam decelerator sectors would be preceded by a short (~ 4 m) energy modulation section, composed by a power source and 3 (or more) accelerating structures. A total of 2 × 20 klystrons at 7.5 GHz, of reasonable power (< 30 MW) would be needed for the whole CLIC complex. The drive beam energy modulation will be converted in phase modulation of the bunches in the drive beam return arcs, yielding in turn an optimized ramp profile for the RF pulse amplitude at the exit of the PETS. The main beam energy spread that can be obtained with such a method is < ± 0.05 %, to be compared with the requirement of a maximum spread of ± 0.1 %. Some of the potential problems, e.g., short and long-range wake-fields, have been investigated, and pose no major problem to the scheme implementation. One potential drawback is the decreased drive beam stability in the decelerator sectors, as shown in some preliminary simulation [6]. The effect looks substantial, but can be possibly tolerated. At present, a different scheme for beam loading compensation adapted to constant current drive beam pulses is under investigation [7], and it could be preferred to the one presented here since it does not need any additional hardware. Still, the phase modulation scheme can be used in addition as a fine tuning, in which case the power requirements would further drop, and the beam stability would be an issue no more.

REFERENCES

[1] H. Braun, CLIC RF Power Source Meeting Minutes n. 44, 28 January 1999.
[2] K.A. Thompson and R.D. Ruth, “Simulation of Multibunch Energy Variation in 0.5 and 1 TeV Linear Collider Designs”, SLAC Pub. 5882.
[3] L. Thorndahl, “Drive Beam Bunchlet Trains for Multibunching”, CLIC Note 291.
[4] H.H. Braun, R. Corsini, T. D’Amico, J.P. Delahaye, G. Guignard, CD. Johnson, A. Millich, P. Pearce, L. Rinolfi, A.J. Riche, D. Schulte, L. Thorndahl, M. Valentini, I.. Wilson, W. Wuensch and R.D. Ruth, “The CLIC RF Power Source, A Novel Scheme of Two Beam Acceleration for $e^{\pm}$ Linear Colliders”, CLIC Note 364 (1998).
[5] K. Bane, M. Timm and T. Weiland, DESY-M-97-02, January 1997.
[6] D. Schulte, CLIC RF Power Source Meeting Minutes n. 53, 22 April 1999.
[7] D. Schulte, CLIC RF Power Source Meeting Minutes n. 58, 3 June 1999.