A Fifth Harmonic RF Bunch Monitor for the ANL-APS Electron Linac*

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Abstract

The function of a fifth harmonic (14.28 GHz) bunch monitor is to provide a signal which is proportional to the electron beam bunch size. The monitoring of the rf power signal at 14.28 GHz enables the operator to optimize the rf bunching of the beam at the end of the first accelerating section where the full bunching has been formed and remains mainly constant in size throughout the rest of the electron linac. A modified version of the SLAC original bunch monitor has been fabricated and its rf properties measured. This paper describes the design and the initial measurement results.

I. Introduction

Knowledge of the electron beam bunch size in a linear accelerator provides useful information about the beam energy spread. The electron beam bunch length in the APS electron linac is about 12° in phase or 12 ps after the first accelerating section where the beam energy is nominally 56 MeV. Bunch length of this size is too short to be measured directly by conventional timing techniques. In recent years several time-resolved imaging techniques have been developed and used to measure charged particle beam profiles (particularly e-beam) with very short time structures (typically 10 – 20 ps) [1]. These techniques rely on the detected optical radiation in the visible region by optical transition radiation (OTR), Cherenkov radiation, and synchrotron radiation (SR) using gated or streak cameras. These methods have the distinct advantage of providing precise information about a detected charge distribution. For the APS electron linac operation, however, it is desirable to dynamically monitor the electron bunch length due to the changes in the low energy linac parameters (for example, rf power and phase variation of the pre-buncher and the buncher). An indirect measuring method, using an rf cavity resonant at the fifth harmonic of the SLAC main linac fundamental frequency (2856 MHz), was proposed by R. Miller [2] and successfully used to measure the bunch length at the SLAC main linac. The modified bunch monitor consists of only a single rf induction cavity resonant at 14.28 GHz. Figure 1 is a cross sectional view of the bunch monitor. As the beam traverses the bunch monitor, it excites the cavity. The rf power from the cavity is detected with a broad-band detector. The detected signal is then displayed on a scope. This signal is proportional to the second moment of the charge distribution in the bunch.

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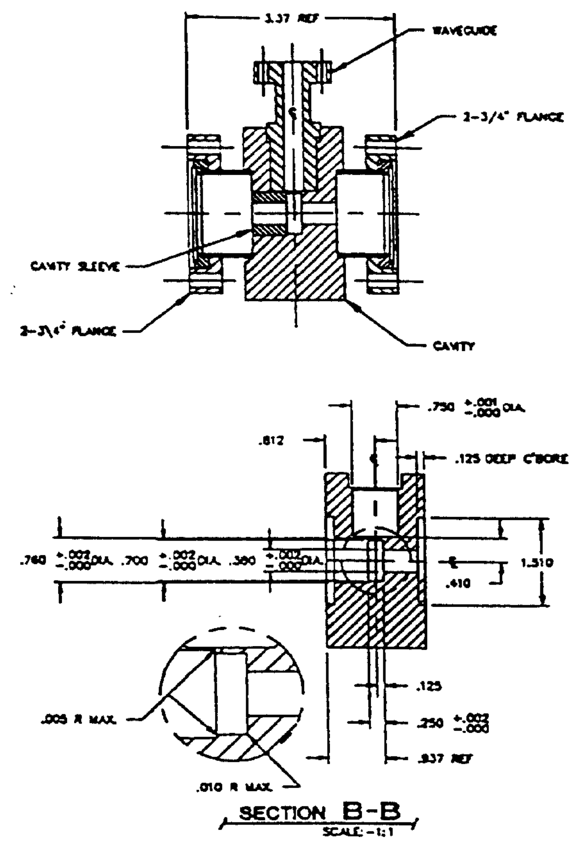

Figure 1
Bunch monitor cross section

II. Analytical Derivations

We give a brief derivation based on the moment method suggested by R. Miller [2]. If $I(t)$ is the instantaneous beam current, then the m^{th} moment of the current distribution is defined as

$$E_m(t^m) = \frac{1}{q}\int_{-\tau}^{+\tau} t^m I(t)dt \qquad (1)$$

where q is the total charge per bunch

$$q = \int_{-\tau}^{+\tau} I(t)dt, \qquad (2)$$

$\tau = \frac{1}{2f_o}$, and f_o is the linac fundamental frequency.

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By definition, $E_o \equiv 1$ and the origin of t is chosen so that

$$E_1(t) = \frac{1}{q}\int_{-\tau}^{+\tau} tI(t)dt = 0. \tag{3}$$

Assuming a Gaussian beam distribution, the half-width of the bunch is defined as

$$\sigma = \sqrt{E_2(t^2)}. \tag{4}$$

The beam current can be expressed by a Fourier series

$$I(t) = \sum_{m=-\infty}^{m=+\infty} I_m e^{im\omega_o t} \tag{5}$$

where

$$I(\omega) = \frac{\omega_o}{2\pi}\int_{-\tau}^{+\tau} I(t)e^{-i\omega t}dt. \tag{6}$$

The n-th derivative of the current distribution, $I(\omega)$ evaluated at $\omega = 0$ is

$$\frac{d^n I(\omega)}{d\omega^n} = \frac{(-i)^n\omega_o}{2\pi}\int_{-\tau}^{+\tau} t^n I(t)dt \tag{7}$$

or

$$\frac{d^n I(\omega)}{d\omega^n} = (-i)^n I_o E_n \tag{8}$$

where $I_o = \frac{\omega_o q}{2\pi}$. So $I(\omega)$ can be expanded in a Taylor series about $\omega = 0$:

$$I(\omega) = I_o(1 - \frac{1}{2!}E_2\omega^2 + \frac{1}{3!}E_3\omega^3 + \frac{1}{4!}E_4\omega^4 + \ldots). \tag{9}$$

For low harmonics one can write:

$$\mid I_m \mid = I_o[1 - \frac{\sigma^2}{2}(m\omega_o)^2] \tag{10}$$

where m is the rf harmonic number (here, m=5). The beam-induced power from a cavity resonating at the m-th harmonic is

$$P_m = \frac{\mid I_m \mid^2}{2}R_m, \tag{11}$$

where R_m is the cavity shunt impedance. With the half-width of the bunch (in radians) defined as $\theta = \sigma\omega_o$, the beam-induced power can be expressed as

$$P_m = \frac{I_o^2 R}{2} \mid (1 - \theta^2 m^2) \mid . \tag{12}$$

Therefore, the power from the cavity is proportional to the second moment of the bunch, θ^2. For $m = 5$, $\theta = 0.21$ radians, $I_o = 6.8 \times 10^{-4}$ Amperes, and a shunt impedance of 1.3×10^5 Ω, the power is

$$P_m \approx 3\ mW. \tag{13}$$

The choice of the fifth harmonic cavity was based on maximizing the resulting signal. For a tube size of about 1.0 cm, the fifth harmonic provides the highest signal which is sufficiently beyond the cutoff.

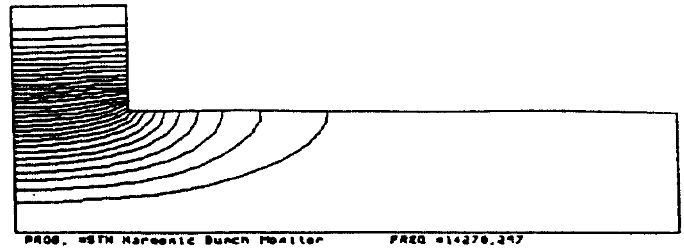

Figure 2
Bunch monitor cavity E-field plot

III. Cavity Design and Construction

The initial SLAC two-cavity design was modified to include only a single rf induction cavity resonating at 14.28 GHz. The bunch monitor consists of three separate pieces- -copper cavity, copper rectangular waveguide, and drift tubes- -all copper brazed together after machining. The assembled structure was checked for leaks around the brazed joints with a helium leak detector. No leaks were found at a pressure of 2×10^{-10} Torr. A vacuum flange fabricated from 304 stainless steel was subsequently brazed to the rectangular wavequide to facilitate attachment of a ceramic vacuum window. The window is mounted in a standard brass WR-62 rectangular waveguide and the one-atmosphere side uses a standard waveguide flange. A standard WR-62 to SMA adaptor completes the basic assembly. When the bunch monitor is installed in the APS electron linac a coaxial attenuator and a zero bias schottky diode detector will also be used. The basic rf properties of the bunch monitor were determined using the SUPERFISH program. For the dimensions shown in Figure 1, SUPERFISH gives a resonant frequency of $f = 14.27$ GHz and a $Q = 3655$. Figure 2 is the E-field plot for this cavity.

IV. Measurements

The cavity was excited with an antenna (E-probe) with about 10 mW of rf power ($\sim$ +10 dBm) provided by the network analyzer. The signal coupled from the cavity through the WR-62 waveguide was displayed and the cavity resonant frequency and the quality factor, Q, was determined. Figure 3 shows a plot of the relative amplitude (dB) versus frequency (GHz). It can been seen from this plot that the dominant frequency (the cavity's fundamental resonant frequency) is 14.28 GHz. The cavity's quality factor, Q, was determined by finding the 3-dB points relative to the resonant frequency (see Figure 4). The 3-dB point half-bandwidth is $\Delta f = 2.0$ MHz. The Q-value is determined by

$$Q = \frac{f_o}{2\Delta f} = 3571.$$

Two other measurement attempts were made, unsuccessfully, to characterize the cavity by exciting it using a central wire. In the first setup, since the diameter of the central tapered rod (matched 50 Ω) was comparable to the diameter of the fifth-harmonic cavity, all the cavity's modes were suppressed by the central rod and no signals (beyond the noise level) were observed either by using a short (45 ps) pulse source and reading the response on an HP-8562A spectrum analyzer or with an HP-8510 network analyzer. Nothing but noise was observed in the region of interest. Next, the central rod was replaced by a thin wire (~ 1 mm diameter) and the measurements were repeated. With the pulsed excitation there was still no signal observable above the noise. On the network analyzer, there was a slight rise in the region of interest but it had no resemblance to the predicted high Q response.

V. Summary

An indirect bunch length monitor using an rf cavity is a simple and non-destructive method of providing on-line information about the relative longitudinal bunch length of the electron beam. In this paper we described the design of the bunch monitor and reported on the rf characterization of the rf cavity. Measurements with the network analyzer using an E-probe gave f_o = 14.28 GHz and Q = 3571 (Q = 3655 from SUPERFISH). No beam measurements have been made yet; however, the bunch monitor is being installed in the electron linac beamline. Final calibration tests will be done using the APS electron linac beam.

VI. Acknowlegements

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References

[1] A. Lumpkin, "Advanced, Time-Resolved Techniques for Electron-Beam Characterization," Second Annual Workshop on Accelerator Instrumentation, Batavia, IL, p.151, 1990.

[2] R. Miller, private communication.

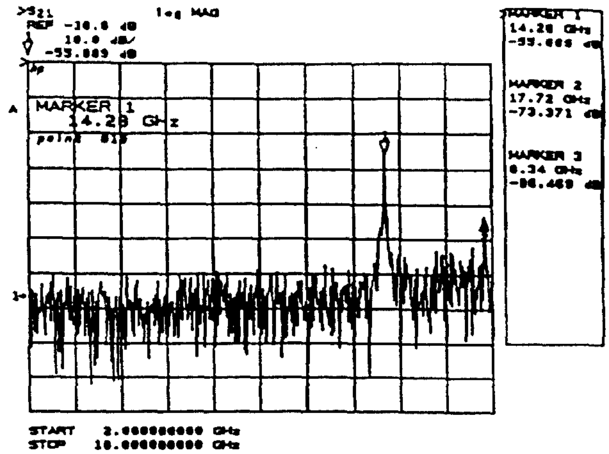

Figure 3
Frequency response

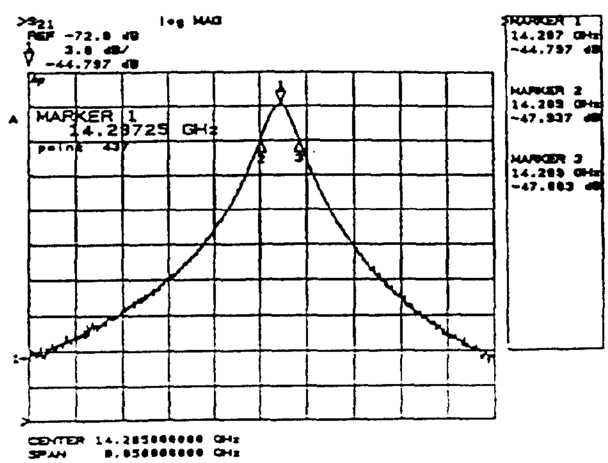

Figure 4
Resonant frequency