DETERMINATION OF 100 psec SHORT LINAC BUNCHES BY BROADBAND PICKUPS AND RECONSTRUCTION TECHNIQUE

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Abstract

A new method for detecting short linac bunches is proposed and verified on a teststand.
With broadband pickups a voltage signal is obtained and Fourier analyzed. From the amplitude at low frequencies we can reconstructed the rms bunch width. With two pickups the rms energy spread can be obtained without knowing the pickup properties explicitely. The bunch shape can be detected from amplitude and phase signals at high frequencies.
This method has been verified on a teststand for capacitive probes using a pulser and Fourier analysis. The obtained smooth amplitude response up to 5 GHz allows the detection of 100 psec relativistic bunches. The reconstruction method is insensitive against amplitude and phase fluctuation.

Introduction

At most accelerators the bunch shape is obtained directly from the measured voltage signal. But this correspondence of the two signals is limited at low and high particle energies. At high energies, where the bunches are short, the pickup response in no longer flat up to the highest needed frequencies. Also cable attenuation has to be taken into account. At low energies even low frequency components can be damped due to the non-relativistic signal widening effect /1/. If the linac operating frequencies are high, like in the case of the proposed Kaon factories /2/, then the bunch shape determination is a problem.
By operating in the frequency domain these difficulties can be overcome. But here the analysis is more complicated because the voltage signal did not correspond directly to the beam pulse. In Chapter I it is shown how to get the rms bunch width and the particle distribution in this case. In Chapter II the method is verified on a teststand for capacitive probes with non-flat frequency response.

I. Analysis of the Pickup Response in the Frequency Domain

1. Fourier Analysis of Different Beam Pulses

In Fig. 1 the normalized Fourier components $I(N)/I_0$ for three different beam pulses are plotted. Shown are the components of a Gaussian pulse, of a at $T_m = \pm 2\ T_{rms}$ truncated Gaussian and of a parabolic pulse $I(t) \sim (1-(t/T_m)^2)^{1/2}$. The parabolic pulse corresponds to an uniform filling of the longitudinal phase space area. The rms pulse width is $\Delta\varphi_{rms} = \pm\ 10^0$ for all three pulses.
For a Gaussian pulse the current per Schottky band I(N) is given by

$$I(N) = 2\ I_0 \exp\left(-1/2\ N^2\ \Delta\varphi^2_{rms}\right) \qquad (1)$$

I_0: dc-current $\quad$ N: $f/f_0 \geq 1$
f_0: bunching frequency; $\Delta\varphi_{rms}$: ±rms width

whereas for the other two pulses no simple formula can be given.
From Fig. 1 it can be seen that up to harmonic number 6 all three curves are identical whereas they differ significantly above harmonic number 12.
Therefore the rms pulse width can be determined from low frequency components without assuming anything about the distribution itself. For all longitudinal matching purposes the rms width is the important parameter. For getting the particle distribution high frequency components have to be added.
At low frequencies the Fourier components are identical only by keeping the rms and not the total width

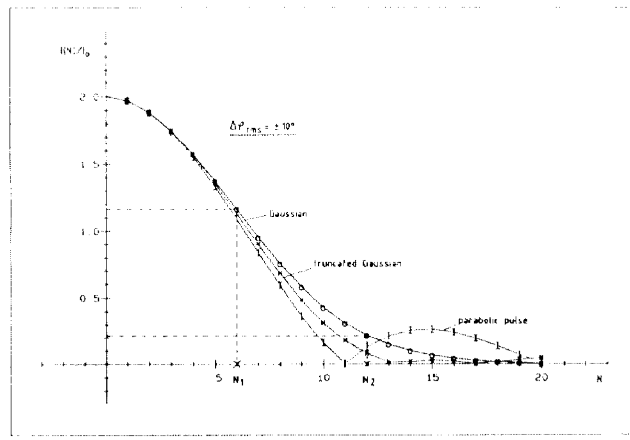

Fig. 1: Normalized Fourier components of 3 different pulses with $\Delta\varphi_{rms} = \pm\ 10^0$

constant. The zero crossing of I(N) should not be used to determine either the rms or the total width because its value depends on the particle distribution /3/.

2. Determination of the RMS Bunch Width

Let us assume a system where the beam pulse is travelling along the axis of a vacuum pipe and any kind of pickup is located at the pipe surface. The pickup is connected to a measuring device.
The so obtained voltage signal can be a complicated function in time depending on the pickup and beam parameters. The signal should not be affected by microwave contributions /1/.
In frequency domain the pickup response is described by the complex transfer impedance or sensitivity S(f) /4/.

$$S(f) = Z(f) \exp(i\varphi(f)) \qquad (2)$$

where Z(f) is the amplitude response and $\varphi(f)$ is the phase shift. Both functions can be arbitrary and non-flat.
From the measured voltage signal U(f) the quantity

$$\tilde{I}(f) = U(f)/Z(f) \qquad (3)$$

can be obtained if Z(f) is measured before.
$\tilde{I}(f)$ is the Fourier component of the to be known beam pulse. If necessary $\tilde{I}(f)$ must be corrected for damping effects like cable attenuation and non-relativistic signal widening.
The corrected quantity $\tilde{I}(f)$ behaves like a Gaussian up to harmonic number N_1, where $N \cdot I(N)$ peaks for a Gaussian

$$\begin{aligned} N_1 &= 0.32\ (\pi / \Delta\varphi_{rms}) \\ N_1 &= 6 \text{ for } \Delta\varphi_{rms} = \pm\ 10^0 \\ \text{or} \quad f_1 &= N_1 f_0 = 0.16 / T_{rms} \qquad (4) \\ I(N_1) &\sim 1.2\ I_0 \end{aligned}$$

T_{rms} : ± rms bunch length
$I(N)$: current per Schottky band

The value for $\Delta\varphi_{rms}$ is then obtained by doing a least square fit of $\tilde{I}(f)$ to a Gaussian up to harmonic number N_1. A much more simpler way is plotting the function

$$\widetilde{\Delta\varphi} = \left(-N^2/(2 \ln(\tilde{I}(f)/2I_0))\right)^{-1/2} \qquad (5)$$

which directly corresponds to $\Delta\varphi_{rms}$ for the low frequency components, see Fig. 2. Here $\widetilde{\Delta\varphi}$ is plotted for a square, a triangular and a Gaussian pulse. For a Gaussian $\widetilde{\Delta\varphi}$ is identical to $\Delta\varphi_{rms}$ for all frequencies, for the other two pulses only up to harmonic number N_1.

The Fourier decomposition of a square and a triangular pulse are given by /3/. Also shown in Fig. 2 is the $\Delta\varphi_{rms}$ dependence of N_1.
For short bunches $\Delta\varphi_{rms}$ can be reliably determined for $N \sim 0.7\ N_1$. A relativistic bunch with a rms width of $T_{rms} = \pm$ 25 psec or a total width of $T \sim 100$ psec is Gaussian like up to f = 6.4 GHz which means a signal up to f = 4.5 GHz is enough. Such short bunches are produced by the 1 GeV high frequency injector linac of Kaon factories /2/.

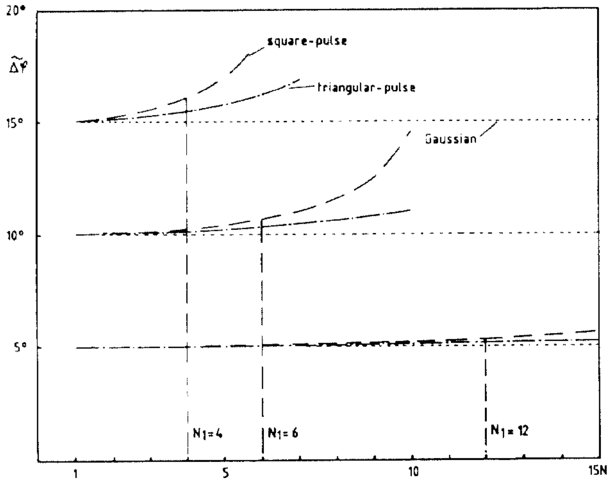

Fig. 2 Determination of the rms width $\Delta\varphi_{rms}$

3. Detection of the RMS Energy Spread

With two identical pickups, some distance L apart, the voltage signal $U_2(f)/U_1(f)$ can be obtained without knowing the pickup properties explicitely. This ratio behaves like a Gaussian with the width

$$\Delta\varphi_p = \sqrt{\Delta\varphi_2^2 - \Delta\varphi_1^2}\ ;\ \Delta\varphi_i:\ \pm\ \text{rms-values} \qquad (6)$$

up to harmonic number N_p, where N_p is the value of N_1 for $\Delta\varphi_{rms} = \Delta\varphi_2$.
In Fig. 3 the quantity $\widetilde{\Delta\varphi}_p$ (in Eq. (5) for $\widetilde{\Delta\varphi}$ replace $\tilde{I}(f)/2I_0$ by $U_2(f)/U_1(f)$) is plotted for a square pulse with $\Delta\varphi_1 = \pm\ 11.2^0$ changing to a triangular pulse with $\Delta\varphi_2 = \pm\ 15^0$, which gives $\Delta\varphi_p = \pm\ 10^0$. For this extreme case the ratio $U_2(f)/U_1(f)$ is greater than 1 around harmonic number 9 due to the zero crossing of the square pulse amplitude. But even here $\widetilde{\Delta\varphi}_p$ corresponds to $\Delta\varphi_p$ up to harmonic number 4 determined by $\Delta\varphi_2 = \pm\ 15^0$. Therefore $\Delta\varphi_p$ can be detected in such a way if $\Delta\varphi_2$ is greater than $1.4\,\Delta\varphi_1$.
For a low intensity beam or at high energies the quantity $\Delta\varphi_p$ is given by

$$\Delta\varphi_p = \frac{L \cdot \Delta W_{rms} \cdot 2\pi}{\lambda\,(\beta\gamma)^3\, m_0 c^2} \qquad (7)$$

ΔW_{rms} : ± rms energy spread; λ: bunching wavelength
The energy spread can be obtained without knowing the bunch width and the pickup properties explicitely.
An elliptical phase space distribution and a longitudinal waist position at the first pickup is assumed for Eq.(7). By not starting from a waist ΔW_{rms} can be get by using 3 or more pickups.
At low energies, where space charge forces cannot be neglected Eq.(7) is no longer valid. But here the use of two pickups allows a test of the high frequency corrections in Z(f). If we choose $\Delta\varphi_2 \geq 2\,\Delta\varphi_1$, then $\Delta\varphi_p \sim \Delta\varphi_2$ and therefore $\Delta\varphi_2$ can be determined without knowing Z(f) explicitely.

4. Asymmetric Particle Distribution

All above given arguments for getting the rms bunch width are also valid for an arbitrary asymmetric particle distribution as long as each nonsymmetric

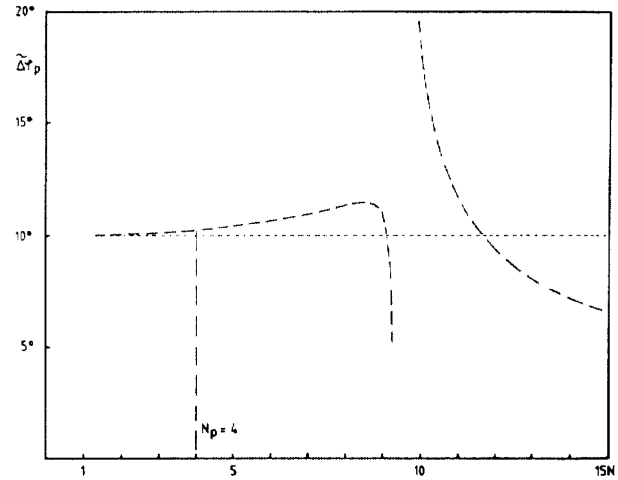

Fig. 3: Determination of the width $\Delta\varphi_p$

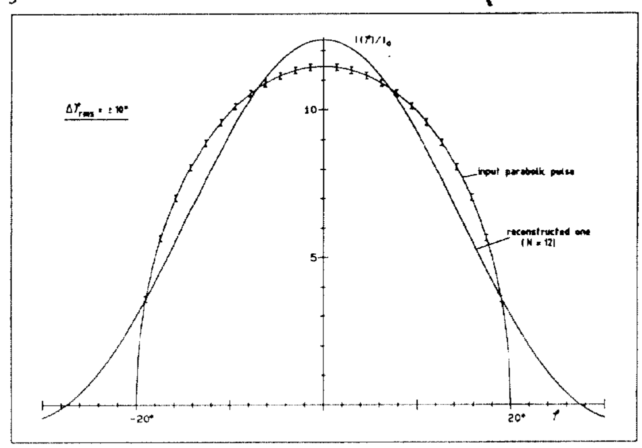

Fig. 4: Input pulse and reconstructed one (N=12)

Fourier component is less than 30% of the symmetric one and the shift of the beam center is less than 50% of the rms bunch width /5/.

5. Determination of the Bunch Shape

Whereas all resonable beam pulses are identical at low frequencies they differ drastically at high frequencies (Fig. 1). For getting the bunch shape no smoothing procedure can be applied. Here amplitude and phase response of the pickup have to be known and a Fourier analysis of the voltage signal U(t) has to be done. By complex vector multipication and adding up the different Fourier components the bunch shape is obtained /3, 6/. For a symmetric beam pulse only the amplitude information is needed.
For a reasonable good reconstruction all components up to harmonic number N_2 are needed. As a guidance N_2 is given by that value where a Gaussian has fallen down to 1/10 of the initial value:

$$N_2 = 0.68\ (\pi/\Delta\varphi_{rms}) \qquad (8)$$

$$N_2 = 12 \text{ for } \Delta\varphi_{rms} = \pm\ 10^0$$

or $f_2 = N_2 f_0 = 0.34/T_{rms}$; T_{rms}: ±rms bunch length
In Fig. 4 a normalized parabolic beam pulse with $\Delta\varphi_{rms} = \pm\ 10^0$ is compared with the reconstructed one (N = 12). The agreement is quite reasonable.

II. Results from the Pickup Teststand

In order to verify the above mentioned ideas a teststand for capacitive button electrodes was built. The pickup behaves like a RC-highpass, described by the parameter f_c, over a wide frequency range ($f \gtrsim$ 3GHz) /4, 7/. Amplitude and phase response are non-flat at low frequencies where the beam Fourier components are quite high.
We wanted to see how good amplitude and phase response

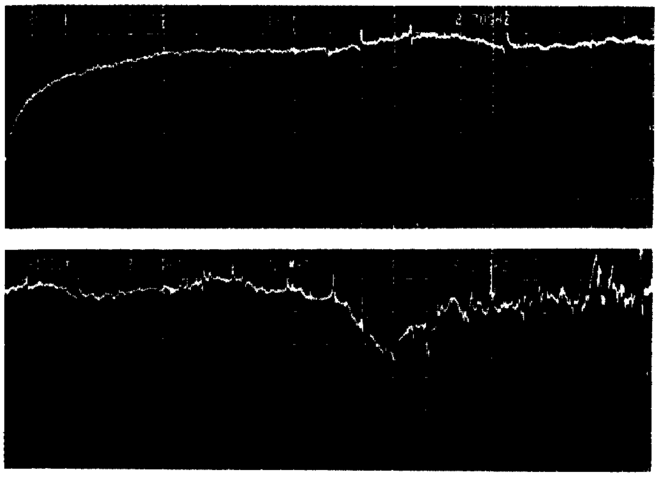

Fig. 5: Measured amplitude response of the 'small' pickup (scale div.: 10db, upper curve: 180 MHz, lower curve: 320 MHz)

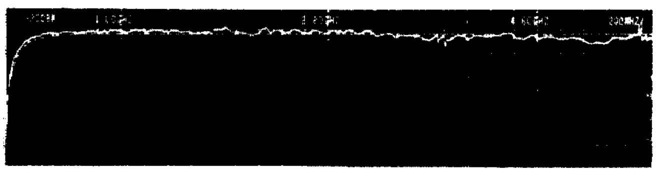

Fig. 6: Measured amplitude response of the 'large' pickup (scale div.: 10db, 200 MHz)

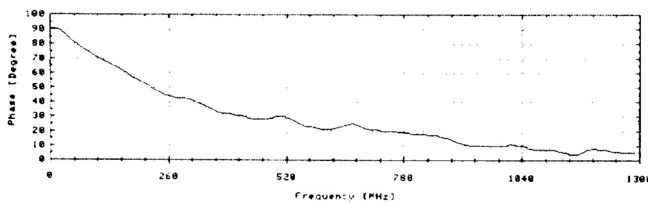

Fig. 7: Measured phase shift of the 'large' pickup

can be predicted at high frequencies and specially how sensitive is the bunch shape reconstruction to pickup noise. Here you expect some difficulties because at the needed high frequencies the beam components are small (Fig. 1) and amplitude and phase response are fluctuating.

In Fig. 5 the measured amplitude response Z(f) is shown for a 'small' pickup (d = 15 mm, C_e = 4.3 pF) up to f = 8.4 GHz. Below 5.2 GHz the pickup behaves exactly like a RC-highpass with fc = 700 MHz. The notch at f ~ 5.6 GHz is caused by a non optimal connection of the electrode to a 50 Ω cable. Afterwards microwave oscillations can be seen caused by the too large pipe radius b = 3.5 cm of the testbox. For the used coaxial 50Ω transmission line /7/ the lowest TE_{11} mode occurs at f = 1.9 GHz.

The obtained smooth amplitude response up to 5 GHz allows the detection of short bunches with T_{rms}=±25psec or a total length T~100 psec (see Chapter I).

A new design is going on with a smaller radius of the testbox (b = 2 cm) and with a better connection of the electrode to the 50 Ω cable in order to improve the response up to 8 GHz. This will allow a bunch detection up to T_{rms} = ± 12.5 psec or a total length T ~ 50 psec.

In Fig. 6 and 7 the amplitude response (up to f=5.6GHz) and phase shift (up to f = 1.3 GHz) are shown for a 'large' pickup (d = 35 mm, C_e = 10.9 pF). This pickup behaves like a RC-highpass with fc = 230 MHz.

In Fig. 8 and 9 a nonideal input pulse and the reconstructed one (dotted line) are shown together with the voltage signal of the 'large' pickup. The pulse repetition rate is 200 MHz and the rms pulse length is about ± 750 psec. According to Eq. 8 an approximate reconstruction can be done with about 3 harmonics. With more than 10 harmonics you get a detailed reconstruction. The shown almost identical reconstruction is done with 15 harmonics (f = 3 GHz). For amplitude and phase response the theoretical values of a RC-highpass with f_c = 230 MHz are used. The reconstructed pulse shape is insensitive to the fluctuations in the pickup amplitude and phase response.

The shape of the voltage signal does not correspond to the form of the input pulse. But the peak to peak distance of the voltage signal is given by the F.W.H.M. value of the input pulse signal. This behaviour is typical for all highpass devices where the bunching frequency f_0 is smaller or equal than the lower 3 db frequency f_c.

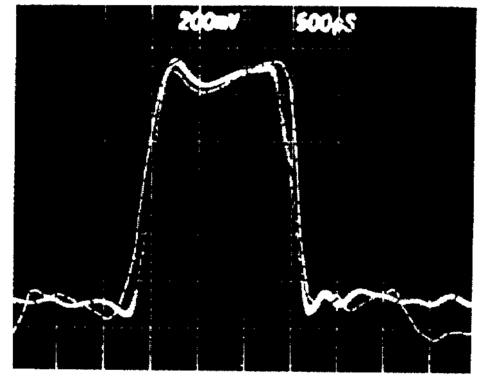

Fig. 8: Input and reconstructed (dotted line) pulse for a complete 200 MHz period

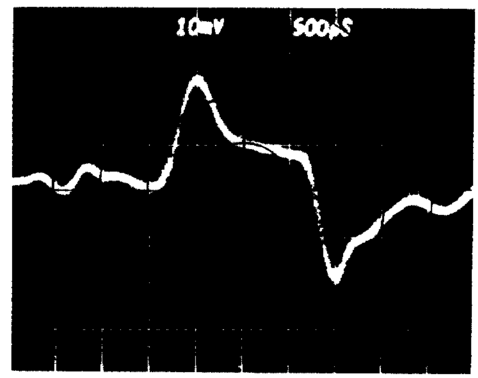

Fig. 9: Response signal of the 'large' pickup

Acknowledgement

The authors thank H.G. Hereward and A.K. Mitra for numerous stimulating discussions. They are quite thankful to M. Herschbach for helping with the teststand and to M. Nonn for doing the calculations.

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