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Design and Test Results of a Beam Instrumentation Monitor for CERN Linear Collider Test Facility

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Abstract

The instrumentation monitor for CTF (CERN Linear Collider Test Facility) requires measurement of the position and intensity of each micro-bunch (3-50 ps FWHM) at a spacing of 330 ps. The charge of a single bunch is from 10^9 to 10^{11} electrons. A monitor designed to meet these requirements is presented. Particular emphasis is given to the sensitivity and frequency response appropriate to such short bunches.

Introduction

The ordinary button-type pickup senses the signal across the capacitance between the button and the wall. A resonance may occur, if the structure of the button and its housing form a cavity.(1) When the bunch length is much longer than the button size, the beam frequency spectrum does not extend up to the resonance frequency, then the resonance is not excited. When the bunch length is comparable to the button size, and if the resonance is within the frequency range of interest, it may be excited and observed. Therefore the pickup has to be carefully designed to avoid the parasitic resonance due to the pickup structure.

Beam Parameters

The CTF beam parameters are: (2)

Number of bunches in the train:	1-24
Bunch length (FWHM)	3-50 ps
Bunch repetition frequency in the train:	3 GHz
Train repetition rate:	10 Hz
Minimum clear aperture:	40.5 mm
Beam energy:	4.5 Mev

Normally, the bunch spacing is 333 ps, each bunch has a charge ≥ 9 nC, and a bunch length (FWHM) ≤ 12 ps.

The following calculation derives the beam signal properties.

1). The electron bunches have a Gaussian longitudinal distribution, and the charge density per unit length is: $\rho(x)=\frac{Q}{\sigma\sqrt{2\pi}}e^{\frac{-x^2}{2\sigma^2}}$, and $\int \rho(x)\,dx = Q$.

When $x=0$, $\rho(x)=\rho_{\max}=\frac{Q}{\sqrt{2\pi}}\frac{1}{\sigma}$, which is the peak charge density of the bunch. With a charge per bunch of 9 nC, each bunch contains 5.6×10^{10} electrons. When σ is 25 ps, the peak current is 144 A. When σ is 6 ps, the peak current is 598 A.

2).The frequency spectrum is also a Gaussian distribution with a half width of $1/\sigma$, where σ is half the rms bunch length in units of time. For a bunch with σ=25 ps, equivalent to 40 GHz, the wavelength λ=0.75 cm. The broadening effect is: $\delta=r/(\sqrt{2}\,\gamma\beta c)$. For a pulse of 12 ps in a pipe of radius of r=2 cm, it will be 5.4 ps, and the total duration of electric fields on the detector will be 22.8 ps.

Pickup Design

The beam is highly relativistic. Since the pickup detects the near field of the beam, only the TEM mode is considered here. Therefore, we can represent the field of the beam with the field induced by an infinitely long line charge to calculate the E field near the pickup and then calculate the induced current in the detector. Because the bunch is much shorter than the pipe diameter, the bunch spectrum contains frequencies above the pipe cutoff. These high order modes, such as wakefields, could be induced and travel in the pipe; such wakes have been observed and it is a future project to eliminate them.

The amount of signal the monitor picks up not only depends on the source field, but also on the design of the detector. In order not to form a cavity in the housing of the pickup, which might cause ringing, the pickup is made with a coaxial cone shape and directly welded into a Kaman feedthrough, which is useable up to 40 GHz (50 GHz is specified by the manufacturer Kaman Instrumentation Co). The cone shaped pickup has a smooth transition to the feedthrough. The ratio of the cone and the outer conductor diameter is kept constant at b/a=2.3 in order to keep the impedance a constant at 50 Ω. Here, a and b are the radii of the cone and the outer conductor, see fig.1.

The peak of the induced signal on this kind of pickup can be estimated by the following model, which has been developed since 1970's. The beam can be considered to be a constant current source, therefore the pickup with a 50 Ω load still can be studied with a short-circuit equivalent circuit.(3) The TEM wave of the beam moves along the center of the beam pipe, see fig.1, and we define the time when the wavefront passes the center line of the pickup as t=0. The induced signal depends on the wave's angle of incidence; which is measured from the normal to the ground plane to the direction of propagation of the field. In our case, the wave is moving along the ground, which is the pipe wall, so the incident angle is $\theta=\pi/2$. The induced current signal, I_{sc} due to an electric field impulse E^i can be expressed by the following formula: (4)

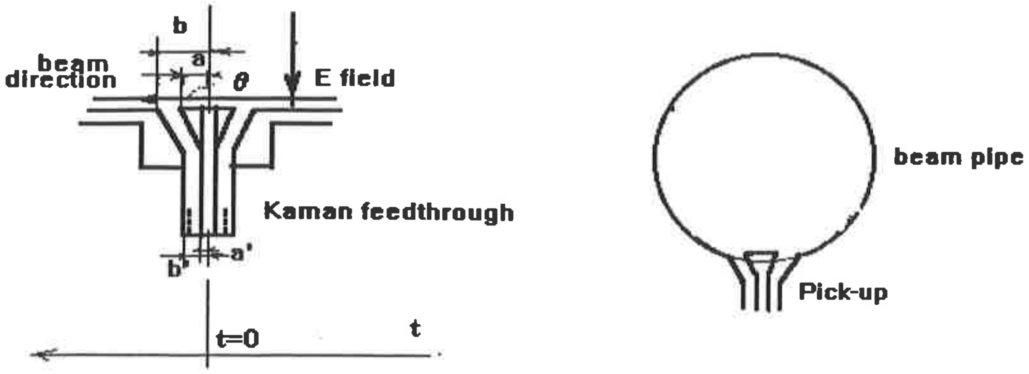


Fig.1. Cone pickup made with a Kaman feedthrough

$$\frac{I_{sc}}{E^i}=\frac{c}{2\zeta_0}\begin{cases} 0, & -\infty< t<-\frac{b}{c} \\ \frac{\pi}{2}+\sin^{-1}\frac{ct}{b}, & -\frac{b}{c}<t<-\frac{a}{c} \\ -\sin^{-1}\frac{ct}{a}+\sin^{-1}\frac{ct}{b}, & -\frac{a}{c}<t<\frac{a}{c} \\ -\frac{\pi}{2}+\sin^{-1}\frac{ct}{b}, & \frac{a}{c}<t<\frac{b}{c} \\ 0, & \frac{b}{c}<t<\infty \end{cases}$$

ζ_0 is the free space impedance of 377 ohm and $E^i=\int E_0(t')\,dt'$, where E_0 is the incident field at the pickup aperture. The reason for a field integral appearing in the formula is as follows. The pickup is based on the principle of EM field induction. When a bunch passes the pickup, the pickup sees a TEM wave, changing with the time. The varying electrical field, which is perpendicular to the pickup surface, induces a changing magnetic field around the pickup, and this varying magnetic field induces a current in the pickup to form the output voltage. Because in our case the bunch length is comparable to or even smaller then the pickup, the pickup senses the field induced by the whole bunch, and therefore an integral should be applied to the whole bunch. To avoid confusion, we use *t'* instead of *t* as the variable.

The above formula shows that the impulse response is a doublet whose time duration is *2b*/c. Evidently, the pickup gives an approximation to the derivative of the incident signal. By integrating the pickup output, the original shape of the pulse can be recovered.

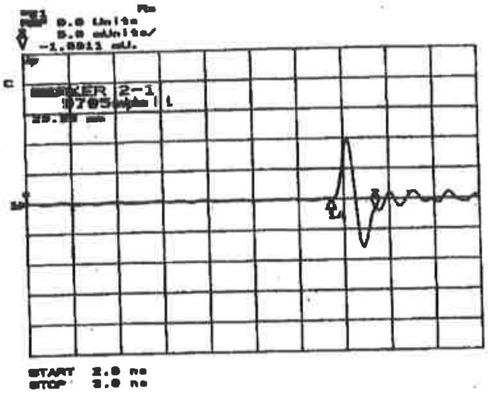
The peak current occurs at roughly $t=-a/c$ and is given by $\frac{I_{sc}}{E^i}=\frac{c}{2\zeta_0}\left[\frac{\pi}{2}-\sin^{-1}\frac{a}{b}\right]$.

I_{sc}/E^i can be transformed to the ratio V_{pu}/V_{tr} where V_{pu} is the voltage at the output of the pickup and V_{tr} is the voltage applied to the wire antenna. The calculation shows that the ratio of peak to incident signal (V_{pu}/V_{tr}) should be 1.37 percent. The measurement, using a pulse of 25 ps FWHM, shows that the pickup gives out 1 percent of the incident signal, see fig. 2,3. The discrepancy occurs because the above formula is for an impulse with wavelength much shorter than the pickup size whereas the bunch length is the same as the aperture of the pickup.

The frequency response is limited by the size of the pickup and the length of the cone.(4) The minimum cone length *h* is determined by the maximum allowable difference Δ_t between the path length along the inner and outer conductors. For small cone angles this is given by $\Delta_x=(1/h)\left[(b-b')^2-(a-a')^2\right]$. Ideally Δ_t should be much less than the smallest wavelength present in the spectrum., so that the signal induced in the cone will come in a TEM mode. In our case, b = 3.9 mm, a = 1.8 mm, b'= 2.9 mm a'=1.27mm, h is 4 mm. Δ_x is about 1 mm, which is much less than the wavelengths of interest.

Bench Test Setup and Results

The bench tests were performed with two HP network analyzers, one of 6 GHz and one of 40 GHz bandwidth; both have time domain low pass impulse modes. The 6 GHz network analyzer can synthesize a 150 ps impulse, while the 40 GHz analyzer can synthesize a 25 ps impulse. The monitor consists of a 5 cm section of beam pipe with the pickup and feedthrough. Two 0.5 m long pipes are connected to either side of the monitor, and the ends terminated in two cones to form smooth transitions to the analyzer cable and a 50 Ω termination. A ¼ inch pipe passes along the center to form a 100 Ω coaxial structure, which is tapered to 50 Ω at both ends. Because the pipes are very long, reflections from both ends can easily be distinguished from the parasitic resonance at the pickup. In order to eliminate resonance caused by the setup, some microwave absorbent material was used.



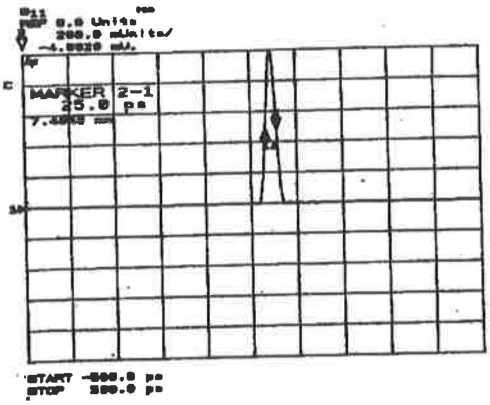


Fig.2 Cone pickup response to synthesized pulse with BW of 40 GHz (left)
Fig.3 Synthesized Incident pulse with BW of 40 GHz (right)

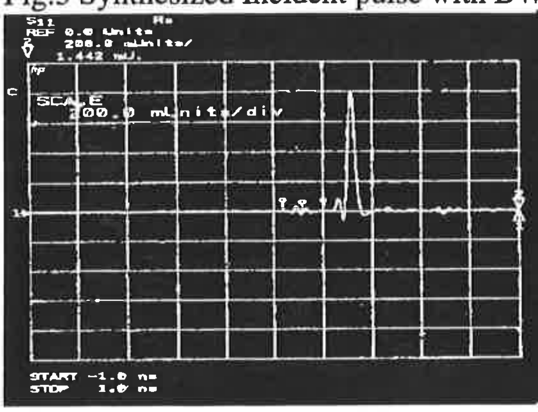


Fig.4 S_{11} for the cone pickup

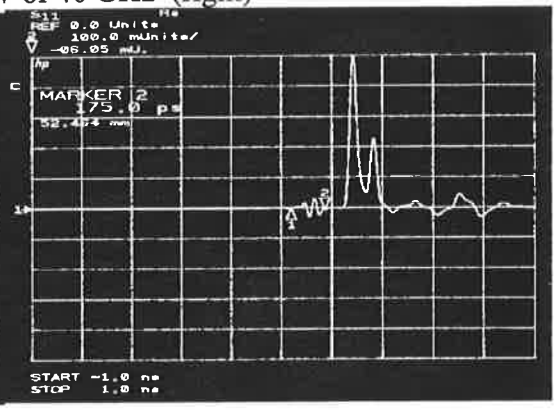
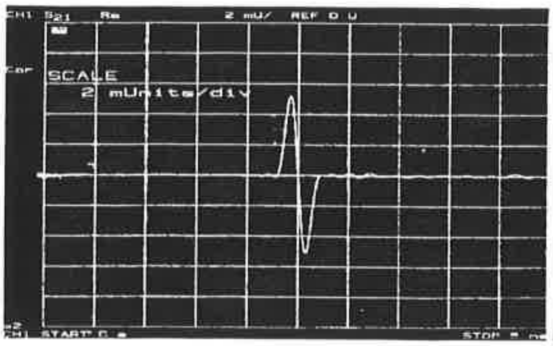


Fig.5 S_{11} for Kaman feedthrough only

Fig. 4 and 5 are measured with signal directly fed into the feedthrough to see the reflections. The figures show only a tiny reflection from the Kaman feedthrough vacuum seal, and this shows that the feedthrough is 50 Ω up to our measurement limit, i.e. 40 GHz.

When the wavelength is much longer than the pickup size, the shape of the pickup is not important, and so simpler geometries such as the button and pin can be used in place of the cone. In addition to the cone pickup discussed earlier, 3 prototype pickups (with no vacuum requirement) were manufactured in order to do some preliminary bench tests and make comparisons. The feedthroughs of these prototypes are ordinary SMAs used for printed circuit boards. Among the pickups, one is a 20 mm long stripline pickup with stripline width of 4 mm, one is a short-rod 5 mm long pickup, the last is a 4 mm ordinary button inserted into the pipe by 3 mm, without a smooth transition. These three prototypes were measured only with the 6 GHz analyzer and without the microwave absorbent material. The stripline pickup shows a periodic oscillation behind the doublet response because the geometrical distortion caused by a 4 mm wide stripline in a 40 mm diameter pipe cannot be neglected any more.



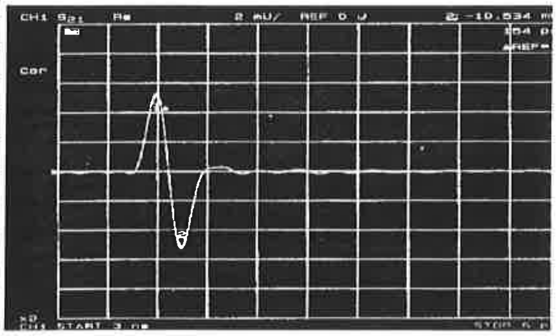


Fig.6 The cone response at 6 GHz, with microwave material.(left)
Fig.7 The small regular button at 6 GHz without microwave material(right)

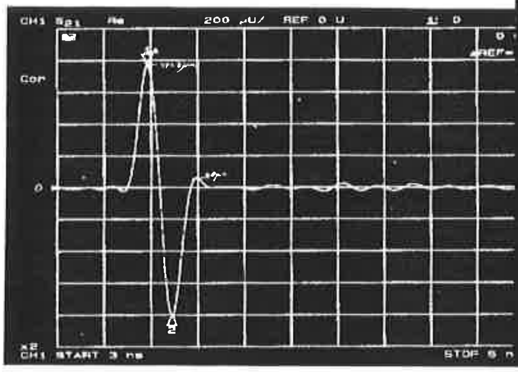
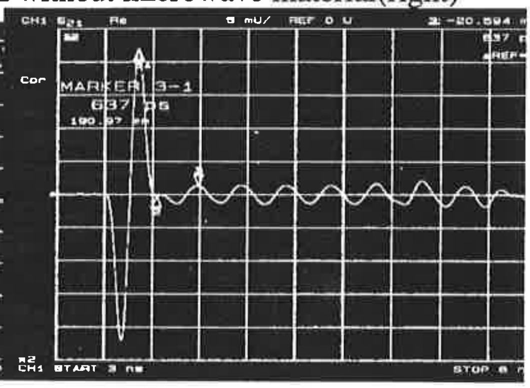



Fig.8 Response of a pin at 6 GHz . Fig. 9 Response of stripline at 6 GHz

Beam Tests Results

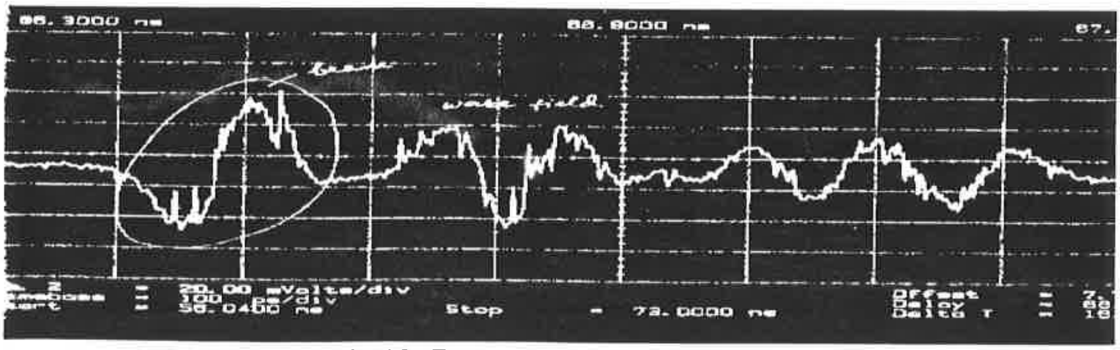
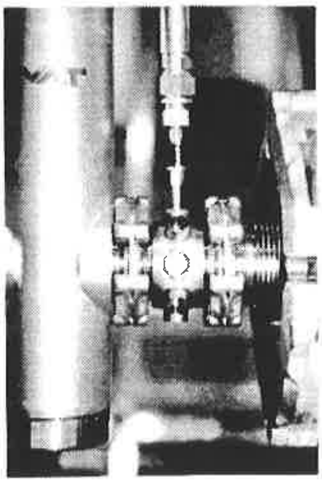


Fig.10 Test results with CTF beam

The cone pickup made with a Kaman feedthrough has been installed in the CTF to observe the beam signal, see fig.10. Due to use of a 15 meter long dispersive cable, the signal was stretched to 150 ps. After the beam signal, there is irregular ringing for

100 ns caused by wakefields. The wakefields can be distinguished from ringing of the pickup because the waveform is aperiodic and commences almost a half wavelength after the beam induced doublet. Since the beam tests were made with a single bunch mode, the signals of multi-bunch mode have not been observed. Further study is required to devise a method to observe a beam signal in the presence of strong wakefields.



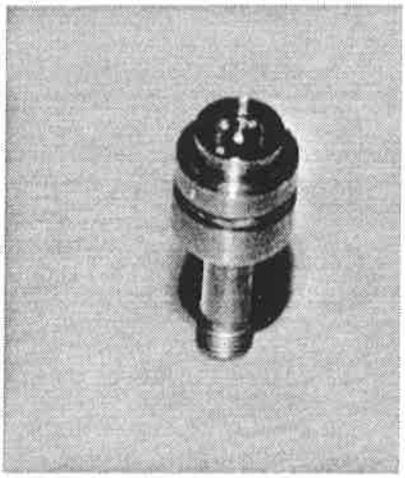


Fig.11. The pickup installed on CTF. Fig.12. The cone pickup .

Acknowledgment

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