IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

THE RF REFERENCE LINE FOR PEP*

H. D. Schwarz and J. N. Weaver†

Summary

A RF phase reference line in 6 segments around the 2200 meter circumference PEP storage ring is described. Each segment of the reference line is phase stabilized by its own independent feedback system, which uses an amplitude modulated reflection from the end of each line. The modulation is kept small and decoupled from the next segment to avoid cross-talk and significant modulation of the RF drive signal. An error evaluation of the system is made. The technical implementation and prototype performance are described. Prototype tests indicate that the phase error around the ring can be held below 1 degree with this relatively simple system.

Introduction

The RF system for the PEP storage ring will be operated at a nominal frequency of 353.210 MHz, which will be produced by a master oscillator. From this master oscillator RF drive signals will be provided for each of the 12 RF stations, which are located in three groups approximately equally spaced around the hexagonal storage ring. In addition, at three in between points, a RF signal is required as a timing reference for the experiments. These requirements suggest a two-armed reference line with each arm consisting of three line segments in series as shown in Fig. 1. Each line segment is approximately 400 meters long and is installed in the same tunnel as the beam line. Each end of each segment is brought up to stations accessible to personnel during storage ring operation.

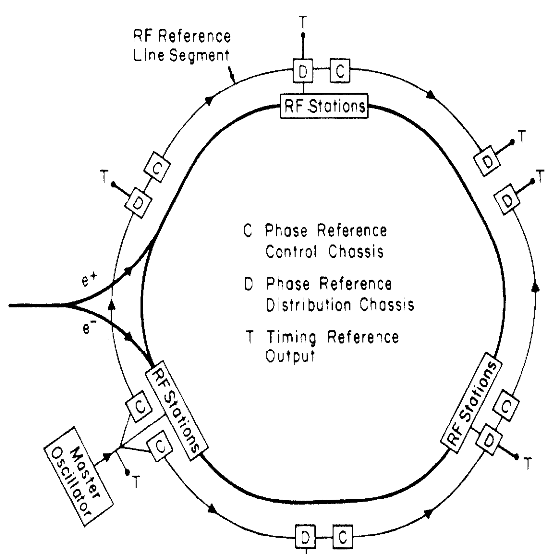

Fig. 1. PEP RF reference line layout.

The phase of the drive signal at each of the RF stations must be stable to within ±1 degree with reference to the master oscillator signal. Since the electrical length of a coax line at a fixed RF frequency is influenced by ambient temperature, humidity and barometric pressure, special techniques are necessary to stabilize it. One can utilize a controlled thermal and atmospheric environment, which is very expensive, but necessary when many reference outputs along the line are required. The reference line for the two-mile Stanford Linear Accelerator was built using this technique. For the larger uninterrupted runs around the PEP storage ring a less costly electronic feedback technique can be used. This technique, which is described in some detail in this paper, is based upon a phase comparison between a modulated reflection from the end of a line segment and a sample of the input signal to that same line segment. A detected change in phase between the two signals causes a phase shifter in series with the line to compensate for it. The phase detector consists of a detector diode which indicates a null in the amplitude modulation of the resultant signal, when the two compared signals are approximately in quadrature and the modulated reflection is small compared to the input reference signal. This method of phase measurement was first described by S. D. Robertson,[1] later modified by G. E. Schafer[2] and used for a variety of applications (Refs. 3,4).

Description of a Reference Line Segment

All the elements of one segment of the phase reference line are shown in Fig. 2. The reference signal at a level of +15 dBm enters on the left through an isolating attenuator A1. In the following 3 dB hybrid, HY1, a portion of the signal is separated out to be used as a reference for the phase comparison. The main signal travels through the reference line and a feedback phase shifter into another 3 dB hybrid, HY2, where half of the signal is coupled out for further use. The other half of the signal is attenuated by 10 dB (A3) and a small fraction of it is then reflected after it has been sine-wave, amplitude modulated at an audio frequency by a PIN diode modulator. This modulated signal then returns back through A3, HY2, and the reference line and is coupled out and added to a portion of the CW input reference signal in HY1. According to the theory outlined in Schafer's paper[2] the vector resulting from the addition shows no amplitude modulation at the modulation frequency, if the two signals are approximately 90° apart in phase and the modulated signal is very small compared to the reference signal; i.e., the vector diagram describes an isosceles triangle. To detect the null in the amplitude of the modulation the combined RF signals are amplified and rectified in a RF peak detector. The amplitude modulation on the detected signal is then filtered and converted to a dc error signal with a synchronous detector, consisting of a sample-hold circuit gated by the same oscillator that modulates the reflection at the end of the line segment. The dc error signal, after being amplified by an amplifier with a high dc gain and a very slow response time, is fed to an electronic phase shifter in series with the reference line, thus closing the loop to keep the total phase length of the reference line between HY1 and HY2 constant. Components outside the feedback loop at the end of the line include a phase stable linear RF amplifier and various power dividers to provide drive signals for the next reference line segment and the RF stations.

Design Considerations

The main sources of error within the feedback loop are reflections with varying phase angle. In order for these not to change the phase of any of the signals

---
*Work supported by the Department of Energy under contract no. EY-76-C-03-0515.

†Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305.

0018-9499/79/0600-3956$00.75 © 1979 IEEE

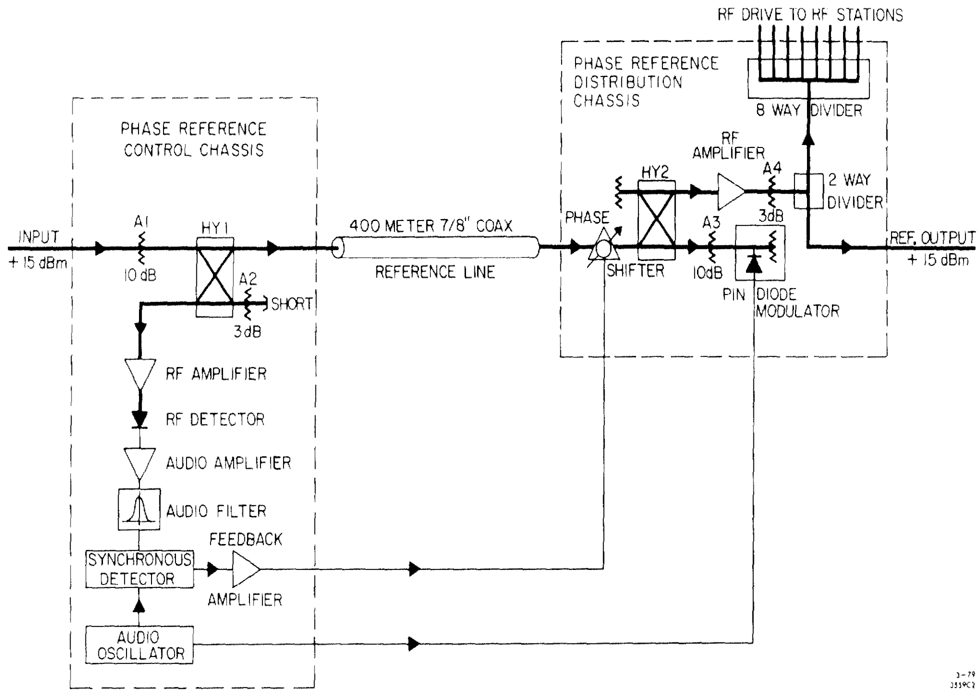

Fig. 2. RF reference line segment.

compared in the detector by more than 1/2 degrees, they have to be -40 dB or less in amplitude. One device which produces a phase variable reflection as big as -20 dB from its incident signal is the feedback phase shifter. It therefore is placed at the output end of the reference line in order to buffer the phase shifter's effect by twice the cable attenuation or a total of approximately 20 dB. All other reflections should be fixed in phase or if they are at the far end of the cable should be attenuated enough to have no significant effect.

Two more areas of concern are the noise in the system and modulation on the outputs of the reference line. The noise aggravated by a total feedback gain of almost 10^8 is held within limits by using a band pass filter at the modulation frequency with a 1% bandwidth, a synchronous detector and a RC-network at the feedback amplifier with a time constant of 880 s.

The modulation on the output of the reference line must have no deleterious effect on the beam in the storage ring. This is the dominant requirement for the determination of the amplitude of the modulated reflection, since the limited isolation of nominally 26 dB of the 3 dB hybrid (HY2) allows a fraction of the modulated reflection to be coupled to the output. Depending on the phase, with which this signal adds to the main output signal, the resulting output signal is amplitude or phase modulated or both.

For design purpose a modulation level on the output signal of less than -60 dB was considered tolerable. In addition to this criterion the modulation frequency was chosen to be less than 1 kHz in order not to excite synchrotron oscillations of the stored beam, which occur above 1 kHz. Interaction between different segments of the reference line is avoided by choosing slightly different modulation frequencies for each line segment in the range of 550 to 850 Hz.

Component Description

A phase-stabilized, 7/8 inch, foam-dielectric, coaxial cable (Heliax[5], Type LDF5-50) was chosen for the six reference line segments. The phase-temperature coefficient of the cable is 7 ppm/°C as quoted by the manufacturer, which corresponds to a phase-temperature coefficient of 1.4 degrees/°C for a 400 meter length at 353.21 MHz. The attenuation is 2.7 dB/100 meter.

The RF linear amplifiers are commercially available thin film hybrid amplifiers (TRW Type CA2870) with a maximum output power of 500 mW and a nominal gain of 33 dB. The phase shift due to variations in power level or temperature is negligible.

The SLAC designed and built phase shifter[6] uses two varactor diodes (IN5461A) and a 3 dB hybrid in a microstrip configuration. The unit is capable of a 0 to 180 degree phase shift with a 0 to +10 V control voltage. The voltage-phase response is almost linear over the above range and the phase-temperature coefficient is less than 0.04 degrees/°C. The same phase shifter design is used for all other phase shifter applications in the PEP RF system, in particular in the phase locked loops around the klystron-waveguide-RF cavity networks.

The PIN diode modulator consists of a PIN diode (HP5082-3040) shunted across a terminated microstrip line. The diode is biased and modulated to produce a small reflection, approximately -18 dB with an amplitude modulation index of 0.5.

The RF detector utilizes a hot carrier diode (HP5082-2800) which charges the capacitor of a RC-network to the peak of the RF voltage swing. The time constant of the RC-network is selected so that the voltage on the capacitor will follow the audio modulation on the RF voltage. The RF detector, with a 200 mW RF input signal, produces approximately a 5 V dc output voltage. If the phase shifter is manually set at 45° away from a phase detector null, the audio modulation superimposed on the RF detector's dc output is on the order of 5 mV peak.

The audio amplifier following the RF detector has a voltage gain of 100. The audio filter uses an active filter (Burr Brown UAF 31) with a voltage gain of 50 and a Q of 100. The audio signal is then rectified by the synchronous detector, which consists of a sample-hold amplifier gated by a 14 μs sampling pulse from the audio oscillator. The feedback amplifier has a voltage gain of 500 and also contains a RC-network with a time constant of 880 s. The audio oscillator is a precision quadrature oscillator (Burr Brown 4423) with external frequency adjustment capability.

All other components are commercially available coaxial devices and have no special requirements.

Test Results of a Prototype Line

A test model of the system was built and tested using a 70 meter length of RG214 coax cable as a reference line. This cable has about the same attenuation as the planned reference line, but a much higher phase-temperature coefficient of approximately 15 degrees/^{o}C. The system was operated with this cable in the laboratory where the ambient temperature changed by 5^{o}C. It was established using other test equipment that the prototype system's phase length varied less than ±.5 degrees. The phase noise on the output to the RF stations and the next reference line segment was less than 0.01 degree. The peak amplitude of the audio modulation on the output was measured to be a factor of 3000 down from the output signal, which is on the order of -70 dB.

Acknowledgments

The authors wish to thank J.-L. Pellegrin for his suggestions and helpful discussions.

References

1. S. D. Robertson, "A Method of Measuring Phase at Microwave Frequencies," Bell Sys. Tech. J. 28, 99-103 (1949).

2. G. E. Schafer, "A Modulated Subcarrier Technique of Measuring Microwave Phase Shifts," IRE Trans. I-9, 217-219 (1960).

3. G. Swarup and K. S. Yang, "Phase Adjustments of Large Antennas," IRE Trans. AP-9, 75-81 (1961).

4. J. Weaver and R. Alvarez, "Accurate Phase Length Measurements of Large Microwave Networks," IEEE Trans. MTT-14, 623-9 (1966).

5. A trademark of Andrew Corporation, Orland Park, Illinois, U.S.A. 60482.

6. H. Schwarz, Stanford Linear Accelerator Center technical note, PEP-283 (1979) (unpublished).