STUDIES OF MULTI-DRIVE EXCITATION FOR ALVAREZ STRUCTURES*

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Introduction

To accelerate protons in an Alvarez type linac the cavity must be excited in the TM_{010} mode. For proper beam dynamics it is necessary that the RF amplitude and phase distribution along the length of the cavity be kept constant. The amplitude and phase variation along the tank are the result of both the propagating characteristics of the structure and the method used to excite the cavity with RF power. The analysis and measurements in this paper deal primarily with the effects of multi-drive systems and the resultant improvement in the steady state and transient case.

The TM_{011}, TM_{012}, etc. modes are excited by the RF drive system, and since these modes are in time quadrature with the TM_{010} mode, the resultant field has both an amplitude and phase variation along the structure. There is also the effect associated with mechanical detuning perturbations of the cavity, resulting in an additional amplitude variation, but essentially no phase variation. It will be shown that the two phenomena are essentially uncoupled, and a simple procedure can be used to reduce the amplitude and phase variations.

Theory

It has been shown[1] that the amplitude and phase variations due to beam loading can be substantially reduced with the use of a multiple RF drive system. The above effect has recently been analyzed by Nishikawa[2,3] in terms of higher order mode excitation. Nishikawa's work is based on the linear combination of the TM_{010} mode and the time quadrature components of the higher order TM_{01n} modes, resulting in both an amplitude and phase variation along the structure. The resultant field is described by

$$E(z) = E_o \left(1 + \sum_{n=1}^{\infty} E_n \cos \frac{n\pi z}{L} \right) , \qquad (1)$$

and where

$$E_n = j \frac{N_n}{Q_n} \frac{\omega_o}{(\omega_n - \omega_o)} . \qquad (2)$$

[$E(z)$ is the electric field along the structure, E_o is the average field, E_n is the amplitude of the n^{th} higher order mode, N_n is the relative coupling coefficient to the n^{th} mode, Q_n and ω_n also refer to the n^{th} mode and ω_o is the resonant frequency of the TM_{010} mode.]

The resultant phase shift along the structure can be expressed as

$$\varphi(z) = \tan^{-1} \frac{\sum_{n=1}^{\infty} E_n \cos \frac{n\pi z}{L}}{E_o} \qquad (3)$$

It can be seen from Eq. (2) that the excitation or suppression of these higher order TM_{01n} modes are strongly dependent on the RF drive system employed.

We will now consider the resultant frequency perturbation relationship as developed by Panofsky.[4] Where the frequency variation along a structure is defined by the Fourier series

$$f(z) = f_o \left(1 + \sum_{n=1}^{\infty} P_n \cos \frac{n\pi z}{L} \right) , \qquad (4)$$

and the corresponding electric field variations defined by another Fourier series

$$E(z) = E_o \left(1 + \sum_{n=1}^{\infty} \epsilon_n \cos \frac{n\pi z}{L} \right) , \qquad (5)$$

Panofsky has shown that

$$\epsilon_n = P_n \frac{8}{n^2} \left(\frac{L}{\lambda} \right)^2 = P_n \frac{\omega_o}{\omega_n - \omega_o} . \qquad (6)$$

It should be pointed out that the above equations are based on the perturbation of the TM_{010} mode and its spatial harmonics, and not the higher order modes as considered by Nishikawa. It is important to note that the spatial harmonics as given by Eq. (6) are all in time phase with respect to the TM_{010} mode, as opposed to the higher order modes as given in Eq. (2) which are in quadrature time phase with respect to the TM_{010} mode. It may appear that there is a similarity between Eqs. (2) and (6), but the time quadrature difference results in these two field components having markedly different effects.

As will be shown later in the section on experimental results, Eqs. (2) and (6) are independent, uncoupled functions for small perturbations (for tank tilts of 20% of less). Using this empirical result, we can now make a linear combination of the above field equations. If we start out with an ideal cavity [no frequency detuning,

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f(z) = constant, then the field distribution, depending upon the RF drive system, will be given by Eq. (1). If we now detune the cavity in some prescribed manner, the field variation for this perturbation will be described by Eq. (5). If we now consider both of the above effects, viz. the RF drive system and a superimposed perturbation detuning, we may now write the total field as

$$E_T(z) = E_o \left(1 + \sum_{n=1}^{\infty} E_n \cos \frac{n\pi z}{L} \right)$$

$$+ E_o \left(\sum_{n=1}^{\infty} \epsilon_n \cos \frac{n\pi z}{L} \right) . \qquad (7)$$

From Eq. (7), since E_n is imaginary the additional field as introduced by ϵ_n can never correct for the phase angle but it can be made to cancel the amplitude variations arising from the higher order mode excitation as described in Eq. (1).

The magnitude of Eq. (7) may now be written as

$$|E_T(z)| = E_o \left[\left(1 + \sum_{n=1}^{\infty} \epsilon_n \cos \frac{n\pi z}{L} \right)^2 + \left(\sum_{n=1}^{\infty} E_n \cos \frac{n\pi z}{L} \right)^2 \right]^{\frac{1}{2}} \qquad (8)$$

It can be shown, with appropriate approximations, that a very good solution that makes $|E_T(z)|$ a constant is for $E_1^2 = 4\epsilon_2$, $E_2^2 = 4\epsilon_4$, or for the general case

$$(E_n)^2 = 4\epsilon_{2n} . \qquad (9)$$

Experimental Results

A hollow cylindrical cavity 20 ft long and approximately 10 in. in diameter, having a TM_{010} mode frequency of 938 Mc, was used to make measurements. This cavity has approximately the same electrical length (L/λ) as the 50-MeV Brookhaven proton linac. To make perturbation measurements, a tuning screw was inserted in the end wall, and adjusted to give frequency changes of 0.01, 0.02 and 0.03 Mc.

For the case of a single drive at one end of the cavity, Figs. 1a and 1b, representing amplitude and phase changes along the length of the cavity for frequency perturbations of 0.01, 0.02 and 0.03 Mc, clearly show that there are large amplitude changes but relatively small phase changes. The results are consistent with Eqs. (1) and (3), where the TM_{011}, TM_{012}, etc. modes are excited. It should be pointed out that the frequency perturbation of 0.03 Mc is an extremely large perturbation, representing an amplitude change of 5 dB, resulting in a shift that departs somewhat from what would be predicted from linear theory.

We will now consider a single drive at the center of the cavity. Fig. 2a indicates the resulting amplitude distribution for the various perturbations being considered, and these sets of curves are almost identical to Fig. 1a, showing that the amplitude variations are independent of the RF power feed position considered. Figure 2b clearly indicates an improvement in the phase distribution along the structure as compared to Fig. 1b. This improvement is brought about by the fact that for a single RF drive at one end of a cavity, all higher odd modes are excited, which conforms to what is to be expected from the theory as given by Eqs. (1) and (3).

Figures 3a and 3b are for the double drive case, where each drive is located at λ/4 from each end of the cavity. It is clear from the above two figures that there is no essential change in the amplitude distribution as compared to Figs. 1a and 2a, but the phase distribution along the tank is greatly improved for the double drives. For this particular double drive system, the results are consistent with Eqs. (1) and (3), where we not only suppress the TM_{011} and TM_{013} modes as for the single center drive previously considered, but we also suppress the TM_{012} mode.

From the above discussion it is clear that the effect of a tuning perturbation is to give an amplitude variation which is essentially independent of the RF drive configuration used, which is consistent with Eq. (5). It has also been shown that the phase shift is independent of the tuning perturbation, but is strongly dependent on the RF drive configuration used, which can be explained by Eqs. (1) and (3). It is clear that for frequency perturbations of 0.02 Mc or less, and within the measurement accuracy obtained, the two equations (5) and (1) are uncoupled and independent. It should be pointed out that the excitation of the higher order modes does contribute a small amplitude variation, but the amplitude effects are small as compared to the phase shifts introduced.

Transients

Transient measurements were made on the Brookhaven 50-MeV linac. Figures 4, 5 and 6 show the results of the three drive conditions previously considered. In Fig. 4, where all the higher TM_{01n} modes are excited, we see that the RF envelope of the build-up pulse contains the beat frequencies between these TM_{01n} modes and the driver TM_{010} mode. In Fig. 5, where we have a center feed corresponding to suppressing the TM_{011} and TM_{013} modes, we see that the RF envelope of the build-up pulse does not contain the beat frequencies of the two suppressed modes, resulting in a much improved transient response. For the case shown in Fig. 6, we not only suppress TM_{011} and TM_{013} but also the TM_{012}, resulting in an RF envelope relatively free of beat frequencies.

Conclusion

In order to have the amplitude and phase along each tank (and between tanks of a multi-tank linac), and with the added beam loading effects, the use of a multi-drive RF system is dictated. The results to date are very encouraging. Work is progressing on looking at three and four RF drive systems.

References

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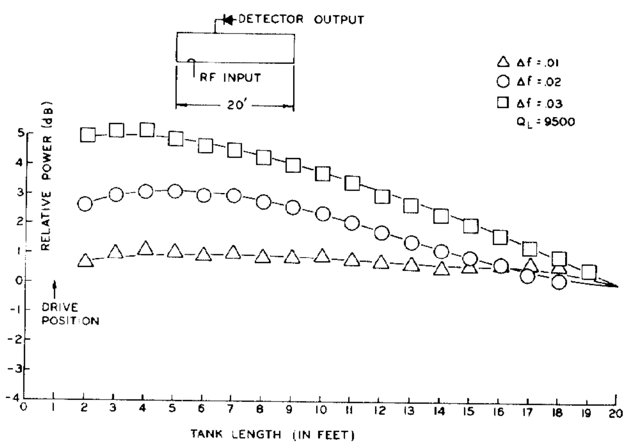

Fig. 1a. Field amplitude vs. length—drive at end.

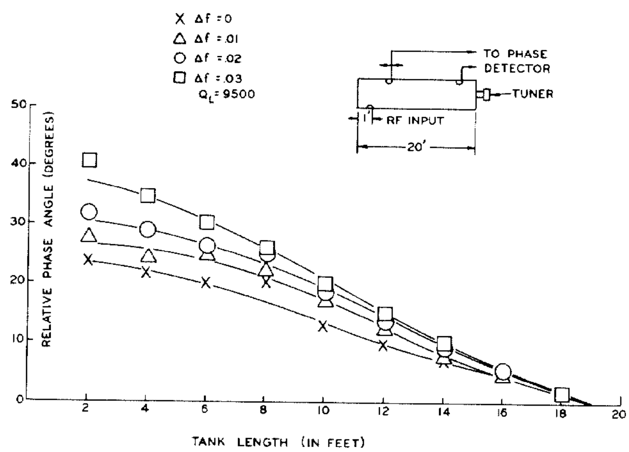

Fig. 1b. Phase distribution vs. drive at end.

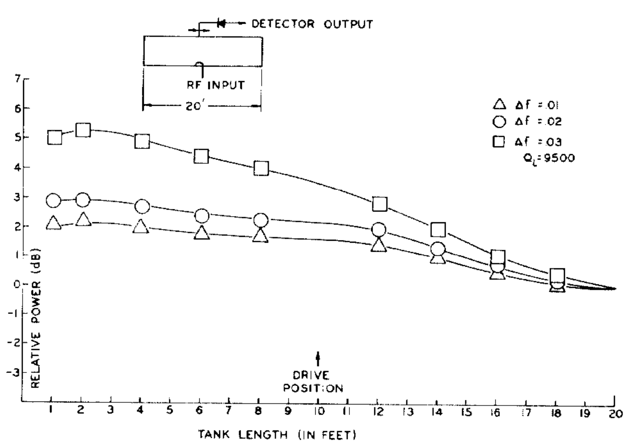

Fig. 2a. Field amplitude vs. length—drive at center.

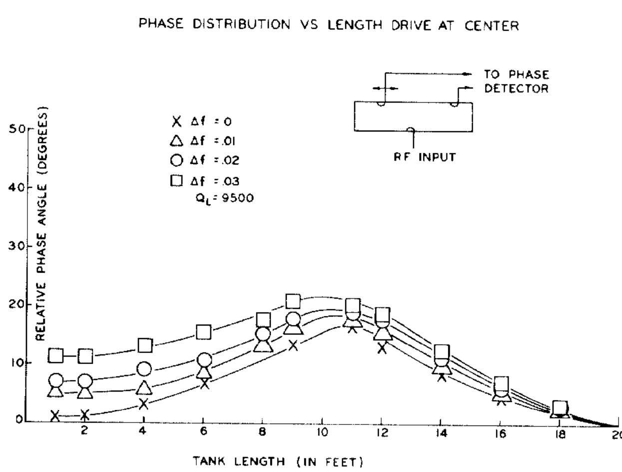

Fig. 2b. Phase distribution vs. length—drive at center.

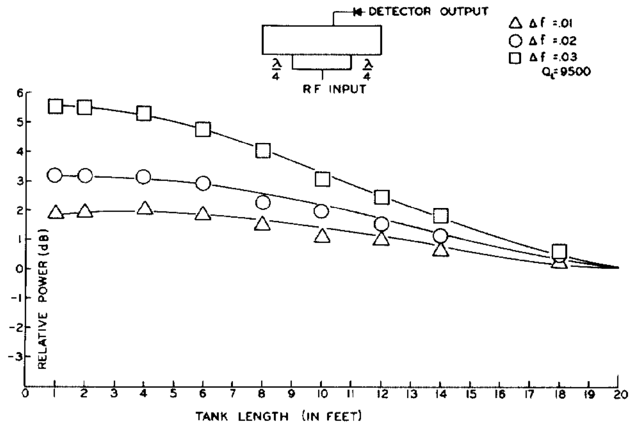

Fig. 3a. Field amplitude vs. length—double drive at λ/4 from ends.

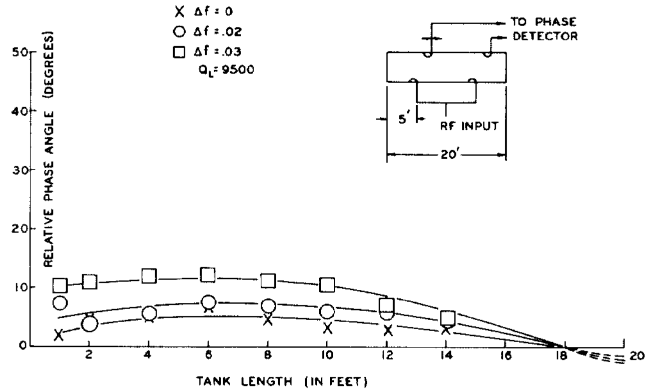

Fig. 3b. Phase distribution vs. length—double drive at λ/4 from ends.

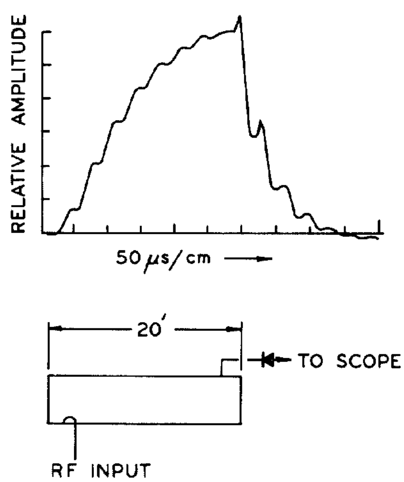

Fig. 4. Transient response—end drive.

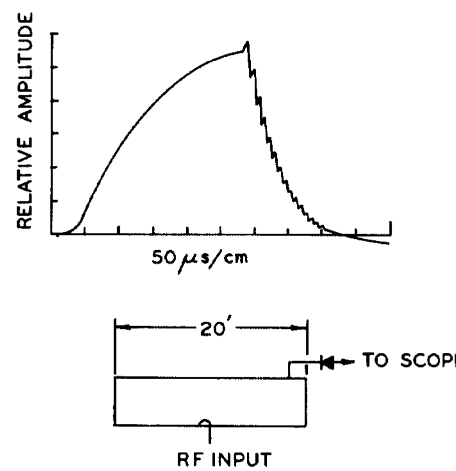

Fig. 5. Transient response—center drive.

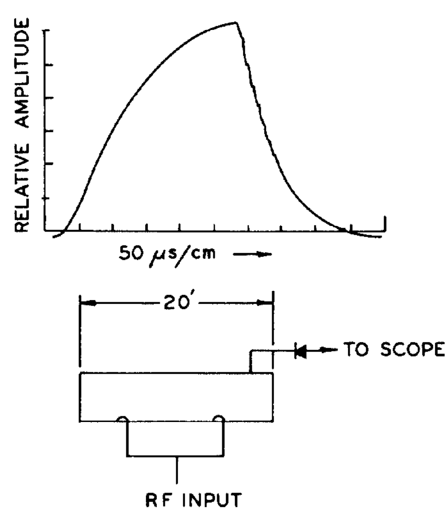

Fig. 6. Transient response—double drive.