Multibunching Studies for CLIC

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Abstract

Studies aimed at increasing the luminosity of the CERN Linear Collider (CLIC) for a given power by introducing multiple bunches during a single RF fill are described. Long range transverse wakefields are reduced by detuning the dipole mode frequencies and beam loading is compensated by partial section filling and tapered power pulses.

INTRODUCTION

Operation of CLIC in a multibunch mode is being studied in an attempt to increase luminosity without significantly increasing power consumption, and to reduce the charge per bunch. Lower bunch charges result in less disruption at the interaction point: consequently there is less energy spread in interactions and easier physics analysis. Multiple bunches during a single RF fill can be accelerated to the same energy by adding extra energy to compensate the beam loading. The compensation must however be compatible with the rather small $\pm 0.23\%$ energy acceptance of the final focus system and the physics requirement of a small energy spread.

As a starting point, a train of *four* bunches with 4.24×10^9 particles per bunch has been chosen - this doubles the present single bunch luminosity (6×10^9 particles) and reduces the bunch charge by a factor $\sqrt{2}$. Beam simulations with such charges in the 500 GeV version of CLIC indicate that long range transverse wakefields must be reduced by factors between 200-1000 (depending on the way the linac is optimised) for the passage of a second bunch without excessive loss in luminosity [1]. This value is a factor 10 more severe than that needed for X-band multibunching [2]. The major difference comes from the cubic dependence of wakefield on frequency, but some ground is regained on the shorter linac length due to higher accelerating gradients, and tighter alignment tolerances.

BEAM LOADING COMPENSATION

The simplest beam loading compensation scheme minimises energy spread by having the section only partially filled when the first bunch passes but completely filled when the final bunch.passes. The energy flowing in during the time between bunches ($\Delta s/c$) balances the energy being taken out by the bunches thus keeping the net voltage constant. The energy gain of the b^{th} of n bunches is given by,

$$\Delta E_b = E_0[L-(n-b)\Delta s\frac{v_g}{c}]-(b-\frac{1}{2})2k'qL+k'q\Delta s\frac{v_g}{c}b(b-1)$$

Using E_0=80MV/m, q=$4.24\times10^9\times 1.6\times10^{-19}$ C and assuming k'=1.25×10^{15} V/Cm, v_g/c=6.3% for a stagger-tuned CLIC section, the optimum bunch spacing is Δs = 0.3ns = 9 RF cycles resulting in energy variations well within the energy acceptance of the final focus.

DETUNED DIPOLE FREQUENCY DISTRIBUTIONS

The level of the transverse wakefield can be significantly reduced by creating a spread in the frequencies of the first dipole modes. The transverse wakefield in a section is given approximately by the Fourier transform of this distribution. Decay characteristics are nearly optimum for truncated Gaussians [3]. To evaluate major effects Fourier transforms of continuous distributions were first used. A reduction in the wakefield by a factor 1000 as required by beam simulations in 0.3 ns (see Fig.1) would require a distribution with a frequency span Δf=13.3 GHz (36%) and a σ=2 GHz (5.4%). The value of the ratio of $\sigma/\Delta f$ results from a compromise between a fast rolloff time (large ratio) and low sinx/x behaviour (small ratio) and has been set to 1/6.7 to have an attenuation of 1000 at the first lobe.

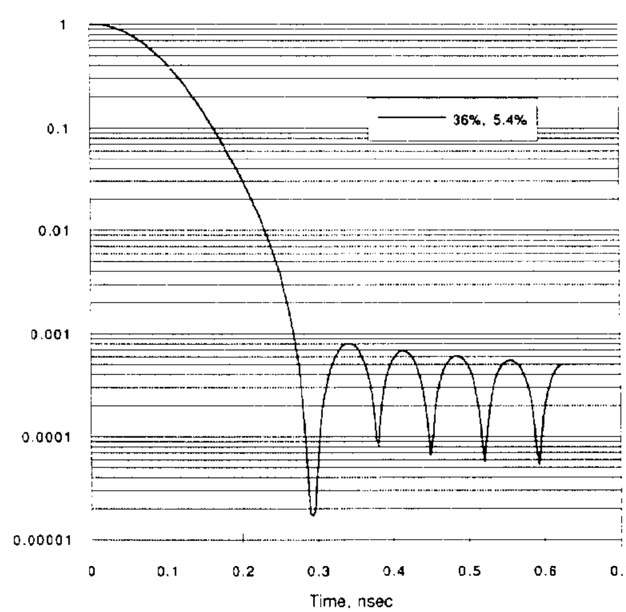

Fig.1: Wakefield resulting from a *continuous* truncated Gaussian distribution (Δf=36%, σ=5.4%)

Such bandwidths are unfortunately well outside practical limits. The smallest iris (giving the highest dipole mode frequency) which can be machined is about 3.5 mm. The largest iris (giving the lowest frequency) is limited to 5.0 mm

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- this is the largest iris with a dispersion curve which does not cross the fundamental frequency. The risk here is that fundamental power would be fed into the dipole mode by imperfections if the two modes were degenerate. These two limiting iris dimensions fix the practical dipole mode frequency span to be 3.89 GHz (10.4% of the center frequency 37.4 GHz). The fundamental and dipole mode characteristics over this range are shown in Figs. 2 and 3 as a function of iris diameter.

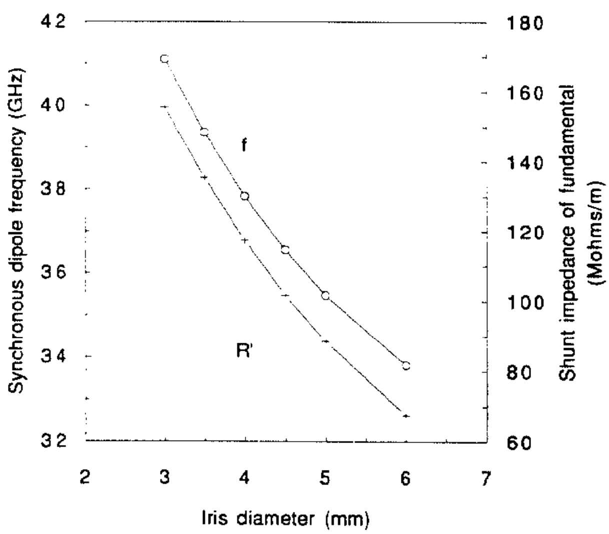

Fig. 2: Synchronous dipole mode frequency and fundamental mode shunt impedance versus iris diameter

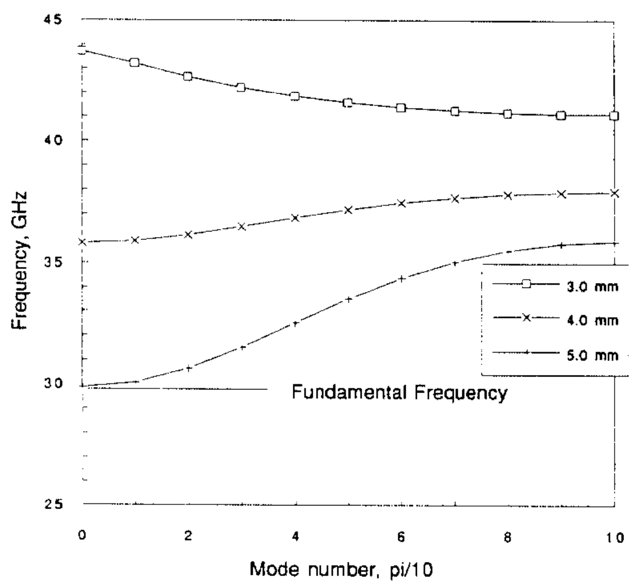

Fig. 3: Lowest dipole mode dispersion curves for iris diameters of 3, 4, and 5 mm

The wakefield resulting from the use of this reduced bandwidth is shown in figure 4. An attenuation of 1000 can now only be achieved after 1 nsec. With bunches spaced at 1 nsec intervals the simple beam loading scheme gives an unacceptable energy spread and has to be modified - too much power is flowing into the sections compared to the amount being taken out by the bunches [4]. One way to bring the differences in energy gained by the four bunches back within the energy acceptance of the final focus is to taper the voltage of the power pulse linearly downwards by 15% during the passage of the bunch train. With such a large bunch spacing compared to the total fill time, the effective accelerating gradient due to partial filling is now reduced by a factor 1–3/11.4 = 0.73. If the length of the linac and the total beam energy are kept constant a higher nominal gradient requiring a $1/.73^2 = 1.9$ increase in input power is needed. In addition there is a loss of shunt impedance in the detuned structure compared with the constant impedance geometry of about 5% because the iris diameters are on average larger. Multibunching has therefore only improved our luminosity to power consumption ratio by 5%. It would be much simpler to get the two-fold increase in luminosity for the same increase in power by doubling the repetition rate.

The problems of tolerance on charge, the effect of the non linear distribution of the accelerating gradient (due to the non linear distribution of shunt impedance), the effect of a non linearly varying group velocity, and the effect of dispersion on the finite bandwidth power pulse have not been considered.

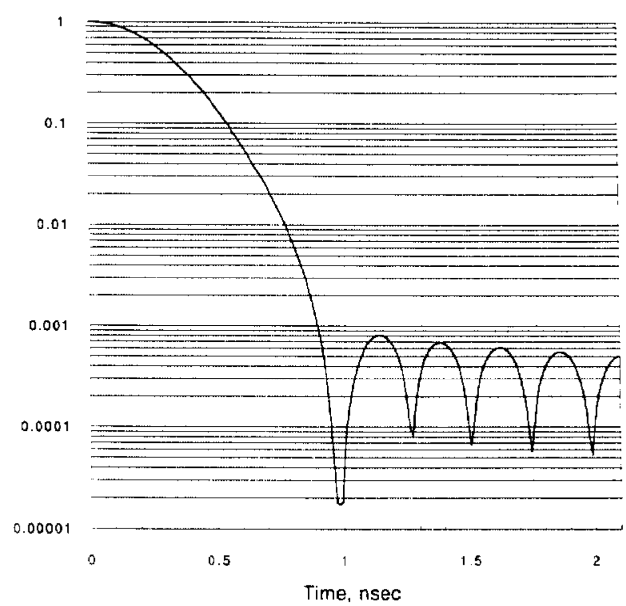

Fig. 4: Truncated Gaussian (Δf=10.4%, σ=1.6%)

WAKEFIELDS FROM DISCRETE CELL DISTRIBUTIONS

In order to have a better approximation to the wakefield in a section, discrete frequencies as opposed to continuous distributions will now be used. To maintain a power attenuation α=0.5, an accelerating section with a range of iris diameters from 3.5 to 5.0 mm will have 101 cells. The fit of the discrete dipole frequencies of the 101 cells to the truncated Gaussian of Δf=3.89 GHz and σ= 0.58 GHz is shown in Fig.5

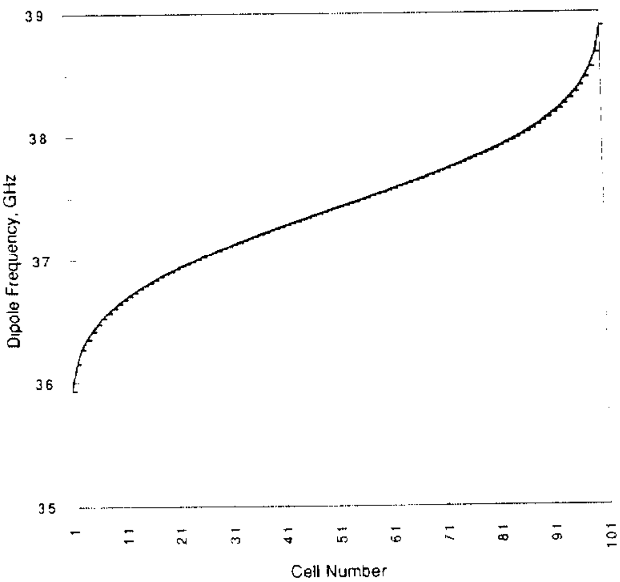

Fig. 5: Dipole frequency versus cell number

The wakefield in this case (see Fig.6) is approximately the sum of the wakefields of all the cells considered individually (uncoupled cell model). The wakefield attenuation is degraded from 1000 to 100 when the distribution becomes discrete. The limiting value of attenuation factor seems to be of the order of the number of cells. Thus one could recover by distributing the frequencies over 1000 cells which would mean over many sections. The wakefield from 1001 cells is shown in fig. 7. This assumes however that the two coupler cells of each section are accurately included in the distributions, otherwise they represent an attenuation limit of about 101/2. All of these calculations ignore coupling between cells and have assumed that the voltage produced in each cell is the same, which is of course not true if iris diameters vary.

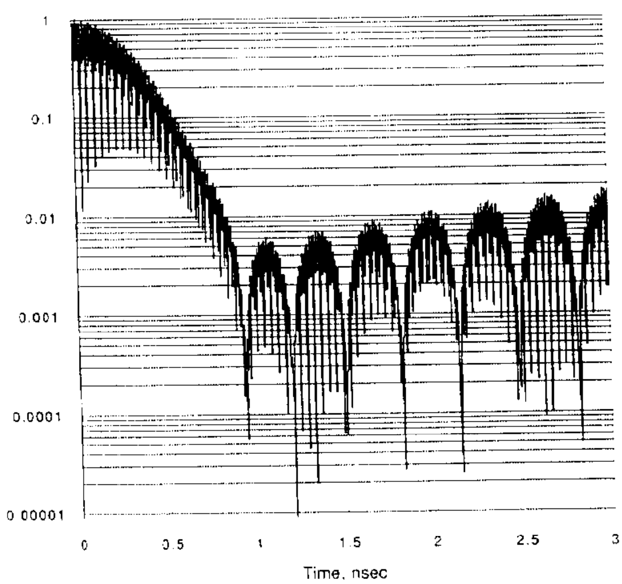

Fig. 6: Wakefield from 101 cells

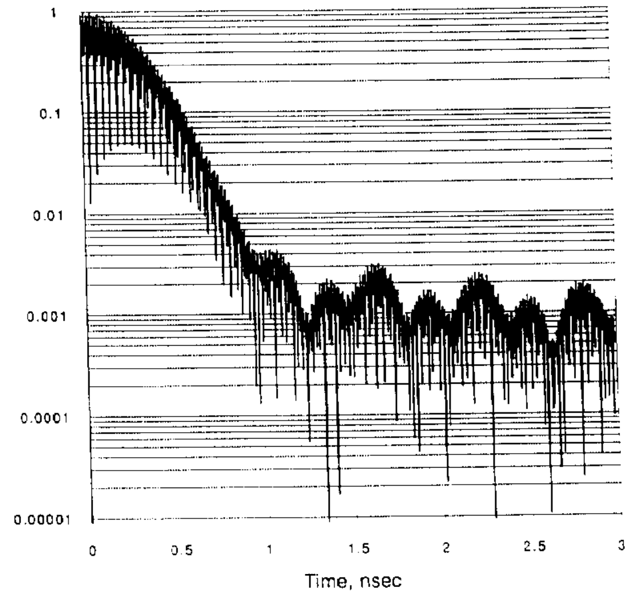

Fig. 7: Wakefield from 1001 cells

FREQUENCY BEATING

A scheme in which only two frequencies Δf apart are used was also investigated. The wake in this case

$$w(t) = A\sin\{\pi(f_1 + f_2)t\}\cos\{\pi(f_1 - f_2)t\}$$

would have a null at a time $t=1/2\Delta f$ after the passage of the first bunch. For t=0.3ns, Δf would be 1.6 GHz. The rate of change of the envelope of the wakefield with frequency however at this null $dw/d\Delta f=\pi t$ requires that for a tolerable residual wakefield of say 0.004 (an attenuation of 250) the frequencies would have to be correct to within 2 MHz - this is considered unrealistic.

CONCLUSIONS

Doubling the luminosity of CLIC by passing four bunches of reduced charge through stagger-tuned structures during one RF fill seems to be difficult and would in any case have to be paid for by almost doubling the power.

The two-frequency beating technique requires too tight a tolerance on the dipole frequencies and is considered unrealistic.

REFERENCES

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