PRECISION PHASE ADJUSTMENT OF A LINEAR ACCELERATOR HIGH POWER WAVEGUIDE FEED NETWORK*

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Summary

Each klystron of the SLAC accelerator feeds four consecutive 10-foot accelerator sections through approximately 25 feet of earth shielding. The high power waveguide network which divides and guides the power to the four sections is adjusted so that the rf waves traveling within the accelerator sections are, at the end of each section, phased within ± two degrees of an ideal wave traveling at the velocity of light.

A modulated reflection technique is used to compare the electrical phase length from a single input port through the four arms of the network during adjustment. The inclusion of the previously tuned accelerator sections in the network allows the total phase error to be minimized if careful control is exercised over the section temperatures.

The measuring system, the reflection modulators, and the possible errors involved are discussed.

Introduction

The SLAC accelerator utilizes a high power waveguide network to feed rf energy from each klystron amplifier through 25 feet of earth shielding to four independently fed and terminated 10-foot accelerator sections. The design specification is that the electrical phase lengths through the four arms of the S-band waveguide network (Fig. 1) be equalized to within ± 2°.

In operation the rf wave appears to move at the velocity of light along the entire machine in a single coherent wave. This requires that each section have an rf phase velocity equal to c at the operating frequency, and that the rf wave entering each section be phased correctly with respect to the bunched electron beam. Four sections are assembled on a forty-foot support module. One of the sections and its feed arm form part of a closed loop phasing system.[1] Thus, the other three feed arms must be permanently adjusted with respect to the reference arm. To simplify the adjustment, the axial distance between inputs is made an integral number of wavelengths (29). There are approximately seventy-five feet of S-band waveguide or 150 wavelengths between the klystron and the accelerator sections. There are several flange joints which compress a thin copper gasket to obtain both a vacuum seal and an rf joint. Small physical distortions occurring in the components of the waveguide network during installation plus variations in the joints make it necessary to adjust the phase of the network after installation.

The physical dimensions of most structures whose phase shift is desired are sufficiently small so that they may be incorporated in a network which again has laboratory-sized dimensions. For large networks having many wavelengths between input and output, and particularly where the phase at a number of output ports must be compared, most of the commonly used methods have drawbacks.[2,3] The difficulties arise primarily from phase changes resulting from mechanical and temperature variations in the long parallel transmission line required. The method used by Swarup and Yang[4] minimizes these problems with the measuring circuit by reflecting the test signal back along the branch under test. To distinguish the desired signal from others which may be returning to the input port, the test signal is modulated at the point of reflection. Since the test signal traverses the device twice, its phase variations will be twice that between the input port and the point of reflection. The point of reflection was chosen to be at the output of the accelerator sections in order to minimize some of the error accumulation occurring between the tuned waveguide and tuned accelerator structure.[5]

Principles of Operation

The principle of phase detection used in this system is based on the relationship illustrated in Fig. 2. When a small amplitude modulated signal (Esc) is added to a large unmodulated signal (Ec) of the same frequency, the resultant signal will exhibit no amplitude modulation at the modulating frequency when the carriers of the two are nearly in quadrature ($\phi = \pm 90°$).

Robertson[6] appears first to have used amplitude modulation in one branch of a phase comparison circuit in order to avoid having to use equal-amplitude signals in both arms to obtain a null. By using balanced modulators to obtain a double-sideband suppressed-carrier signal, he obtained a null when the suppressed carrier and unmodulated signal were exactly in quadrature. If the carrier is completely suppressed, the null occurs at ± 90° regardless of the amplitude of the sidebands.

Shaeffer[7] subsequently suggested the use of simple amplitude modulation with sufficient attenuation of the modulated signal. A narrow band audio amplifier (VSWR indicator) following a crystal detector results in adequate sensitivity.

Following Shaeffer and referring again to Fig. 1, the relation between the angle ϕ and the resultant signal (Er) is given by the law of cosines

$$E_R^2 = E_c^2\left[E_{sc}\left(1+m\sum_{n=-\infty}^{\infty} C_n e^{\frac{in\omega_m t}{2}}\right)\right]^2 - 2E_c E_{sc}\left(1+m\sum_{n=-\infty}^{\infty} C_n e^{\frac{in\omega_m t}{2}}\right)\cos\phi \qquad (1)$$

(2,3) These articles give very good summaries of current approaches to phase measurements.

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Expanding gives

HIGHER HARMONIC TERMS

$$E_R^2 = E_c^2 + E_{sc}^2 + 2E_{sc}^2 m\Sigma + [E_{sc} m\Sigma]^2 - 2E_cE_{sc}\cos\phi - 2E_cE_{sc}\cos\phi\, m\Sigma \qquad (2)$$

CONST. AMPLITUDE TERMS

The modulation envelope of the resultant is seen to have no component at the fundamental frequency of the modulating waveform when the fundamental component of

$$2E_{sc}^2 m \sum_{n=-\infty}^{\infty} C_n e^{\frac{in\omega_m t}{2}} - 2E_cE_{sc}\cos\phi\, m \sum_{n=\infty}^{\infty} C_n e^{\frac{in\omega_m t}{2}} = 0 \qquad (3)$$

or

$$\cos\phi = \frac{E_{sc}}{E_c} \qquad (4)$$

The angle at which a null is obtained versus the relative amplitude in decibels of modulated and reference waves is shown in Table I.

TABLE I

$20 \log_{10}(E_c/E_{sc})$	Angle ϕ at Null Response
0	0.00°
10	71.56°
20	84.26°
30	88.19°
40	89.43°
50	89.82°
60	89.94°
70	89.98°
80	89.99°
90	90.00°

With the reflected signal down 50 db with respect to the carrier, the error is less than 0.2°.

With arbitrary modulation and detection the waveform obtained from the detection of Er will not in general be free of components at ωm for ϕ given by Eq. (4). These components, however, will arise from intermodulation between higher harmonic terms and consequently will be small in the ordinary case.

Measurement System

Basic System and Network

A diagram of the mesaurement equipment and microwave network is shown in Fig. 1. Fig. 3 shows the early model of the system attached to the input port of the waveguide feed network. The signal from a stable signal generator is divided by a 10 db directional coupler, the larger portion constituting the reference signal (Ec) feeding the crystal detector via one arm of the magic T. The smaller portion passes through a precision phase shifter and a window (used to permit evacuation of the waveguide and accelerator sections) to the network input flange, which connects to the high-power klystron during accelerator operation. The networks consist primarily of a power divider located in the klystron gallery, followed by 40-foot waveguides penetrating the shielding; two additional power dividers in the accelerator housing preceding the four accelerator sections, each of which is terminated with a reflection modulator followed by a load. The design, adjustment and operation of the modulators and modulator switching supply is described in detail below. In use, one of the modulators is switched between a reflecting and passing condition at a 1000 cycle rate while the other three are biased to pass signals to the loads. The signal which enters the input port arrives at all the modulators attenuated approximately 11 db by having transversed two 3 db dividers and five db of attenuation in the accelerator section. It is then reflected with 1000 cycle amplitude modulation from the one modulator which is on, and arrives back at the input port with a peak value which is down 22 db. This signal reenters the phase measurement apparatus (dotted line) and is sampled by a 20 db directional coupler, whence it reaches the magic T and crystal detector where, as Esc, it mixes with the reference signal. Esc is then 52 db down compared with the reference Ec. From Table I a null will be obtained when the phase of Esc is within 0.2 degrees of quadrature with Ec.

By modulating the reflection from each branch in turn, while the other branches are not reflecting, the calibrated phase shifter can be adjusted to maintain a null in amplitude modulation at the modulation frequency, at the detector. The differences in the phase shifter readings give the differences in branch lengths directly.

The actual adjustment of the phase length is done by squeezing the rectangular waveguide walls with a modified C-clamp. A motorized trolley* that runs along the waveguide and whose position and indenting depth may be remotely controlled is also being tried. After tuning, a final VSWR check is made with a slotted line to assure that appreciable reflections are not produced by the phase length adjustments that are made by mechanical deformation of the waveguide walls.

The signal source is a stabilized oscillator with low residual AM and FM noise. A frequency counter continuously monitors the output frequency to better than ± 1 kc. The VSWR meter serves as a 1 kc amplifier and null meter. The scope is used in resolving ambiguities as described below.

Ambiguities

Two conditions of phase ambiguity arise. The first, as can easily be seen in Fig. 2, is the result of nulls occurring at both $\phi = \pm 90°$. This ambiguity can be resolved by rotating the phase shifter from the null condition in the same direction for each of the branches in turn and noting the phase of the detected wave on the oscilloscope whose sweep is synchronized with the modulating power supply. The waveform near + 90° will be negative of that near - 90°.

*Designed by M. Heinz

The second ambiguity arises when the phase length of two branches differs by 180°. The signals returned will have traversed each branch twice and will differ in phase by an indistinguishable 360°. This condition is avoided during final adjustment by making a preliminary phase check and, if necessary, a tuning adjustment. The method presently in use employs a slotted line as a null detector, with a length of coaxial cable to feed the rf signal in turn into each end of the waveguide branches. Another method, now under investigation, will utilize the basic phase measurement circuitry, but will feed the reference signal through a modulator flange acting as a coax-to-waveguide adaptor. Both of these preliminary 180° ambiguity check methods have an accuracy better than ± 10°, which is sufficient.

Errors

We consider three sources of error: that due to variations in modulators; the combined effect of variations in the operating conditions (temperature and frequency); and that due to instrument errors, mismatches and noise. The sum of these must not exceed the ± 2° phasing specification. This has been achieved with the following tolerances: ± 0.5° in the modulator flange, ± 0.5° in the measurement system and tuning error, and ± 1.0° caused by fluctuations in the operating conditions. Further efforts are being made to reduce the first two errors. Reductions of the last error would require temperature control closer than the present ± 0.1°F. This does not appear feasible.

Instrument errors. These can arise from leakage signals and reflections. The isolators on each side of the magic T prevent the signals from either arm of the bridge from entering the other arm. The input directional coupler feeds a signal into the measurement arm. The isolator in that arm prevents reflections from the phase shifter and the feed branches from leaking back through the reference arm. The most serious mismatch is that associated with the phase shifter since it varies with phase shifter position. Most of the reflections have been kept below 1%, while that due to the phase shifter is less than 3%. Errors also result from reflections, which are less than 5%. Thus the expected error due to mismatches is less than 0.1°. The error due to poor directivity and isolation should be less than 0.2°. The phase shifter, as used, has an accuracy of ± 0.1°, so the total phase error in the phase bridge circuitry is less than 0.4°.

Flange errors. Each flange modulator is measured prior to placement at the end of the accelerator section. Records are kept of the calibration history of each flange. Phase variations exceeding 1/2 degree are rare.

Variations in operating conditions. Probably the greatest source of error results from fluctuations in the operating conditions. The phase length is basically dependent upon the frequency, the waveguide dimensions, and the dielectric constant within the waveguides. These in turn are affected by temperature, external atmospheric pressure, and the internal gas pressure and composition. The metal temperature is dependent upon the temperature of the water circulated through the cooling tubes and, to a lesser extent, on the ambient temperature and the water flow rate. Some of the "phase shift versus operating condition" coefficients are given as follows:

	OFHC S-Band Waveguide	10-Foot Accel. Sec.
Change in phase with temperature	0.0144°/deg.F	10°/deg.F.
Change in phase with frequency	0.53°/mc foot	0.35°/kc

Evacuation of the network during tuning eliminates the dielectric effects of air and water vapor and subjects the waveguide to the deformation resulting from atmospheric pressure. It is apparent from the above table that careful control is required to maintain the total phase length of any one path constant. However, the differences in phase lengths are the quantities of interest and are to first order sensitive only to temperature differences from section to section and differences in rectangular waveguide branch lengths, which at most is about 15 feet. Also, in practice other factors minimize the possible errors, such as the thermal inertia of the various copper masses. Indeed, the phase is observed to vary by a degree or so over periods greater than twenty seconds or so, but a phase comparison between the various branches can easily be made in less than ten seconds when all the brances have been adjusted to nearly the same length. The temperature of the accelerator and the waveguide feed system is maintained at 113.0° ± 0.1°F by a temperature regulated water system.

Modulator Flange

The unit consists of a diode+ switch mounted in a special male-female flange* (Fig. 4) that is sandwiched in between the output port of a 10-foot accelerator section and its high power load (see Fig. 1). The diode is spring loaded on a post which connects through a TNC fitting in the flange to a 1 kc switched bias power supply. The post and the two vacuum-tight, adjustable, matching screws are sealed with teflon O-rings. The switching characteristics of this type of configuration are discussed at length in the literature.[8,9] Forward biasing the diode causes the equivalent circuit of the modulator to be that of a large shunt impedance which results in little reflection. Reverse biasing causes a resonant impedance of low value, which results in a large reflection. Generally, one is not concerned with the phase of the reflected signal; however, in this case it is very important, especially since 6% to 15% of the voltage is reflected during the transmitting state and 90% to 96% during the reflecting state. It is found that the position of the tuning screws has

+ The diodes we have used are Philco type L4133.

*This is a modification of the waveguide vacuum flange designed by K. Skarpaas for use throughout the SLAC machine.

very little effect on the phase of the reflected wave when the diode is reverse biased. When the diode is forward biased, the tuning screws can be adjusted so that the small reflected wave is in phase with the reflected wave that results from reverse biasing. Thus, the effective positions of the reflection planes can be adjusted to be in the same place for a set of four flange modulators.

The phase versus bias voltage characteristics of the switch are non-linear; thus, in order to simplify the design and tuning procedure, square wave modulation is used to switch the diode from a reflecting to a transmitting state. The square wave generator alternately applies -20V and +100ma to the diode.

Results and Conclusions

To date, this sytem has been used to adjust the approximately thirty waveguide networks feeding 1200 feet of accelerator. A sample network was checked after adjustment using an independent method.[10] The results, limited by the relative inaccuracy of the checking technique, showed a maximum possible disagreement of 3 degrees. Preliminary testing with a beam on the first 600 feet of the machine[11] demonstrated that no errors resulted from the possible phase ambiguities described above.

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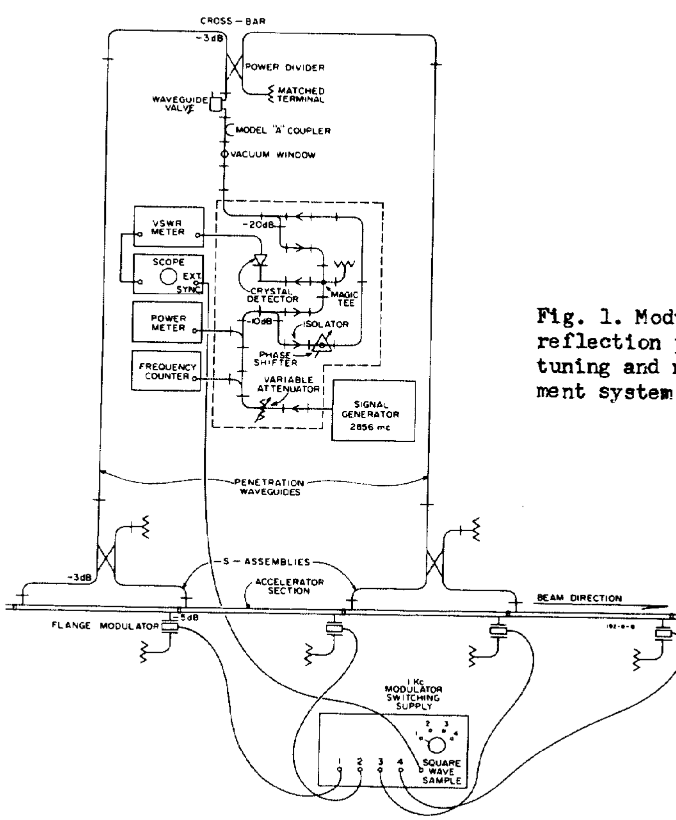

Fig. 1. Modulated - reflection phase tuning and measurement system.

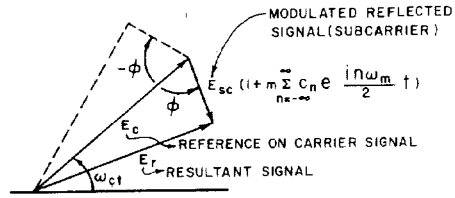

FIGURE 2 VECTOR DIAGRAM SHOWING THE ADDITION OF THE REFERENCE AND REFLECTED SIGNALS. THE PHASE DIFFERENCE BETWEEN THE TWO IS $180° + \phi$. E_r WILL HAVE NO AMPLITUDE MODULATION WHEN $\cos\phi = \frac{E_{sc}}{E_c}$.

Fig. 2. Vector diagram showing the addition of the reference and reflected signals. The phase difference between the two is $180° + \phi$. E_r will have no amplitude modulation when $\cos\phi = \frac{E_{sc}}{E_c}$.

Fig. 3. Prototype test console and waveguide in Klystron Gallery.

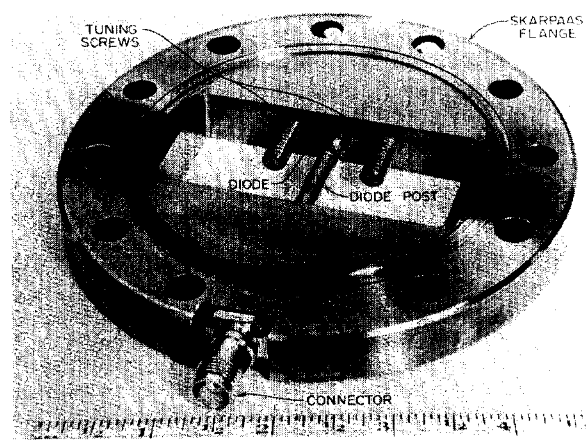

Fig. 4. Modulator Flange.