DISTORTION OF A SHORT RF PULSE IN TRAVELLING-WAVE ACCELERATING STRUCTURES

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ABSTRACT

Travelling-wave accelerating structures for high-energy linear colliders necessitate very short RF pulses. The effect of the structure's dispersion properties on the travelling RF waves is analysed using Fourier analysis.

1. INTRODUCTION

For linear e^+e^- colliders in the TeV range the use of travelling-wave radio-frequency accelerating structures has been proposed [1-3]. Since high beam power is required in these schemes in order to reach a luminosity of at least 10^{33} $cm^{-2}s^{-1}$, a good efficiency of power transfer from the RF generating devices to the beam is important.

In existing linacs the RF attenuation per section length has usually been chosen so as to minimize the necessary peak power. In the high-energy regime, however, a compromise has to be made between peak power and average efficiency.

Since the particles are injected once the structures are filled with RF energy, the RF pulse length has to be at least one filling time τ. For high average efficiency the power dissipation during the fill time has to be small. In Ref. [3] an attenuation coefficient (for stored energy) per section length of $\alpha = 0.5$ is suggested rather than the classical one of $\alpha = 2.5$. ($\alpha = \omega \cdot \tau / Q$ with $\omega = 2 \cdot \pi \cdot$frequency, τ = structure filling time, Q = quality factor). This leads to RF pulse lengths of only several hundred RF cycles if structure parameters scaled from the SLAC design are taken. The relative width $\Delta f/f$ of the passband of accelerating waveguides ranges from a few per cent for SLAC-type disc-loaded circular waveguides [4,5] to 30-40% for crossbar and ladder-type structures [6]. These and the dispersion characteristics of the accelerating waveguide can lead to a deformation of the wave travelling down the structure and hence a reduction of efficiency. These effects were studied numerically using Fourier analysis. All examples have been calculated for constant impedance structures.

2. FORMALISM USED IN COMPUTER CODE

The wave train distortion has been studied by Fourier analysis. The frequency spectrum of the RF pulse is calculated and each frequency component within the structure bandwidth is delayed by a certain phase shift ϕ according to the dispersion characteristics of the structure before the pulse is reconstructed in time domain.

2.1 Fourier analysis

The RF pulse is assumed to be a cos signal of N cycles at frequency $\omega_0/2\pi$ extending from time $-T/2$ to $+T/2$.

$$E(t) = \begin{cases} E_0 \cdot \cos \omega_0 t & \text{for } |t| < T/2 \\ 0 & \text{elsewhere.} \end{cases}$$

The Fourier spectrum of such a signal is given by

$$E(\omega) = \sqrt{2/\pi} \cdot E_0 \cdot \frac{\sin(\omega_0 - \omega)T/2}{\omega_0 - \omega} .$$

2.2 Dispersion of the accelerating waveguide

The dispersion relation of the accelerating structure is approximated by a cos function as shown in Fig. 1.

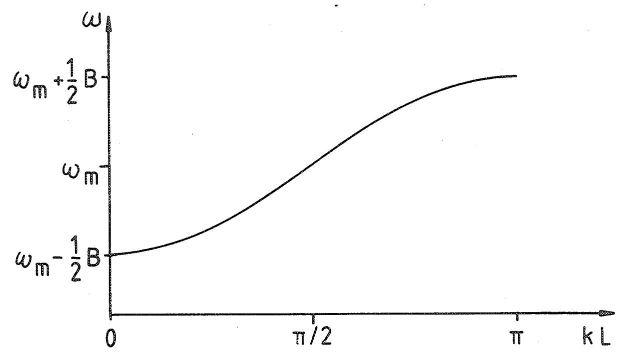


Fig. 1 Dispersion of accelerating waveguide

$$\omega(k) = -\frac{B}{2} \cdot \cos \phi + \omega_m$$

where

ϕ = kL
k = $2\pi/\lambda$, λ = wavelength in structure
L = cell length
ω_m = mid-band frequency
B = bandwidth

The design phase shift per cell of the structure where the phase velocity $v_p = \omega_0/k$ equals the speed of light c at the operating frequency ω_0, can be chosen freely.

2.3 Reconstruction of RF pulse in waveguide

For the reconstruction in time domain of the propagating wave from its spectral components only the frequency components inside the structure's bandwidth are taken and their phase shifts ϕ from cell to cell are derived from the dispersion relation as a function of frequency. The electric field in the centre of the n^{th} cell is then given by

$$E(t,n) = \frac{E_0}{\sqrt{2\pi}} \cdot A(n) \cdot \int_{\omega_m - B/2}^{\omega_m + B/2} E(\omega)\, \cos(\omega t - n \cdot \phi(\omega))\, d\omega$$

where

$A(n) = e^{-\frac{\alpha}{2} \cdot \frac{n}{N_s}}$

α = attenuation constant for stored energy

N_s = number of cells in waveguide section.

E_0 = input amplitude

The attenuation given by the factor A is an approximation because it does not take into account the dependence of damping on frequency within the passband.

3. RESULTS OF NUMERIC COMPUTATIONS

3.1 Deformation of the travelling RF pulse

As the RF pulse described in 2.1 travels along the accelerating structure its time structure changes due to the limited bandwidth and dispersion of the structure. Figure 2 shows the shape of a pulse after having travelled through a

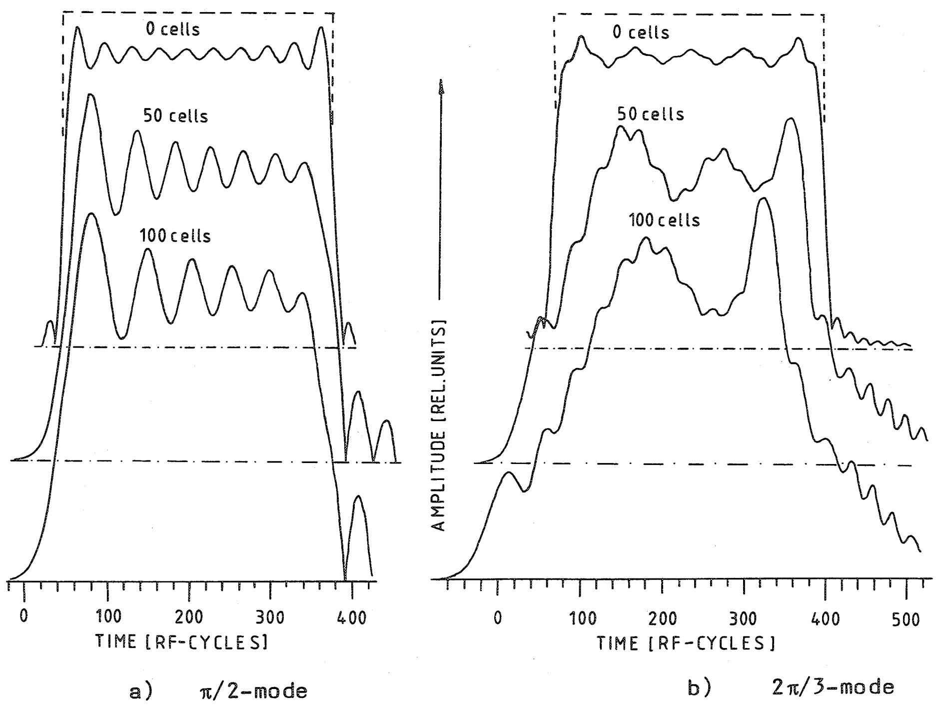
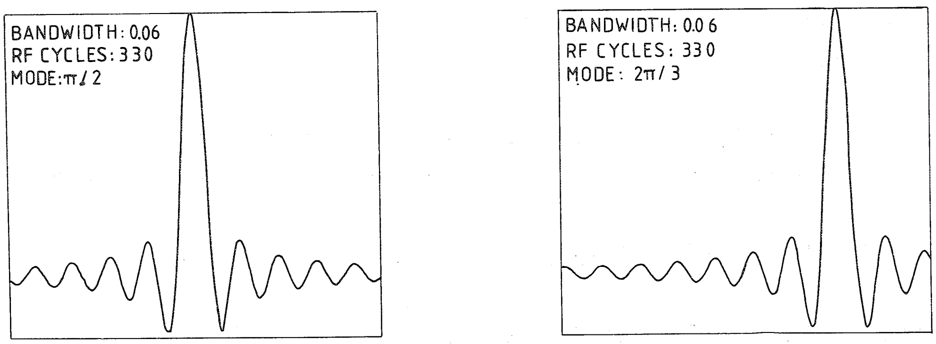


Fig. 2 Time structure of an RF pulse of 330 cycles' length after different structure lengths

structure with a relative bandwidth referred to midband frequency of 6%. The RF pulse length is 330 cycles, which corresponds to an attenuation constant of $\alpha = 0.5$ and a structure Q of 4147 at 29 GHz. The different graphs show various structure lengths from 0 to 100 cells; For the top curve the bandwidth of the signal was already clipped to 6%. The square-shaped input pulse is shown as a dotted line.

Figure 2a) shows the case of a structure with a $\pi/2$ phase shift per cell, Fig. 2b) that of $2\pi/3$. In Fig. 3a and 3b) the corresponding frequency spectra of the pulse within the passbands are shown.



a) $\pi/2$-mode b) $2\pi/3$-mode

Fig. 3 Fourier spectrum within structure passband

Figure 4 shows the variation of pulse width at design field between the rising and the falling edge with structure length for different bandwidths and

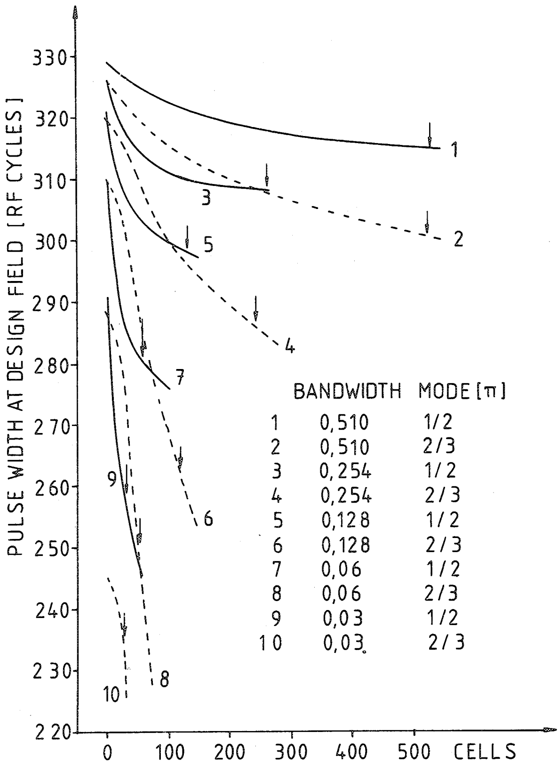


Fig. 4 Width of an RF pulse of 330 cycles as a function of structure length

structure design phase shifts. This width has been taken between the moment the pulse first reaches the design field and the moment it last falls below it. The arrows indicate the structure length one would have in order to match the filling time to the pulse length. A comparison of $\pi/2$ and $2\pi/3$ structures shows significantly wider pulses for $\pi/2$ structures.

3.2 Distribution of the accelerating fields along the structure

The accelerating fields relativistic particles see as they travel through the RF structure were computed by calculating the fields in successive cells at the times the particles cross their centres.

The results for different times during an RF pulse are shown in Figs. 5 and 6 for two different bandwidths of 12.8% and 4%. The section lengths have been so chosen that the filling time equals the duration of the RF pulse, which was taken to be 330 cycles. The particles and the pulse travel from left to right. Time is measured in units of RF periods.

In Figs. 5 and 6 the pulse length is 330 cycles, stretching from -165 to +165 cycles. The structure mode is $\pi/2$, α = 0.5.

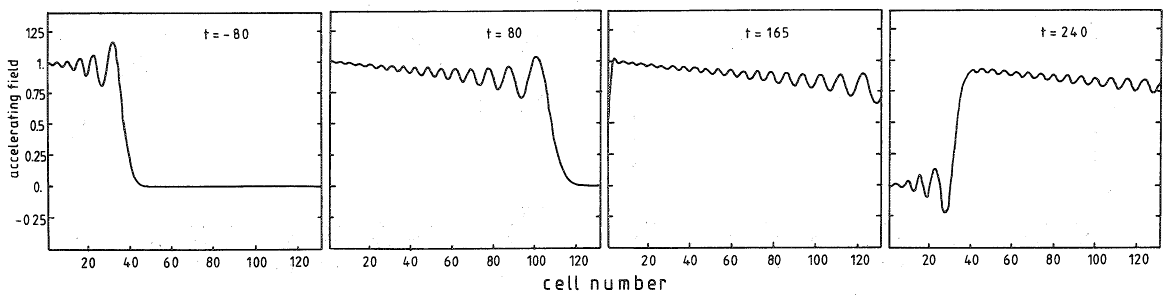


Fig. 5 Accelerating field seen by a particle at different times after switch-on of the pulse. Bandwidth = 12.8%.

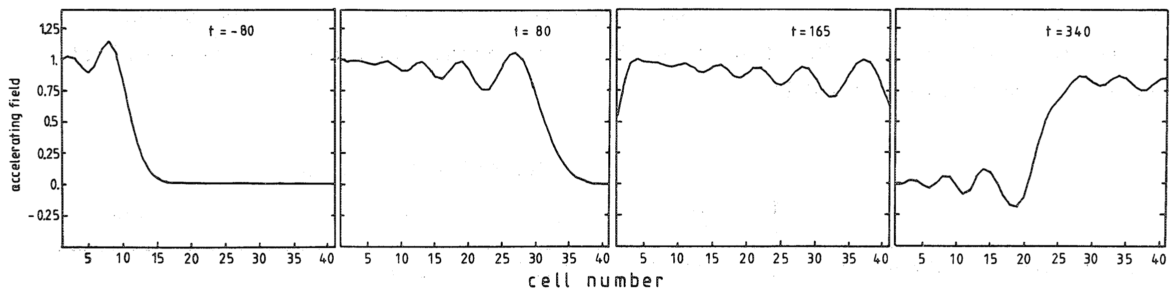


Fig. 6. As Fig. 5.
Bandwidth = 4%.

3.3 Energy gain of particles

The total energy gain per section length is shown as a function of input phase for structures with different bandwidths and a design phase shift of $\pi/2$ in Fig. 7a) and of $2\pi/3$ in Fig. 7b). The dotted line gives the theoretical energy gain if the RF wave had the design amplitude in all cells (attenuation being taken into account). The particles are injected after the filling time τ.

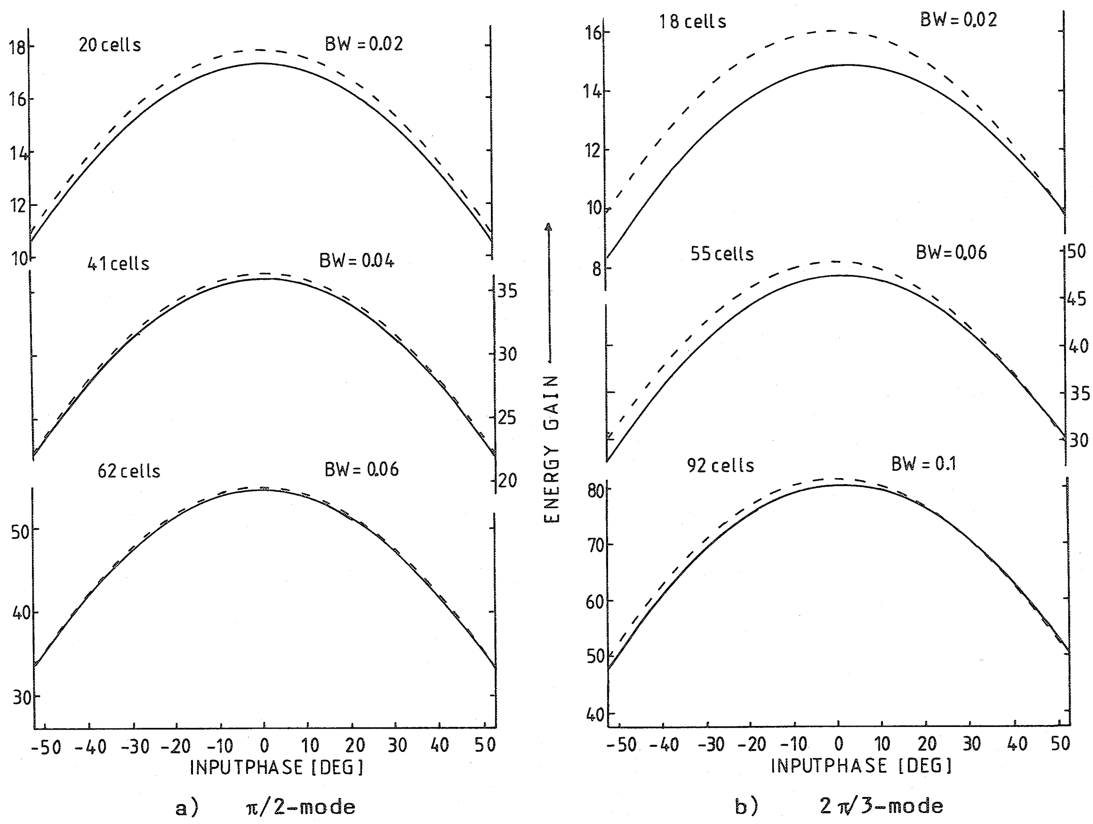


Fig. 7 Energy gain in one section for an amplitude of the input RF pulse of 1, so that the energy gain would be unity per cell with an ideal pulse and no attenuation. α = 0.5, pulse width 330 cycles.

Figure 7 shows that $2\pi/3$ structures not only give less energy gain but also introduce a phase shift as is also shown in a different analysis using Laplace transformation [7]. The reduction $\Delta E/E$ in energy gain due to these effects is given in the following table:

	Relative bandwidth				
	2%	4%	6%	8%	10%
$\Delta E/E$ for $\pi/2$ structure	3%	1.2%	0.3%		
$\Delta E/E$ for $2\pi/3$ structure	7.1%	4.2%	3%	1.8%	1.2%

4. CONCLUSION

These results show that dispersion effects lead to a loss in energy gain of several per cent. This is particularly pronounced for structures with the conventional choice of $2\pi/3$ phase shift per cell. The use of accelerating structures with bandwidths of ≈ 5% for $\pi/2$-mode and ≈ 10% for $2\pi/3$-mode reduces this loss considerably. Disk-loaded waveguides with large beam holes - although with reduced shunt impedance - or other structures such as crossbar, jungle gym, ladder etc. could be used for this purpose.

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