A GENERAL ANALYSIS OF WIRELINE-TYPE MONITOR FOR RELATIVISTIC ELECTRON BEAMS

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Abstract

The output signal waveform of the wireline-type beam monitor with an arbitrary termination, caused by a relativistic electron beam is studied theoretically. The pickup is set on the inside wall of a metal cylinder, with one end arbitrarily connected to the wall and the other end led to the output. The response of the beam monitor and its energy dependence are derived. As the limit for extremely short wireline and low frequency the response of a capacitive monitor is obtained for the open-ended pickup and that of a loop monitor subject to Faraday's law for the short-circuit ended pickup, respectively.

The experiment was performed for single bunched electron pulses from a linac at ISIR. The experimental results and the calculation are compared and discussed.

Introduction

The wireline-type monitor is simple, low-cost and therefore good choice for a beam position monitor, a large number of which are required for operating an accelerator. This type of the monitor is known to be sensitive up to extremely high frequency region. If the response of a monitor is determined in detail, we can use it to describe the waveform of a short beam pulse. At present, however, few calculation with experimental confirmation have been made for such waveforms.

Lamberston treated a matched stripline.[1] Barry derived frequency response of this type of monitor and reported the bench test on an open-ended wireline.[2] They applied the result to a position monitor. In the present paper, a waveform of the wireline-type monitor is derived by a general analysis and tested by electron beam from an accelerator. As limiting cases of low frequency or/and small loop, the ordinary expression for an inductive loop and an capacitive plate are derived.

Experimental results from the Osaka university L-band linac at ISIR(The Institute of Scientific and Industrial Research) are compared with the calculation.

Monitor Response

A wireline is mounted in the z-direction on the wall of a metal cylinder of radius a as shown in Fig.1(a). The wireline consists of two short wire-sections perpendicular to the wall and a long wire stretched between them, parallel to the wall, with length ℓ and a distance b from the center-axis. The end of the wire at z=0 and the wall constitute the output terminals, and the other end is terminated to the wall through a load resistance Z_2 at $z=\ell$. We observe the beam-induced signal by connecting load resistance Z_1 at the output terminal. The voltage $V(\omega)$ across Z_1 is given by

$$V(\omega)=(V_o(\omega)Z_1)/(Z_{in}(\omega)+Z_1)$$

or

$$V(\omega)=I_s(\omega)/(Y_{in}(\omega)+Z_1^{-1}) \quad ,$$

where $V_o(\omega)$ and $I_s(\omega)$ are the open voltage and short-circuit current, respectively when there exists an electromagnetic field induced by beams, and where $Z_{in}(\omega)$ and $Y_{in}(\omega)=Z_{in}(\omega)^{-1}$ are monitor impedance and admittance at the output terminal when no beam exists. The long wire and the wall can be modeled as a transmission line such that the wireline-pickup is equivalent to Fig.1(b). Accordingly we get $Z_{in}(\omega)$ or $Y_{in}(\omega)$ as

$$Z_{in}(\omega)=Y_{in}(\omega)^{-1}=(AZ_2+B)/(CZ_2+D),$$

$$A=\cos(\beta\ell), \qquad B=jZ_c\sin(\beta\ell),$$

$$C=j\sin(\beta\ell)/Z_c, \qquad D=\cos(\beta\ell),$$

here, Z_c and β are characteristic impedance and propagation constant of the transmission line, respectively.

Next, we obtain $V_o(\omega)$ and $I_s(\omega)$ by using the reciprocity theorem[3][4]. According to the theorem $V_o(\omega)$ and $I_s(\omega)$ are given by:

$$V_o(\omega)= -\int_v E\cdot J dv, \qquad I_s(\omega)= \int_v E\cdot J dv$$

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Here, E is the beam-induced electric field with the wireline removed. J is the current density in the wireline when the the output terminals supply the line with a unit current source for $V_o(\omega)$ or a unit voltage source for $I_s(\omega)$.

When the beam proceeds along the center-axis of the cylinder in the +z-directon, the electric field is easily determined. For extremely relativistic beam, $E \sim E_r i$ (i is unit vector of radial direction). Therefore the above integral is carried out solely on the short wire-sections.

To estimate J, we can use Fig.1(b) again. Connecting a unit current or voltage source, instead of Z_1, to the terminal at z=0, we get the currents j_1 and j_2 at z=0 and z=ℓ, respectively. As an example, those for the current source are given by

$$j_1=1, \quad j_2=-2\exp(-j\beta\ell) \times Z_c/[\{1-\Gamma_2\exp(-j2\beta\ell)\}(Z_2+Z_c)]$$

and
$$V_o(\omega)=V_{u1}-j_2V_{u2},$$

$$V_{u1}=\int_{\text{on short section}} E_r dh \text{ at } z=0, \quad V_{u2}=\int_{\text{on short section}} E_r dh \text{ at } z=\ell.$$

We also use the transfer impedance introduced by Barry to express the monitor response[2];

$$Z_t(\omega)=V(\omega)/I_b, \quad I_b\text{:beam current}$$

Then $Z_t(\omega)$ is given as

$$Z_t(\omega)==\{Z_1(V_{u1}-j_2V_{u2})/I_b\}/(Z_{in}(\omega)+Z_1)$$

Since E at z=ℓ is retarded by the time $\Delta t \sim \ell/v_b$ compared with E at z=0, here v_b=beam velocity, $V_{u2}/V_{u1} \sim \exp(-\omega\ell/v_b)$.[1] By $\{V_{u1}/(Z_cI_b)\}=G$, $Z_t(\omega)$ becomes

$$Z_t(\omega)=G\{1-j_2\exp(\omega\ell/v_b)\}(Z_1Z_c)/(Z_{in}(\omega)+Z_1)$$

For extremely relativistic electrons $v_b \sim c$ and then $\beta \sim \omega/c$. Thus, $Z_t(\omega)$ is given by

$$Z_t(\omega)=G\{1-2\exp(-j2\beta\ell)\} \times (Z_1|Z_c)/\{1-\Gamma_1\Gamma_2\exp(-j2\beta\ell)\}.$$

Here, $(Z_1|Z_c)=(Z_1Z_c)/(Z_1+Z_c)$,

$\Gamma_1=(Z_1-Z_c)/(Z_1+Z_c)$, $\Gamma_2=(Z_2-Z_c)/(Z_2+Z_c)$].

For a small loop, $\beta\ell \ll 1$ and $\exp(-j2\beta\ell) \sim 1+j2\beta\ell$. Then for a small open-loop($Z_2 \to \infty$), open voltage V_o' is derived by $Z_1 \to \infty$.

$$V_o'=\lim_{Z_1\to\infty} Z_t I_b \to V_{u1}.$$

On the other hand, short circuit current I_s' approaches the limits, $Z_1 \to 0$, such that,

$$I_s'=\lim_{Z_1\to 0} Z_t Ib/Z_1 \to j\omega(\ell/(cZ_c))V_{u1}=j\omega CV_{u1}.$$

Here $C=\ell/(cZ_c)$, which means impedance of open-ended transmission line having length ℓ <<wave length. The above expressions for V_o' and I_s' agree with the ordinary expressions for those of capacitive monitor as a button type monitor.

For the small short-loop($Z_2 \to 0$), V_o'' and I_s'' are given as

$$V_o'' \sim (j\omega\ell/c)\cdot V u_1, \qquad I_s'' \sim (1/j\omega L)V_o''$$

The expression $L=Z_c\ell/c$ is impedance of short-circuit ended transmission line with length ℓ <<wave length. In this case V_o'' is rewritten by using the relation between beam-induced E_r and B_θ; $B_\theta=-(v_b/c^2)E_r$. Then,

$$-V_o'' \sim (j\omega\ell/c)\int E_r dh=(j\omega/c)\int \frac{c}{v_b} B_\theta dh \sim j\omega \int B_\theta \ell dh$$
$$=j\omega\Phi=j\omega MI_b,$$

which is I_b-induced electromotive force in the wireline and thus corresponds to Faraday's law.

Pulse Response and Comparison with Experimental Results

For simplicity we consider a line beam with $v_b \simeq c$ on the center-axis of the metal cylinder. The induced voltage $V_{u1}(\omega)$ becomes[4]

$$V_{u1}(\omega)=G_0\cdot G_1(\omega)I_b(\omega),$$

$$G_0=(\mu_0 c/(2\pi\beta_b))\ell n(b/a)$$

$$G_1(\omega)=\{K_0(a\omega'/\gamma)-K_0(b\omega'/\gamma)\},$$

$$\omega'=\omega/v_b, \quad \gamma=(1-\beta_b{}^2)^{-1/2}, \quad \beta_b=v_b/c.$$

Here K_0 is a modified Bessel function and $\mu_0 c=377\Omega$. The function $G_0\cdot G_1(\omega)$ indicates that the sensitivity of the monitor depends on electron energy and ω. $G=G_0\cdot G_1(\omega)/Z_c$ and G with $\beta_b \to 1$ and $\omega \to 0$ is equal to g in Barry's expression[2]. Fig.2 shows examples of G/G_0.

When we observe the output waveform by connecting a coaxial cable from the output to an oscilloscope, the observed waveform V_{obs} depends on the transfer function H(ω) of the observing system. Then

$$V_{obs}(\omega)=H(\omega)Z_t(\omega)I_b(\omega), \qquad v_{obs}(t)=L^{-1}[V_{obs}(\omega)]$$

For a gaussian pulse with charge Q per pulse:

$$I_b(\omega)=Q\exp(-j\omega t_0)\exp(-\omega^2\sigma_b^2/2)).$$

An example of the calculations are shown in Fig.4(a) together with the experimental results for Q=7.0 nC, 2τ(half width=$2\sigma_b/(2\ell n\,2)^{1/2}$)=30 psec, a=0.035 m, b=0.033 m, ℓ=0.04 m, electron energy =28 MeV and $H(\omega)=\exp(-\omega^2\sigma_t^2/2))$ with $2\sigma_t/(2\ell n2)^{1/2}$=80 ps.

The experiment was performed using single bunched electron pulses from the Osaka university L-band linac at ISIR(The Institute of Scientific and Industrial Research). The beam monitor used in the experiment is shown in Fig.3. The arrangement of the beam monitor is designed by considering wake field suppression which is described elsewhere.[5]

The observed waveforms from a short-circuit ended wireline are shown in Fig.4(b). The calculations and the experimental results show good agreement of absolute peak values and time-dependent variation which confirms the validity of our procedure.

References

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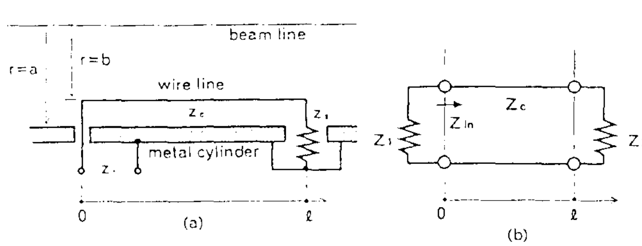

Fig. 1 Beam monitor(a) and its equivalent circuit(b)

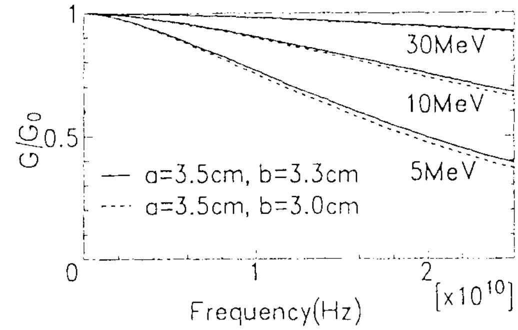

Fig. 2 G/G_0 for a=3.5 cm and, b=3.0 and 3.3 cm.

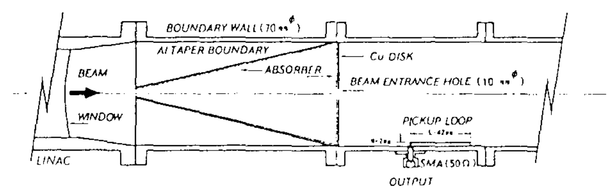

Fig. 3 Beam monitor arrangement used in the experiment

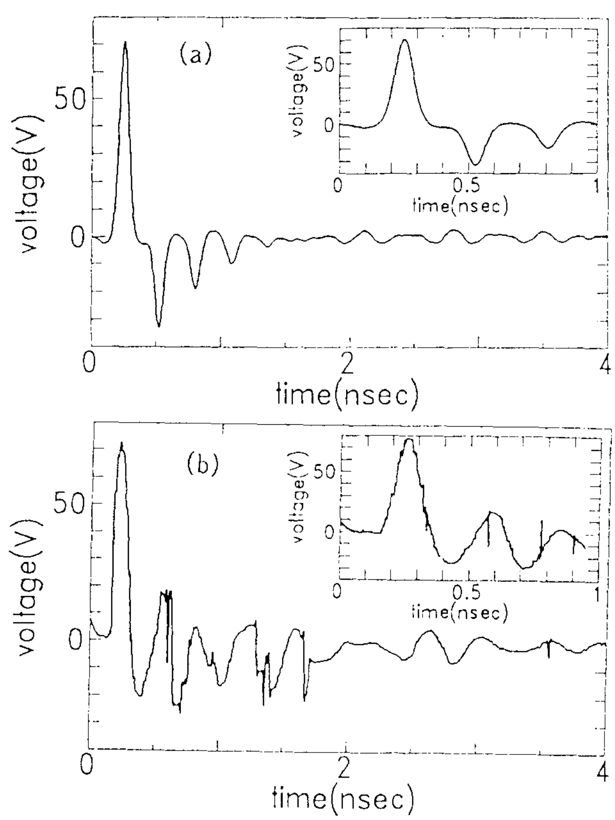

Fig. 4 Results of calculation(a) and experiment (b) on short-ended wireline. Related parameters are given in the text.