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MEASUREMENTS OF PHASE SHIFT DUE TO BEAM LOADING IN KEK LINAC

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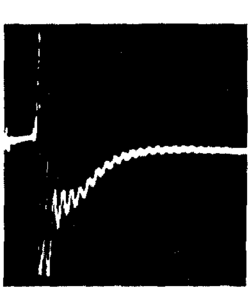
Abstract

Transient rf phase shift due to beam loading in KEK linac was measured. The maximum phase shift of 4.2° was observed by a 130 mA beam of 4 μsec in length. The effects of the beam induced higher order modes on the phase shift were studied. The intensity of the induced TM011 mode was estimated by the amplitude of the wiggles in the phase shift. The results observed are consistent with the results of calculation based on the normal mode analysis.

Introduction

The KEK 20 MeV linac accelerates 130 mA proton beams of 4 μsec at a repetition rate of 20 Hz under normal condition. One of the striking features of the linac is a use of two rf power feeds, one at z = L/4 and the other at 3/4L, where L is the tank length and z is a longitudinal coordinate. This system has an advantage of suppressing an excitation of higher order modes in a transient phenomena. When a tank is excited by an external force, for example, higher order modes are excited as well as fundamental one, leading to the transient phase shift between the driving point and the other points of the tank. Wiggles due to the beat between a fundamental mode and a nearby mode appear in transient phenomena. In our case, the frequency difference of the above two modes is about 200 kHz, thus wiggles of 5 μsec are expected. Figure 1 shows measured transient phase shift between z = 0.3L and z = 0.9L during a build up time excited by one feed at z = L/4. The results are shown in Fig. 2 when the both feeds were used in external driving force. It seems higher order modes are greately suppressed in case of two feeds operation.

Transient phase shift also occurs with beam loading. The stored energy of the tank is about 48 joules, while the extracted beam energy is 10 joules, then heavy beam loading effects, both resistive and reactive, are expected. In such heavy beam loading, the compensation for beam loading is necessary to obtain a high quality and high intensity beam. We have used two methods for compensation, an rf amplitude modulation and detuning. It should be noted that the extra rf compensation pulse causes transient phase shift[1] which is added to the phase shift due to beam loading, making the situation complicated. Although the almost satisfactory beam is obtained now, a slight change of beam energy during a beam period is observed[2], which seems troublesome in acceleration in the booster synchrotron. In order to improve the compensation, the preliminary test of phase compensation was performed[2], where some effects of phase modulation given at the stage of low power level of the driving power were observed. A knowledge of the transient phase shift is desirable to study further the detail of beam loading.



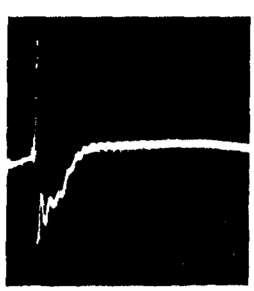


Fig. 1 (one feed) Fig. 2 (two feed)
Transient phase shift during build up time.
vertical: 18°/div. horizontal: 20 μsec/div.

Theory

The transient effects due to beam loading in a standing wave proton linac are well explained by the normal mode analysis[3]. Under some simplifications and approximations, the fields induced by beam are given for TM010 mode,

$$E_{b0}(t) = -\frac{r_{e0} I_0 f_0 Q_0}{T_0\, Q_{00}} (1 - e^{-\omega_0 t/2Q_0}) e^{j(\omega_0 t + \phi_b)} \tag{1}$$

for TM011 mode,

$$E_{b1}(z,t) = -\frac{2L_b}{\pi L} \frac{r_{e0} I_0 f_0}{T_0} \frac{\omega_0{}^2}{Q_{00}} \frac{(e^{-j\Omega_{01} t} - e^{-\omega_1 t/2Q_1})}{\omega_1{}^2 - \omega_0{}^2 + j\omega_1\omega_0/Q_1}$$

$$\times\ e^{j(\omega_1 t + \phi_b)} \cos(\pi z/L) \tag{2}$$

where r_{e0} = effective shunt impedance,

I_0 = beam current averaged over bunches,
f_0 = form factor due to phase spread of particles in a bunch,
T_0 = transit time factor,
Q_0 = total Q for the TM010 mode; $Q_0^{-1} = Q_{00}^{-1} + Q_{ext}^{-1}$,
Q_1 = total Q for the TM011 mode,
ϕ_b = stable phase angle of beam bunches,
ω_0 = TM010 mode frequency,
ω_1 = TM011 mode frequency,
$\Omega_{01} = \omega_1 - \omega_0$,
L_b = a space between two bunches,
L = tank length.

Assuming that the driving field varies as $e^{j\omega t}$, the net field in a tank is given by superposition,

$$E(z,t) = E_0 e^{j\omega t} + E_{b0}(t) + E_{b1}(z,t). \tag{3}$$

After a beam passes through the tank, the induced fields are assumed to decrease exponentially with time constants of each mode. On the assumption that the net field is rewritten by the form, $E_0 e^{j\omega t}(X + jY)$, the phase shift of the resultant field relative to the driving field is

$$\tan\psi(z,t) = \frac{Y}{X} \tag{4}$$

Calculated phase shift for a 130 mA beam in the

KEK linac is represented in Fig. 3, where the amplitude ratio of the beam induced TM010 mode to the driving field is assumed 0.15 and the ratio of TM011 mode to the beam induced TM010 mode is assumed 0.01. It should be noted that wiggles disappear in the center of the tank since it corresponds to a node of TM011 mode.

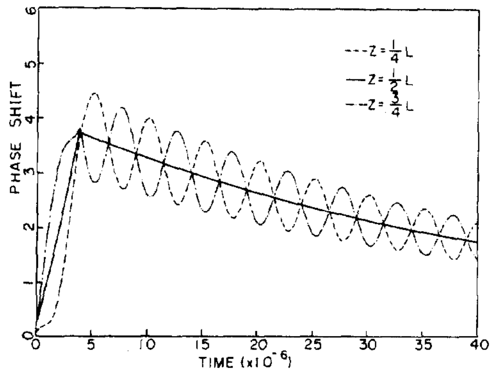
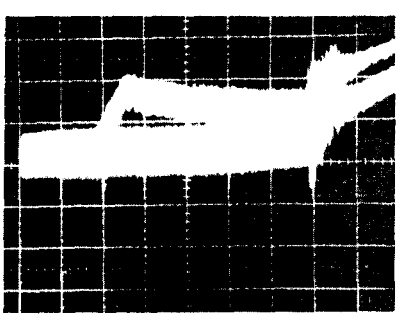


Fig. 3 Calculated phase shift due to beam loading. A 4 μsec beam of 130 mA is assumed.

Measurements

The linac, 15.5 m in length, has ten available rf pick-up monitors distributed along the tank. A phase difference between a master synthesized oscillator and a rf pick-up monitor was measured using a calibrated double balanced mixer. Considerable cares were taken to eliminate phase errors due to both a change of the rf amplitude from the tank and a disturbance of strong rf noise generated in the linac power supply room where the phase measurement detector was located.

Figure 4 shows the typical transient phase shift due to beam loading measured at z = 0.5L. The base line shows the phase with no beam loading. It increases with time and reaches maximum shift of 4.2° at the end of the beam pulse. The calculated TM010 field induced by a 130 mA beam of 4 μsec is 2.9×10^5 V/m. This gives an rf phase shift of 4°, which agrees well with the observed one. The phase shift measured at z = 0.9L is shown in Fig. 5. It is characterized by wiggles of a period of 5 μsec, showing the excitation of TM011 mode by the beam. According to the equations of (1) and (2), the intensity of beam induced TM011 mode is smaller than the beam induced TM010 mode by a factor of $\sqrt{2}L_b/L$. This means that the TM011 mode is smaller than the TM010 mode by 46 dB. The ratio of the TM011 mode to the resultant fundamental mode can be



vertical: 1.6°/div

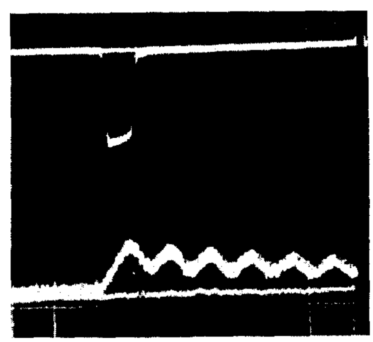
horizontal: 5 μsec/div

Fig. 4 Phase shift due to beam loading measured at z=L/2.

estimated from the amplitude of the wiggles in the phase shift. The intensity of the TM011 mode determined by the above method is − 43 dB of the fundamental one. The measurement of the TM011 mode intensity using a spectrum analyzer gives nearly the same result, that is, − 40 dB of the fundamental one. Beam induced higher order modes except for TM011 mode have little effects on the phase shift because they are much smaller than the TM011 mode[4]. By careful investigation, wiggles of 0.6 μsec, showing the existence of TM013 mode, are observed, however, its amplitude is so small that any quantitative discussions are not available.

Figure 6 shows phase shift measured at z = 0.2L and z = 0.9L. Since TM011 mode has z-dependence through the term of cos(πz/L), the wiggles observed at z = 0.2L and z = 0.9L are nearly 180° out of phase.

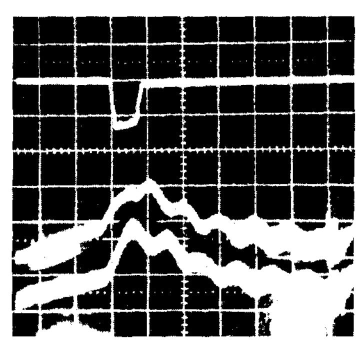
A phase shift caused by an extra compensation pulse under normal operation of the linac is shown in Fig. 7. It increases with time and reaches maximum phase shift of 6° just before the beam comes into the tank. The phase shift due to beam loading is added to that due to the compensation pulse. In our linac, there are two rf power supply systems of the same type, RF-A and RF-B. Each drives one of the power feeds. The compensation pulses are obtained by modulating the control grid of the power tube of RCA 4616 in the power supply of the low energy side (RF-A) or by modulating the screen grid in that of the high energy side (RF-B). Since these modulations give rise to phase shift on the rf power from the tube, the phase shift obtained in the tank due to the compensation pulse is complicated. Steady state phase difference between the driving field of RF-A and that of RF-B also have an effect on the phase shift due to the compensation pulse because the



vertical: 2.4°/div

horizontal: 5 μsec/div

Fig. 5 Phase shift due to beam loading measured at z=0.9L. Upper trace is the output beam.



vertical: 2.5°/div

horizontal: 5 μsec/div

Fig. 6 Effect of TM011 mode on the phase shift. Wiggles of middle trace (z=0.2L) and those of lower trace (z=0.9L) are out of phase.

amplitudes of the two power sources are not exactly equal each other. As seen in Figure 7, the compensation pulse begins to increase before the beam comes into the tank in order to raise the tank level, giving a large amount of phase shift from the steady state phase. Therefore fine tunings of the rf phase of the tank relative to the buncher rf phase are necessary to have a good operation of the linac.

In Fig. 8, the intensity of the output beam of a period of 15 μsec and the phase shift due to beam loading are shown . The beam intensity decreases with time because of an insufficient rf compensation power for such a rather long beam pulse. It seems that the wiggles have some effects not only on the phase shift but on the intensity of the output beam. These wiggles on the intensity give no deterious effect on beam quality in case of normal operating condition (4 μsec beam). A project of H^- beam injection to the booster synchrotron is under way in KEK[5], where a 50 mA beam of 100 μsec will be accelerated in the linac. At that time, careful compensation of both rf amplitude and phase is favorable.

Acknowledgement

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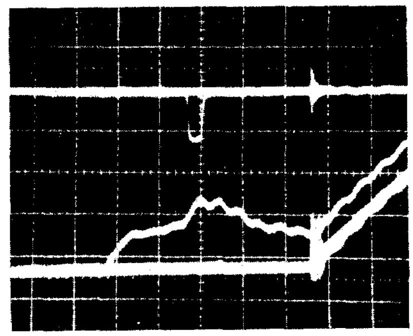
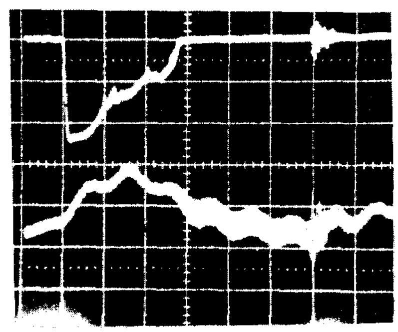


vertical: 5.6°/div

horizontal: 10 μsec/div

Fig. 7 Phase shift due to compensation pulse and beam loading measured at z=0.8L.



vertical: 3.9°/div

horizontal: 5 μsec/div

Fig. 8 Phase shift due to the beam of 15 μsec. Upper trace shows the output beam.