9

THE DRIVE SYSTEM

Z. D. Farkas, C. J. Kruse, G. A. Loew, Editor, and R. A. McConnell

When the operation of a multisection linear accelerator is considered, among the first images to come to mind is that of an array of klystrons and accelerator sections, all working in phase synchronism so that the electron bunches which pass through the accelerator are always on the crests of the traveling wave. This desired situation is provided by the combination of the drive system and the phasing system. Although these two systems are closely intertwined, they are described in separate chapters. The drive system is the subject of this chapter, the phasing system is described in Chapter 12.

9-1 Introduction (GAL)

Three basic requirements were originally placed on the RF drive system for the accelerator klystrons:

1. A drive signal of at least 240 W had to be supplied to each 24-MW klystron.
2. The RF phase of the drive signal to each of these klystrons had to be adjustable so that the traveling RF wave crests in the accelerator and the electron bunches could be made to coincide within $\pm 5°$. This phase relationship had to be preserved in the presence of environmental changes.
3. The phase relationship had to be maintained over a tuning range of ± 0.1 MHz centered around 2856 MHz.

The system which was built to meet these power and frequency stability requirements is the "drive system," the subject of this chapter. The system which actually determines the phase of the electron bunches and automatically optimizes the RF phase of each drive signal is called the "automatic phasing system," which is described in Chapter 12.

In this introduction, the origin of the above basic requirements will be explained, alternative design approaches will be briefly reviewed, and the overall system which was ultimately built and put into operation will be outlined.

The minimum drive requirement for each 24-MW klystron was dictated by the need to operate each tube at saturation.[1] The input power required to do this was specified at 240 W. In order to operate with a comfortable safety margin, the corresponding specification imposed on the drive system was 1 kW per high-power klystron. In addition, it appeared desirable from the beginning to design a system capable of operating under Stage II conditions, i.e., driving as many as 960 high-power klystrons.

For maximum energy gain, the electron bunches in the accelerator must ride on the RF wave crests. There are several reasons why this condition may not be fulfilled, such as incorrect initial phasing, asynchronism of the RF wave with the electrons caused by incorrect frequency or incorrect accelerator temperature, and poor bunching.

To start out, assuming perfect synchronism, the accuracy to which the klystrons must be phased depends upon how closely one expects the output energy to approach the ultimate performance level (perfect phasing). The total electron energy V_T is the sum of the individual contributions of the N accelerator sections,* i.e.,

$$V_T = \sum_{0}^{N} V_n \cos \theta_n \tag{9-1}$$

where V_n is the maximum possible energy gain for a given RF power input, and θ_n is the relative phase angle between the electrons and the wave crests in section n. For small values of θ_n and equal values of V per section, Eq. (9-1) may be written

$$V_T = VN[1 - \tfrac{1}{2}\overline{\theta^2}] \tag{9-2}$$

where $\overline{\theta^2}$ is the average value of θ_n^2. Thus, for the accelerator energy to attain 99.5% of its maximum value, it is necessary that $\theta = 0.1$ rad (approximately 5°). This goal was the origin of the $\pm 5°$ specification on phasing accuracy.

Even in the case of perfect initial phasing ($\theta = 0$), it is possible for a drift or slippage between the RF wave crests and the electron bunches to take place within a 10-ft accelerator section. This slippage occurs either when the entire accelerator is at a single temperature but the frequency is incorrect (asynchronous case) or when the temperature differs from section to section, resulting in deviations of the phase velocity from the velocity of light. The latter condition can occur when different sectors operate at different repetition rates and the constant temperature cooling water causes them to stabilize to different copper temperatures. For the 10-ft constant-gradient section, it can

* This calculation assumes that the four-way rectangular waveguide split introduces no systematic differential phase shifts. For a further discussion of the phase shifts in the rectangular waveguide, see Chapter 11.

be shown that a temperature error of 2°C is equivalent to a frequency error of 0.1 MHz or a maximum slippage of 31 electrical degrees. The resulting energy loss is of the order of 1.5%. In the Stage I configuration, it has been found that the maximum energy dissipated per accelerator section is of the order of 5 kW average, which results in a temperature excursion of slightly over 2°C from maximum to zero repetition rate. In a practical operating case, the differences are less severe, and any frequency averaging or adjustment is less than 0.1 MHz. However, to be prepared for larger power and temperature excursions which would be encountered under Stage II operation, it was decided that the drive system should be capable of frequency adjustment over the range of 2856 ± 0.1 MHz. In turn, for such frequency adjustments to result in measurable energy increases without having to rephase the entire accelerator, the frequency change δf necessary to eliminate a phase slippage $\delta\theta$ within each accelerator section must cause only a negligible phase slippage $\delta\phi$ of the wave along the 2-mile long drive system. This condition must be satisfied because for small angles the change in beam energy varies as the square of the phase shift whether the phase shift occurs in the accelerator sections ($\delta\theta$) or in the transmission line ($\delta\phi$). To assure that frequency and phase adjustments remain essentially orthogonal, it is necessary that

$$(\delta\phi)^2 \ll (\delta\theta)^2$$

As has been shown in Chapter 6,

$$\frac{\delta\theta}{(\delta f/f)} = 8.5 \times 10^5 \text{ deg}$$

Hence, $\delta\phi/(\delta f/f)$ has to be negligible in comparison with this number to meet the third basic requirement of the drive system. Because, as will be seen below, this requirement puts severe restrictions on the allowable group delay deviation from an ideal TEM line, an arbitrary upper limit of $\delta\phi = 1$ electrical degree was chosen for $\delta f = \pm 0.1$ MHz.

The problem of imperfect bunching and the associated problems of energy spectrum width and phase closure are discussed elsewhere (Chapters 8 and 12).

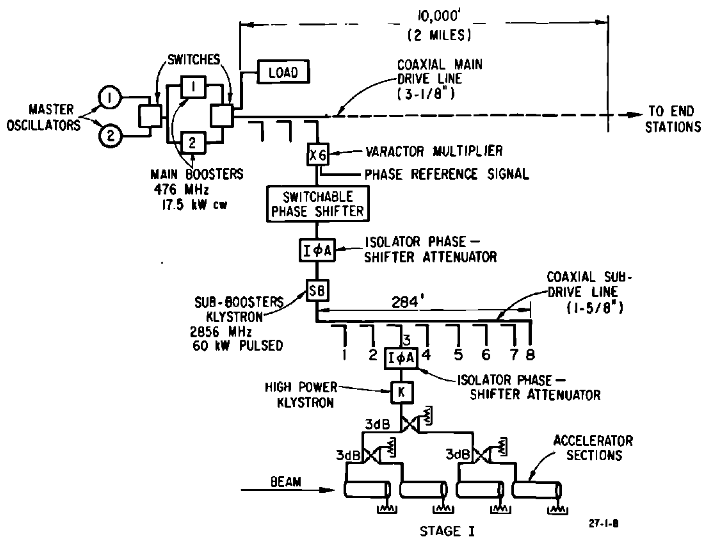
Turning now to the various design approaches which were examined on the basis of the above requirements, it should be noted that work on this system was started in 1958 so that design and engineering had time to evolve through many cycles. A good summary of early ideas can be found in Reference 2. The order in which decisions were made was as follows. First, one had to consider the choice of a main drive line.[3–6] In earlier accelerators, standard rectangular waveguides had been used. However, S-band waveguide was rejected primarily because of its low group velocity ($\delta\phi = 162°$ in a 2-mile length for $\delta f = 0.1$ MHz), but also because of its high attenuation (64 dB for 2 miles) and expensive temperature control requirements. Several types of L-band size waveguides were then considered. For example, a TE_{01} circular waveguide with a 65 cm diameter results in a phase shift error of

10° (for $\delta f = 0.1$ MHz) and an attenuation of 0.12 dB for two miles. However, these special waveguides were rejected for many reasons: their cost, including couplers, would have been 10 times as high as those for coaxial lines; the prevention of cross-sectional expansions would have required very careful temperature control; multimoding would have been difficult to suppress; and finally, the mechanical complications caused by size and weight would have been prohibitive. Point-to-point communication in air was considered but rejected because of the number and cost of antennas and receivers, phase shift problems, and overall noise. Similar difficulties and the status of technology at the time weighed against a modulated laser system with numerous demodulators, one at each feed point. In contrast, a coaxial line system appeared much more appealing. The only major obstacle seemed to be the inherent attenuation (over 100 dB for 2 miles at 2856 MHz for a $1\frac{5}{8}$-in. line). This obstacle could have been surmounted by using a number of booster amplifiers along the way, but overall reliability of the system would have suffered. The timely advent of reliable, high-efficiency varactor multipliers led to the idea of transmitting the main drive signal at a subharmonic of the accelerator frequency. Both the twenty-fourth (119 MHz) and the sixth (476 MHz) subharmonics were considered. The lower attenuation favored 119 MHz, whereas the smaller number of multiplier stages with the reduction of their inherent phase instabilities weighed in favor of 476 MHz.

The drive system which was finally arrived at is shown in Fig. 9-1, and consists of the following subsystems:

1. One on-line "master oscillator" tunable within 476 ± 0.017 MHz, with a second switchable unit on standby for reliability purposes.

Figure 9-1 RF drive system.



2. One on-line "main booster" which amplifies the signal from the master oscillator to a level of 17.5-kW cw, with a second switchable unit on standby, also for reliability purposes.
3. A 2-mile long, $3\frac{1}{8}$-in. diameter, coaxial drive line which transmits this cw signal at 476 MHz over a 2-mile length from the injector end to the experimental end-station areas, and includes thirty coupling points to supply 4 W of cw power to each of the thirty sectors.
4. For each sector (a) a varactor multiplier unit which multiplies the 476-MHz signal by 6 to 2856 MHz, the operating frequency of the accelerator, (b) an "isolator, phase shifter, attenuator" unit ($I\phi A$) which controls the signal at the output of each varactor multiplier, and a switchable phase shifter capable of introducing a predetermined phase shift for positron acceleration or electron deceleration on a pulse-to-pulse basis, (c) a pulsed sub-booster which amplifies the cw signal from the varactor multiplier to a 60-kW, 2.5-μsec pulse with a repetition rate of 360 pulse pairs*/sec, (d) a $1\frac{5}{8}$-in. diameter coaxial drive line with eight coupling points along its length to supply each of the eight 24-MW klystrons in a sector.
5. At each coupling point, a cable with high phase stability feeding an $I\phi A$ unit (which controls the drive signal to each 24-MW klystron), followed by another cable to the input of the klystron.

Each of these subsystems will be described in the following sections. A summary of operating experience to date is given at the end of each section.

9-2 The master oscillator (RAM)

Function and specifications

The master oscillator is the starting point and frequency standard of the RF drive system. The specifications of the master oscillator are summarized in Table 9-1.

Table 9-1 Summary of master oscillator specifications

Output frequency	476 MHz
Output power	0–8 W
Tuning range	±16.7 kHz
Frequency stability	±50 Hz/hour; ±200 Hz/day
Harmonic and spurious frequency suppression	60 dB
Amplitude Stability	±0.2 dB/24 hours; ±0.5 dB/week.

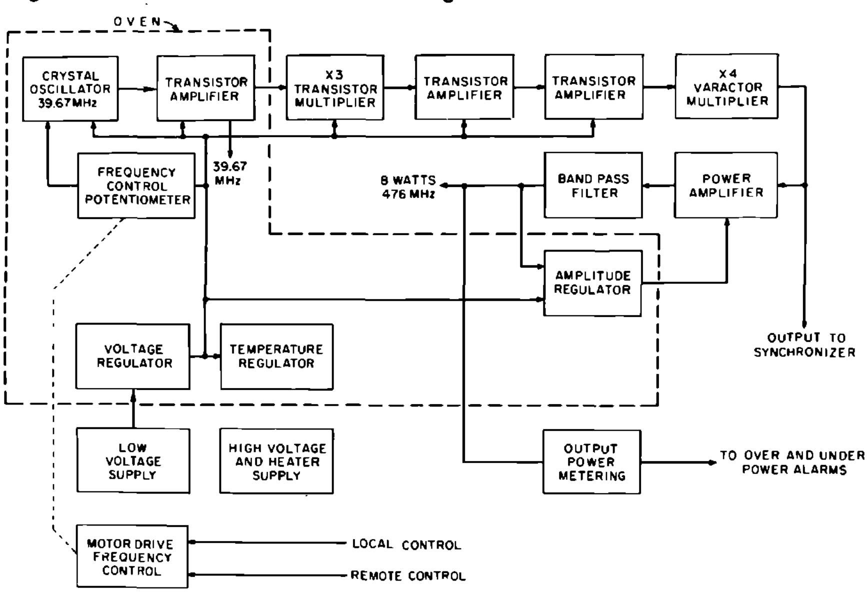
* The reason for using pairs of pulses is explained later in this chapter, in the section on the sub-booster klystron and its modulator.

The output power was chosen so as to provide at least 2W to each of the two klystron amplifiers driven by the master oscillator, with ample margin for losses in the division and distribution of the master oscillator power. The tunability requirement was chosen to provide ±100 kHz tuning range at 2856 MHz. It is imposed by the necessity of tracking accelerator temperature variations in order to maintain the phase velocity equal to the speed of light. The stability specification on the master oscillator was chosen to reduce random frequency variations below the level at which they could affect the operation of the accelerator. Harmonic and spurious signal generation specifications were also low enough to have negligible effect on accelerator operation. This point is discussed in detail below. Amplitude stability requirements were such that the drive level to the subsequent amplifiers would be kept well within the saturation region, maintaining maximum amplitude stability throughout the entire drive system. As will be seen in the discussion of the frequency multipliers, small amplitude variations at the frequency multiplier inputs are converted to large phase excursions at the outputs.

Design

The master oscillator consists of a crystal oscillator at 39.67 MHz, followed by a multiplier–amplifier chain and a vacuum tube power amplifier with an output of 8W at 476 MHz. With the exception of the power amplifier, the entire unit is solid state. In addition, there is an electronic frequency control

Figure 9-2 Master oscillator block diagram.



system, an amplitude regulation system, an oven in which the crystal oscillator is housed, a low-level 39.67 MHz output to drive the "beam knockout" deflector in the beam injector system, and regulated high- and low-voltage dc power supplies. The frequency can be changed either at the master oscillator or from the accelerator central control room. Over–under power alarms are provided locally and at the central control room. A block diagram of the master oscillator is given in Fig. 9-2.

The frequency stability of this oscillator, when combined with a tunability of ± 16.7 kHz, is somewhat above average. The crystal used is of the third overtone type with the crystal in the series resonant mode. A varactor diode in parallel with the oscillator collector tank circuit provides ± 1.5 kHz tuning around the crystal frequency of 39.67 MHz by means of a regulated voltage applied to the varactor through a motor-driven potentiometer. Long-term stability is obtained by enclosing the crystal oscillator and the operating and tuning voltage-supply regulator in an oven which stabilizes the temperature to better than ± 0.1°C.

The requirement for suppression of spurious emission was determined from the following considerations.

Suppose that a maximum deviation of 5° is allowed between the electron bunch in the accelerator and the RF wave crest. Let the master oscillator be phase-modulated by a small noise signal. At some time the phase of the carrier will be displaced from its proper position by an angle θ. Then

$$\tan \theta = \frac{e_1 + e_2}{e} \tag{9-3}$$

where e_1 and e_2 are the upper and lower side-bands and e is the carrier.

Since phase angles are multiplied in the frequency multiplication process, the angle θ at the 476 MHz must be one-sixth that at 2856 MHz, or 0.83°. Assuming e_1 equal to e_2, one finds $e_1/e = 0.0073$. In this case, a side-band suppression of 42.8 dB at 476 MHz is required.

The above analysis disregards higher-order phase modulation side-bands, but these can be shown to be negligible for small phase modulation indices.

With 60 dB suppression at 476 MHz, as specified for the master oscillator, the phase deviation contribution of the master oscillator is 0.7°.

Additional features

Since the master oscillator is an indispensable part of the accelerator RF drive system, a standby unit has been provided for use in the event of failure of the on-line unit. A frequency locking system causes the standby oscillator to track the frequency of the active unit. In case of failure, the standby unit is automatically switched in, remaining on the last frequency of the failed unit until it is retuned by the accelerator operator. In addition, either oscillator can be selected manually from the central control room.

A direct reading counter is provided locally for each master oscillator, so that a continuous watch may be maintained on frequency stability and tracking. In addition, a direct reading counter is installed in the central control room. A small sample of RF from the main drive line in Sector 28 is multiplied to 2856 MHz and applied to the counter. Thus the operator reads the actual accelerator operating frequency, which is more meaningful to him than the main drive line frequency.

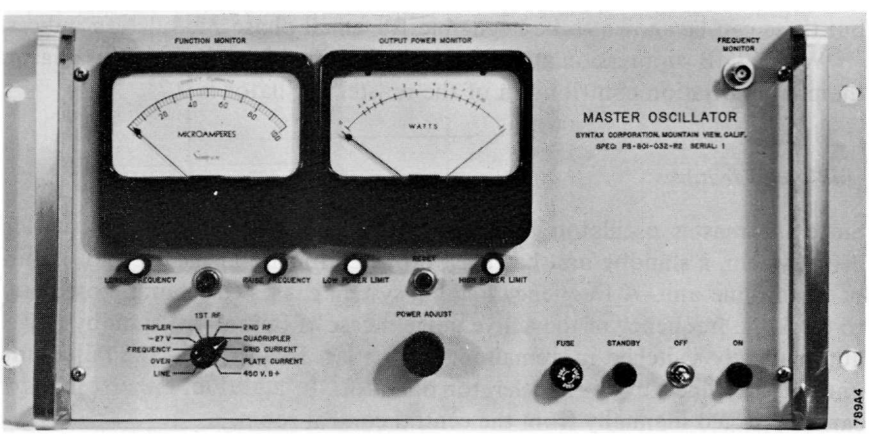
Physical description

The master oscillator is built on a standard rack mounting panel, 19 in. wide by $8\frac{3}{4}$ in. high. The weight is approximately 40 lb. One front panel meter with a selector switch monitors critical voltages and currents within the unit. A second meter displays output power level, and meter relays on this instrument provide switching signals in the event of over- or underpower output. Front panel controls include an on–off standby switch, a power adjustment, a frequency control, and a meter relay reset switch. Figure 9-3 is a photograph of the unit.

Performance

After initial shakedown difficulties, there have been only minor problems with the master oscillators. Since the drive requirements of the klystron amplifiers fed by the master oscillator turned out to be substantially lower than anticipated, it has been possible to reduce the master oscillator output power to 4 W, and the resulting life of the final amplifier tube (an Amperex 5894) is now in excess of 10,000 hours. The power reduction has also improved amplitude stability. The frequency stability specification has been easily met, with typical frequency drifts being on the order of 100 Hz/week.

Figure 9-3 Master oscillator.



9-3 The main booster amplifier (RAM)

Function and specifications

The function of the main booster is to amplify the output of the master oscillator from several watts to 17.5 kW for delivery to the main drive line.

The output power of 17.5 kW was selected to allow approximately 4 W to be extracted from the main drive line at each of thirty sectors with couplers having no closer coupling than 10 dB, and to permit about 50 W to be received at the far end of the 2-mile main drive line for distribution into the end stations.

A stringent output power stability requirement was dictated by the fact that the varactor frequency multipliers driven by the main booster amplifier show substantial amplitude to phase conversion, as was mentioned previously in connection with the master oscillator amplitude stability specification.

Design

The main booster amplifier uses a uhf TV klystron (Eimac 4KM70LA). This tube has four external cavities and a gain greater than 40 dB. It is rated at 17.5-kW cw for SLAC's application. Amplitude stabilization is accomplished through collector voltage regulation by means of a series regulator tube in the collector high-voltage supply. The control grid of the regulator tube (Eimac 4CW50,000) receives a signal which represents the difference between a reference voltage and the output of an RF detector diode coupled to the output of the amplifier. Careful design of the reference voltage source and the following dc amplifiers, and temperature stabilization of the RF detector have made it possible to hold the output power to ± 0.1 dB/week. In the event of failure of the RF detection diode, a backup regulation system is provided in which the high voltage, rather than the rectified RF voltage, is compared to the reference voltage. In addition, the water used to cool both the klystron and regulator tube is stabilized to within a few tenths of a degree centigrade, and the amplifier is operated at saturation.

The amplifier power supply is a conventional three-phase full-wave bridge circuit using solid-state rectifiers.

Cooling is accomplished with deionized water and forced air. The klystron requires 20 gal/min, and the regulator tube 10 gal/min. Water is drawn from the same supply that furnishes water for the 24-MW klystrons. Fans provide cooling for the high-voltage rectifier stacks and the vacuum tubes which are part of the regulator circuit dc amplifiers.

A block diagram of the amplifier is given in Fig. 9-4.

Standby equipment

Like the master oscillator, the main booster amplifier is an indispensable part of the RF drive system. Accordingly, a standby unit is available within seconds

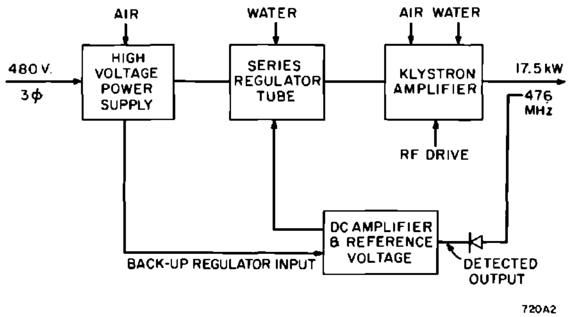


Figure 9-4 Main booster amplifier block diagram.

after a failure of the on-line unit. An automatic switching system removes RF drive from both units, interchanges a dummy load and the main drive line, and returns RF drive to both units. The switching time is determined by a coaxial transfer switch which requires about 2 sec to operate. Rapid switching is necessary in order to prevent the accelerator structure from changing temperature because of the absence of RF power. Further details on the switching system are given in a later section.

Physical description

The main booster amplifier is housed in an enclosure approximately 8 ft high by 4 ft deep by 10 ft long. Important voltages and currents can be monitored on front panel meters. An extensive interlock circuit provides for safe operation, and indicator lights in the interlock chain aid in the location of trouble. Power supplies and the regulator circuit are located in the left-hand portion of the enclosure. The center panel contains metering circuits, while the klystron and cooling systems are located to the right. Figure 9-5 is a photograph of the unit.

Performance

As of July 1967, approximately 28,000 hours of operating time had been accumulated on the main booster amplifiers. Up to that time, there had been four klystron failures, one at 3 hours, one at 2500 hours, one at 3600 hours, and one at 8800 hours.

The high-voltage rectifier stack in one amplifier failed at 4000 hours, possibly because an accumulation of dust and a water leak through the roof of the klystron gallery caused high-voltage breakdown across one of the rectifiers. Changes have been made to prevent recurrence of these faults.

Furthermore, the regulator circuits have been relocated away from the regulator tube, where they were subject to water damage from the regulator tube cooling system.

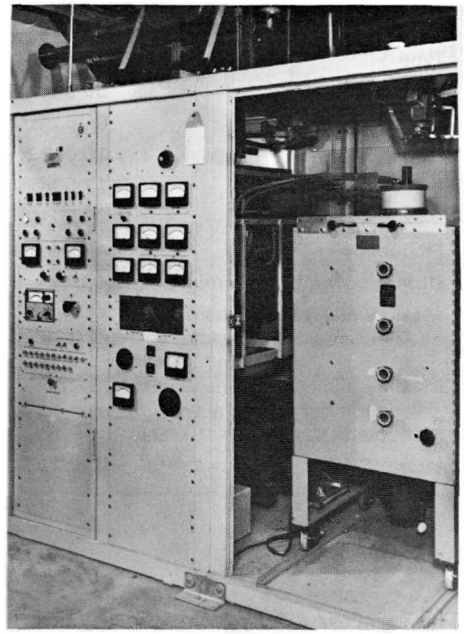


Figure 9-5 Main booster amplifier.

The important specification of amplitude stability has been well maintained, and modifications in the dc amplifier portion of the regulator have further improved amplitude stability.

9-4 Main drive line (ZDF)

Function and specifications

The main drive line transmits the 476 MHz power from the main booster, located in the injector area, to the end of the accelerator. It includes thirty equally spaced couplers to feed 4.1 W of cw power to each of the thirty frequency multipliers, one of which is located at the beginning of each of the thirty sectors that make up the machine. The remaining power, at the end of the main drive line, is transmitted by means of 1200 ft of $\frac{7}{8}$-in. semirigid coaxial line to the end stations.

An extra coupler at Sector 28 provides 1 W for monitoring the power and frequency of the drive signal in the central control room.

In addition, with the aid of multiplexers, the main drive line has the capability of transmitting dc to 100 MHz signals from the injector area to the end stations.

The specifications of the main drive line are summarized in Table 9-2.

Table 9-2 Summary of main drive line specifications

Type	$3\frac{1}{8}$-in. EIA standard copper line
Impedance	50 ohms
Attenuation	0.25 dB/100 ft
Length	10,049 ft
Input power	17.5 kW (cw)
Maximum power	25.0 kW (cw)
Frequency	476 $\pm$ 0.0167 MHz
Output power to each multiplier	4.1 W
Maximum allowable phase variation with frequency	$\pm$0.167° deviation from that of an ideal TEM line of equal length for $\pm$0.0167 MHz.
Maximum allowable phase variation between any two couplers	$\pm$0.167°/24 hours
Input VSWR	1.05 : 1.00

Power input requirements

The varactor multiplier at the beginning of each section has to be driven by 4.1 W at 476 MHz in order to provide enough output power to saturate the sub-booster klystron. This requirement, coupled with the minimum end-station power needs, determines the power input to the main drive line.

The input power required was determined in the following manner:

If a transmission line has N couplers, and each coupler removes P_n watts, then the total input power is the summation from 1 to N of the power from the nth output, multiplied by the attenuation factor from the input to the nth output.

Expressed mathematically

$$P_T = \sum_{1}^{N} P_n r_n \tag{9-4}$$

where P_T is the total input power, P_n is the power output from the nth coupler, and r_n is the attenuation factor from the input to the nth output.

The power input necessary to provide P_o output power at equally spaced coupling points along the line with an attenuation factor r between coupling points is

$$P_T = P_o \frac{r^N - 1}{r - 1} \tag{9-5}$$

This expression led to a required line input power of 8 kW. However, in addition to the couplers feeding each of the thirty sector frequency multipliers, there is a coupler in Sector 1 to drive redundant equipment peculiar to only that sector and an extra coupler in Sector 28 as already mentioned. Finally, it was desired to have about 50 W at the end of the main drive line to be distributed to the end stations. These requirements and a necessary safety factor resulted in setting the input power to the main drive line at 17.5 kW.

Environmental phase stability

Environmental factors affect the phase stability of the main drive line in the following ways:

1. The length varies as a function of temperature.
2. The dielectric constant of the gas inside the lines varies because of changes in the pressure to temperature ratio, that is, in the density, and changes in moisture content.
3. The dielectric constant of the teflon supports for the center conductor changes with temperature. The bulk of the teflon supports was kept low and the effect on phase variations with temperature was found to be negligible.

The total electrical length of the drive line is

$$\phi = \sqrt{\varepsilon_a}\frac{l_a}{c}\omega + \sqrt{\varepsilon_t}\frac{l_t}{c}\omega \tag{9-6}$$

where

ε_a = relative dielectric constant of air
ε_t = relative dielectric constant of teflon center conductor supports
l_a = length of that portion of the line filled with air
l_t = length of that portion of the line filled with teflon
$l = l_a + l_t$ = total length of line

Defining

$$\sqrt{\varepsilon_a} = 1 + \delta_a \qquad \sqrt{\varepsilon_t} = 1 + \delta_t$$

one obtains

$$\phi = \frac{l + l_a\delta_a + l_t\delta_t}{c}\omega = \tau\omega \tag{9-7}$$

where τ is defined as time delay. δ_t has negligible variation, and δ_a is given by[7]

$$\delta_a = 105 \times 10^{-6}\frac{P}{T} \tag{9-8}$$

where P is air pressure in torr and T is air temperature in °K. From Eqs. (9-7) and (9-8) for small δ_a:

$$\frac{d\tau}{\tau} = \frac{dl}{l} + \delta_a\left[\frac{dP}{P} - \frac{dT}{T}\right] \tag{9-9}$$

Table 9-3 Time delay in drive line as a function of air temperature and pressure variations

Initial condition	*760 torr, 80°F*	*760 torr, 112°F*	*10^{-3} torr, 80°F*
δ_a	266×10^{-6}	252×10^{-6}	0.35×10^{-12}
$\frac{d\tau}{\tau}$	-0.492×10^{-6}/°F 18.1×10^{-6}/lb/in.^{2}	-0.440×10^{-6}/°F 17.15×10^{-6}/lb/in.^{2}	-0.648×10^{-12}/°F $0.35 \times 10^{-12}/10^{-3}$ torr
$d\tau$	-4.92 psec/°F 181 psec/lb/in^2	-4.41 psec/°F 171.5 psec/lb/in.^{2}	-0.648 psec/°F 0.35 psec/10^{-3} torr

The relative and absolute changes in time delay for the 2-mile line ($\tau = 10^{-5}$ sec) per unit change in temperature and pressure are given in Table 9-3 for three initial conditions of the air inside the line. The time delay errors are readily converted into phase delay errors since at 2856 MHz they are nearly equal numerically (1 psec = 1.026°).

The relative and absolute changes in time delay because of length variations with temperature are

$$\frac{d\tau}{\tau} = \frac{dl}{l} = 9.7 \times 10^{-6}/°\text{F}$$

$$d\tau = 97 \text{ psec/°F}$$

To control the length variations, all output ports are rigidly anchored to the concrete floor of the klystron gallery.[8] The line is supported on rollers at 10-ft intervals to avoid excessive stresses, and changes in line length are taken up by expansion sections which allow both inner and outer conductors to slide past each other. Thus the length variation, which causes the greatest phase error, is eliminated.

To control the phase shift due to changes in dielectric constant of the gas inside the line, the pressure is maintained constant within ± 0.01 lb/in.^{2}, and the temperature is regulated to within ± 1°F. These variations correspond to phase variations of $\pm 1.81°$ and $\pm 4.92°$, respectively, for the 2-mile line. Dry air is used so that moisture content is not a factor in determining the dielectric constant. If necessary, the phase variation from pressure and temperature effects can be further reduced by partial evacuation of the main drive line, or by filling the line with helium whose relative dielectric constant is one-tenth that of air.

Environmental performance

A portion of main drive line consisting of five sectors was short-circuited at one end, and at the other end the forward and reverse power were sampled with two directional couplers. The outputs of the couplers were fed to a phase bridge to monitor the phase between the forward and reflected signals. The temperature of the line was also monitored.

A three-day continuous test showed the following variations:

Water temperature, 113.2–113.4°F
Water temperature inside insulation, 113.3–114°F
Main drive line temperature near water tracer, 111.5–112.6°F
Main drive line temperature far from water tracer, 110.6–108.0°F
Air temperature inside insulation, 105.5–99.8°F
Gallery temperature, 50–80°F
Phase variation in about 60 hr, ±35° (projected to 2856 MHz and 2 miles)

The above-measured phase variations can be accounted for by the change in dielectric constant of the air in the line as a function of temperature. Normally, as will be discussed in Chapter 12, the entire accelerator is rephased at least once every 24 hours and these variations are automatically compensated for.

Phase frequency response

Since the coincidence of the RF drive signal wave crest and arrival of the electron bunches must be preserved over a tuning range of ±0.1 MHz, and the maximum allowable phase error is 1°, the restriction imposed on the relative group delay of the drive line is as follows[9]: Let ϕ_e be the total phase shift of the beam, ϕ_w the total phase shift of the RF wave, τ_e the total group delay of the beam (beam length divided by beam velocity), and τ_w the total group delay of the RF wave. From the definition of group delay:

$$\delta\phi_e = \tau_e\,\delta\omega, \qquad \delta\phi_w = \tau_w\,\delta\omega \tag{9-10}$$

and the phase error is

$$\delta\phi = \delta\phi_w - \delta\phi_e = \tau_e\left(\frac{\tau_w}{\tau_e} - 1\right)\delta\omega \tag{9-11}$$

The relative group delay of the drive line is related to the phase error tolerance by

$$\frac{\tau_w}{\tau_e} = 1 + \frac{\delta\phi}{2\pi\,\delta f\,\tau_e} \tag{9-12}$$

For an allowable error of $\delta\phi$ of 1°, a time delay τ_e of 10^{-5} sec, and a frequency change δf of ±0.1 MHz, the relative group delay of the wave must fall between 0.997 and 1.003. If the lengths of the beam and wave travel are made identical, the relative group velocity of the RF with respect to the beam,

v_w/v_e, must fall within the same range. The relative group velocity of the beam differs from unity by $1/2\gamma^2$, where γ is the ratio of total mass to the rest mass of the electron. Thus, after the first few feet of acceleration it can be assumed that $v_e = c$.

The relative group delay of the wave is affected by the dielectric loading due to inner conductor supports. These supports slow down the wave and the group velocity is reduced. In addition, the supports present periodic discontinuities along the line. The reflection from the discontinuities may increase or decrease group delay. Of these two effects, the larger is dielectric loading which adds a delay on the order of 2 psec/ft. The reflections add a relative group delay proportional to the product of individual reflection coefficients. The magnitudes of the reflection coefficients are of the order of 0.025 and they add a group delay of ± 0.625 psec/ft. Thus, an additional 2.625 psec/ft is added to the 1000 psec/ft of an ideal line.

Phase frequency performance

The test setup used for the phase-temperature measurements was also used for measuring the phase-frequency response. The frequency was varied around 476 MHz until two successive nulls were obtained from a phase bridge output. A similar measurement was made by bending a sector of main drive line into a U and using a slotted line to monitor the phase of the incident power at each end of the line. The length from the coupling points to the detector probe was made equal, and the frequency was changed around 476 MHz until two successive minima were obtained. The frequency change δf was noted. Using Eq. (9-10), the total group delay was then given by $\tau_w = 1/2\delta f$. The relative group velocity was obtained by measuring l and forming the ratio $(l/\tau_w)/c$. The values obtained were within the specified range.

The measured reduction of beam energy for a 0.1 MHz frequency change is 1.5%. This can be accounted for by considering the slippage of the electrons with respect to the RF wave within individual accelerator sections, indicating that frequency and phase adjustments are essentially orthogonal.

Physical description

The main drive line consists of an assembly of $3\frac{1}{8}$-in.-diameter rigid copper coaxial line sections, each 20 ft, 3 in. long. The sections are joined together with EIA flanges, and directional couplers and expansion sections are fitted at appropriate intervals.

A typical sector consists of sixteen 20-ft-3-in. sections and one 8-ft-4-in. section containing the expansion joint. Section lengths were measured at room temperature and extrapolated to 112°F. As installed and operating at 112°F, the expansion section can contract 1 in. and expand 3 in. Because a sector expands 1 in./25°F, the above limits allow for a temperature range of 112°F(+25°, −75°F).

Because much of the main booster power is dissipated in the first few sections, larger temperature excursions are experienced. To accommodate this, an additional expansion section is fitted in each of the first five sectors.

The first 20-ft section of each sector contains a directional coupler which supplies the input drive to the frequency multiplier. The coupling ratios range from 35.5 dB at the beginning of the drive line to 12 dB at the end.

Drive line extension to end stations

Signals synchronous with the beam bunches are needed in the experimental areas for timing, supplying RF to particle separators, and for other purposes as yet unforeseen. For these reasons the drive line was extended into the end stations. Because of the unavailability of convenient anchor points and the lack of inexpensive means of temperature control, a $\frac{7}{8}$-in. semirigid aluminum coaxial transmission line was used instead of the rigid line. Whenever possible the cables were buried 2 ft underground. Tests showed that the daily temperature variation at that depth is less than a degree centigrade.

The time delay variation with temperature of the semirigid cable is less than that of rigid coaxial line because the linear expansion of the conductors is partially compensated by the expansion of the dielectric support of the inner conductor. The measured variation of time delay with temperature is 0.005 psec/°F/ft. For a length of 1200 ft and an estimated temperature variation of 2°F, a maximum time delay variation of 12 psec can be expected. If this variation should prove excessive, it may be reduced by connecting in series with the line an appropriate length of RG-214/U cable which has a negative coefficient of time delay versus temperature, or by phase-locking the output signal to the beam at a point relatively close to the end stations.

9-5 Subdrive line (ZDF)

Function and specifications

Each of the thirty subdrive lines transmits the 60-kW-peak 2856-MHz power output from the sub-boosters and distributes this power equally to eight 24-MW peak power klystrons. The first seven klystrons are supplied by means of directional couplers. The last one is fed directly by using all the power remaining at the end of the line. A summary of the subdrive line specifications is given in Table 9-4.

Design

Because the length of each subdrive line is one-thirtieth of the length of the main drive line, the restrictions on the relative phase-frequency response and phase-temperature variation per unit length can be relaxed by the same factor.

Table 9-4 Summary of subdrive line specifications

Type	$1\frac{5}{8}$-in. EIA standard copper line
Impedance	50 ohms
Attenuation	1.13 dB/100 ft
Length	284 ft $\pm\frac{1}{2}$ in. at 112°F
Input power	60 kW (peak), 113 W (average)
Maximum power	100 kW (peak), 200 W (average)
Frequency	2856 $\pm$ 0.1 MHz
Output power from each coupler	4 kW (peak), 8 W (average)
Variation of phase with frequency	$\pm$1° deviation from an ideal TEM line of equal length for 0.1 MHz frequency change
Phase stability	$\pm$1°/24 hours
Input VSWR	1.05:1

Expansion sections are not required. With use of Table 9-3 and Eq. (9-10), allowing 1° phase error, the following restrictions are imposed on the subdrive line:

Allowable range of relative group velocity, 0.99–1.01
Temperature stabilization, $\pm$1°F
Pressure stabilization, $\pm$0.1 lb/in.^{2}

These specifications were met.

9-6 The Frequency Multipliers (RAM)

Function and specifications

The function of the frequency multipliers is to multiply the 4.1-W, 476-MHz input power from the main drive line by a factor of 6 to 2856 MHz, and supply approximately 400 mW to drive the sub-booster klystrons. As with most parts of the RF drive system, good phase stability is a prime requirement. At the time the RF drive system was being designed, varactor diode multipliers were quite new and the phase stability properties of such devices were unknown. Consequently, measurement systems had to be devised to determine their capabilities before design work could continue on other major parts of the drive system.

The output power of the multiplier was chosen to be sufficient to provide adequate drive power for the sub-booster klystron and to provide a phase reference signal for the automatic phasing system.

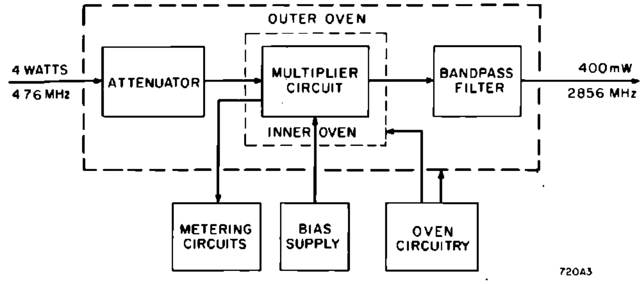


Figure 9-6 Frequency multiplier.

The input power specification was dictated by the efficiency of the multiplier and the output power requirement.

The phase stability specification was chosen on the following basis. The total allowable phase difference between electron bunches and RF wave crests in the accelerator was set at $\pm 5°$. Of this 5°, the frequency multipliers were allowed to contribute 1°. That is, the phase difference between the outputs of a reference multiplier in an invariant environment and a second multiplier subjected to various environmental changes was not to differ by more than $\pm 1°$.

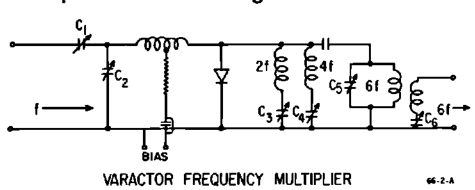
Design

A block diagram of the frequency multiplier is given in Fig. 9-6. The function of the input attenuator is to adjust the input power to the precise value required for maximum phase stability. The double oven maintains the temperature of the multiplier circuit at $68 \pm 0.1°C$. The band-pass filter eliminates spurious outputs, mainly fifth and seventh harmonics of the input frequency. A bias supply rather than a self-biasing circuit is used for two reasons: starting problems are reduced by the use of fixed bias, and it has been found possible to minimize phase shift as a function of drive power by small adjustments of bias.

A simplified diagram of the multiplier RF circuit is given in Fig. 9-7.

Physically, the input circuits are composed of lumped elements, the idler circuits are strip line, and the output circuit is a cavity.

Figure 9-7 Varactor frequency multiplier simplified circuit diagram.



Adjustment

To obtain optimum phase tracking among the thirty-one multipliers used along the accelerator, it was necessary to develop the following technique to ensure that all multipliers were tuned in an identical manner.

Referring to Fig. 9-7, it is convenient to consider C_1, C_2, and the bias voltage as input tuning controls and C_3, C_4, C_5, and C_6 as output tuning controls. Initially, a rough adjustment of all controls is made for maximum output power. Then the input controls are adjusted for minimum reflected input power, and the output controls are adjusted for maximum output power. The above procedure results in a separation of tuning control functions which greatly reduces the time required for tune-up, and also results in multipliers being nearly identically tuned.

Since the capacitance of the varactor diode is a function of applied voltage, it is to be expected that changes in input power to the multiplier will result in changes in tuning, with a resulting phase shift through a single multiplier. When drive power variations occur to two or more multipliers driven in parallel, variations among diodes, circuit Q's, and tuning conditions cause a loss of phase tracking at the multiplier outputs. The tuning technique described above contributed greatly to improvement of the phase tracking and, in addition, it was found that fine adjustments of bias voltage resulted in a minimization of phase shift with drive power. In many cases, the phase tracking between two multipliers could be improved to better than $\pm 0.1°$ for drive power variations of ± 0.1 dB.

Physical description

The frequency multiplier is built behind a standard rack panel, $8\frac{3}{4}$ in. high by 19 in. wide. Front panel controls are limited to a power on–off switch, a screwdriver-adjust attenuator, and a meter function selector switch. The meter monitors line voltage, bias voltage, and input power. A second meter measures output power. Two pilot lights indicate presence of primary power and cycling of the oven heater.

Measurement techniques

Since phase stabilities of better than 1° per week were to be measured, it was necessary to develop phase measuring instruments capable of 0.1° per week stability.[10] A two-detector direct comparison phase bridge, employing a matched magic T and having mechanical and electrical symmetry in both arms, was constructed. The whole structure was built on a heavy pressed-wood table top. Supporting brackets for the waveguide components were placed at frequent intervals. Dowel pins were used to assure proper alignment of all flanges. It was necessary to use coaxial lines at the inputs and outputs of the multipliers. Rigid or semirigid temperature-compensated cables were used in these places. Tunnel diode detectors which required only −15 dBm input and which had better temperature characteristics than crystal diode detectors were used. The detector outputs were combined in a resistive network and fed to a stable dc voltmeter–amplifier–recorder system. Through the use of diode loading and level controls, the detectors were made identical in laws of response and output. As a result, the bridge response to amplitude variations was reduced to a second-order effect. Finally, the whole apparatus was operated in a temperature-controlled room with maximum variations of ±2°F. The result was a phase bridge capable of a stability of better than ±0.01° for measurements requiring only a few minutes, and better than ±0.1° per week.

The bridge was also used in the optimization of phase tracking with drive power changes. About 1% modulation at 500 Hz was applied to the RF source driving two multipliers in parallel. The multipliers themselves caused amplitude-to-phase conversion which was measured at the bridge output with a tuned voltmeter. Very small adjustments in the fixed bias of one multiplier resulted in a minimization of the phase shift between the two multipliers. This was apparently accomplished by shifting the operating point of the diode to a position at which the C–V curves of the two diodes more nearly matched.

Performance

The frequency multipliers have met all their specifications. Phase stability of ±1° between a reference multiplier and all other multipliers has been maintained under the following input and environmental fluctuations simultaneously applied:

Line voltage, ±5%
Temperature, +40° to +120°F
Frequency, ±100 kc (at output)
Drive power, ±0.1 dB

A test period of 1 week was used in all cases.

The diodes are being operated at the upper edge of their power handling capability. Diode life, however, has been good. A number of diodes have been operating with no apparent change in characteristics for more than 15,000 hours. On one occasion the drive power to the multipliers was increased by 1.5 dB because of a failure in the main booster amplifier regulation circuit, resulting in a failure of about half the diodes connected to the main drive line.

An early difficulty was the variation in diode quality resulting in marginal power output. This problem has been solved by closer control of diode characteristics in the manufacturing process.

As more life information has become available, a new problem has appeared. Some diodes exhibit a slow change in characteristics which makes it impossible for a multiplier to meet the input VSWR specifications even after retuning. This condition is at present determining end of life.

9-7 Sub-booster klystron and modulator (CJK)

The sub-booster klystron supplies the subdrive line with 60 kW of pulsed power at 2856 MHz.

In this section only the RF features of the modulator and klystron will be discussed. Details of the modulator electronics will be found in Chapter 13.

Klystron specifications

A summary of the sub-booster klystron specifications is given in Table 9-5.

The output power was designed to be sufficient for Stage II operation, the drive power requirement was based upon the klystron design, and the phase and power stability requirements were determined from the allowable contributions of the sub-booster to the overall phase error in the accelerator.

Physical description of the sub-booster klystrons

The initial complement of sub-booster klystrons was supplied by the Eimac Company and used periodic–permanent magnet focusing, built as an integral part of each tube. Including magnets, the klystrons are approximately 6 in. in diameter, 23 in. long, and weigh 35 lb. The second generation of klystrons was supplied by Litton Industries. These are focused by conventional "barrel" uniform field, permanent magnets, interchangeable from tube to tube. Including the magnets, the tubes are approximately 9 in. in diameter, 23 in. long, and 100 lb in weight. Cooling-water connections are of the Hansen

Table 9-5 Summary of sub-booster klystron specifications

Power output	60 kW (peak)
Drive power	60 mW (cw)
Gain	60 dB
Peak beam voltage	28 kV (maximum)
Pulse length (maximum)	10 μsec
Pulse length (normal)	2.5 μsec
Frequency range	2848–2864 MHz
Efficiency	23.5% (minimum)
Perveance	$\approx 2 \times 10^{-6}$ A/V$^{3/2}$
Allowable phase variations	
pulse-to-pulse	$\pm 0.5°$ (maximum)
during pulse	$\pm 0.5°$ (maximum)
with voltage	0.5°/10 V
Power drift	Less than 0.05%/°C temperature change of inlet water
Phase drift	Less than 0.8°/°C temperature change of inlet water

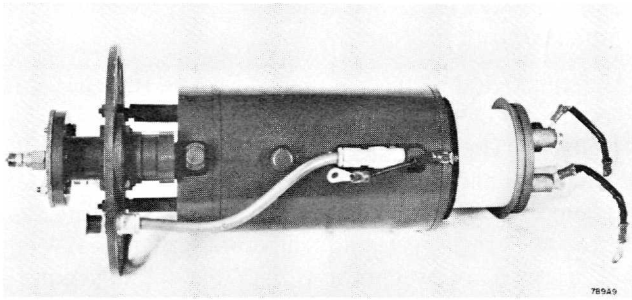


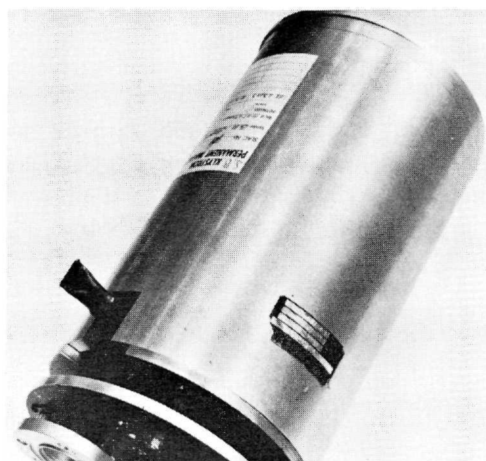
Figure 9-8a Eimac sub-booster klystron.

quick-disconnect type. The klystrons are cooled with deionized water at 113°F. They operate with the isolated cathodes downward and the collectors grounded. The RF input connectors are type N, whereas the outputs are EIA standard $1\frac{5}{8}$ inch. The EIMAC klystron is shown in Fig. 9-8a, and the Litton klystron in Fig. 9-8b.

Sub-booster modulator specifications

A summary of the sub-booster modulator specifications is given in Table 13-8.

Figure 9-8b Litton sub-booster klystron.



Pulse pairing

An explanation of the requirement for pulse pairs is necessary at this time. The sub-booster klystron produces two output pulses separated in time by 20 to 50 μsec. The first pulse is referred to as the accelerating pulse, the second is called the standby pulse. If it is desired to remove a sector from acceleration for phasing, energy control, or maintenance purposes, and yet maintain the sector at normal operating temperature, the 24-MW klystrons of that sector are triggered in synchronism with the standby pulse rather than with the accelerating pulse. Because no beam is present at that time, no acceleration takes place, but the average RF input to the sector and the temperature of the accelerator structure remain constant. In the same manner, a single klystron and its associated accelerator sections can be removed from acceleration and placed on standby.

Provision for longer pulses

Under normal operating conditions, the leading edge of the sub-booster RF pulse occurs about 0.1 μsec after the leading edge of the 24-MW klystron voltage pulse, and the sub-booster pulse is slightly shorter than the 24-MW klystron pulse. Under special operating conditions where, for example, thyratrons within a sector might fire at slightly different delay times, it might be desirable to have a longer RF drive pulse to overlap all 24-MW klystron voltage pulses. For this reason, provision was made to allow operation of the sub-booster klystron and modulator with a voltage pulse length of 3.5 μsec.

Voltage stability requirements

The total phase shift tolerance during a pulse and from pulse to pulse allotted to the sub-booster klystron was $\pm\frac{1}{2}°$. This requirement allowed a corresponding voltage change of $\pm 0.04\%$, as shown by the following derivation.

The phase shift ϕ across a klystron of length L is given by

$$\phi = \frac{\omega}{v} L \tag{9-13}$$

where v is the electron velocity.

Letting V be the klystron beam voltage, e the electron charge, and m its rest mass, and equating the energy supplied to the electron to its gain in kinetic energy, one obtains

$$eV = mc^2[(1 - \beta^2)^{-1/2} - 1] \tag{9-14}$$

where $\beta = v/c$.

Equation (9-14) may be written

$$v = c\left[1 - \left(1 + \frac{eV}{mc^2}\right)^{-2}\right]^{1/2} \tag{9-15}$$

Substituting Eq. (9-15) in Eq. (9-13),

$$\phi = \frac{\omega L}{c}\left[1 - \left(1 + \frac{eV}{mc^2}\right)^{-2}\right]^{-1/2} \tag{9-16}$$

At $V = 26\ kV$ and $eV/mc^2 \approx 0.05$, Eq. (9-16) simplifies to

$$\phi = \omega L(2e/m)^{-1/2}V^{-1/2} \tag{9-17}$$

so that

$$\frac{d\phi}{\phi} = -\frac{1}{2}\frac{dV}{V} \tag{9-18}$$

Substituting the initial parameters for ϕ yields

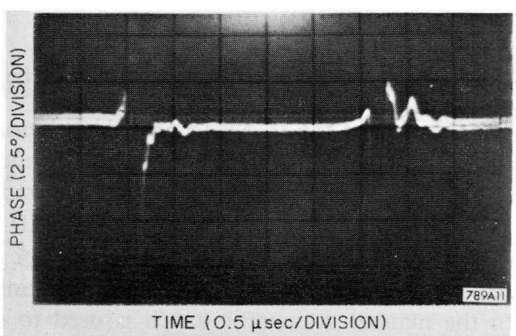
$$d\phi = -180^\circ \frac{L_{cm}}{0.657(V_{kv})^{1/2}} \frac{dV}{V} \tag{9-19}$$

For a voltage V of 26 kV, a length L of 21.2 cm, and a phase excursion of 1°, the total voltage variation permissible across the pulse is 0.088%.

Voltage measurement technique

Tests have shown that the phase variation across the tube from all factors other than beam voltage variation was less than 0.05°. Hence the phase shift across the tube is a very sensitive and accurate method of measuring the voltage droop, ripple, and pulse-to-pulse characteristics of the applied pulse voltage, and a phase measurement was used to verify that the sub-booster modulators met the specifications of ±0.04%, or 22.8 V out of 26 kV peak. The phase bridge was identical to that used in the frequency multiplier phase measurements, with the addition of an oscilloscope for display of the bridge output. Part of the cw input to the sub-booster was coupled into the reference arm of the bridge, while a sample of the pulsed output was fed to the signal arm. Figure 9-9 is a photograph showing the phase-versus-time behavior of

Figure 9-9 Phase versus time in the sub-booster RF pulse.



the RF pulse. The central 5 cm represent that time during which the sub-booster RF pulse is present. The large spikes at the beginning and end of the pulse are indicative of the very large phase excursions that occur during the rise and fall of the voltage pulse. The regions to right and left of the spikes at the edges of the picture represent the time during which only the cw reference signal is present. From Fig. 9-9 it is seen that the sub-booster modulator klystron contributes a negligible amount of phase shift error to the drive system.

Physical description of modulator

The sub-booster modulator is housed in a cabinet 30 in. deep, 72 in. long, and 90 in. high. The sub-booster klystron is mounted within this cabinet. The varactor frequency multiplier and the sub-booster $I\phi A$ unit are installed in two $10\frac{1}{4}$-in. panels in the top of the cabinet.

Performance

A serious shelf life problem became apparent in the early sub-booster klystron procurement program. In general, tubes which were placed in service immediately after delivery performed excellently. However, those stored for several months became gassy and exhibited mechanical detuning. At some times, rejection rates were as high as 50%. Fortunately, the good performance of tubes which were immediately placed in service has eased the situation. For the latter tubes, the MTBF has been greater than 6000 hours.

The sub-booster modulator has proved capable of meeting its stringent voltage stability specifications over long periods of time. Short life on the part of the 4PR1000 switch tubes was initially a problem. The life was improved by the addition of a third such tube to the two in the original design. Later, an improved version of the 4PR1000 was procured, and the life was further increased.

For a more detailed discussion of modulator performance the reader is referred to Chapter 13.

9-8 Isolator, phase shifter, attenuator ($I\phi A$) unit (CJK)

The function of the $I\phi A$ is to provide isolation, phase control and drive level control both to the sub-booster klystrons and to the 24-MW klystrons. The specifications of the $I\phi A$ unit are summarized in Table 9-6.

In the operation of the Stanford Mark III Accelerator it was found that a slow application of RF drive to high-power klystrons upon turn-on greatly reduced the incidence of output window damage. Consequently, in addition to the manual attenuator which is used to set drive level, a "protection"

Table 9-6 Summary of $I\phi A$ specifications

Phase shifter range	0°–360°(+0.0°, −0.5°)
Manual attenuator range	0–25 dB minimum
Protection attenuator range	0–25 dB maximum
Isolation	30 dB minimum
Complete $I\phi A$ unit	
frequency range	2856 ± 0.1 MHz
total insertion loss	3 dB (with attenuators set to minimum attenuation)
Input VSWR	1.1 : 1.0 maximum

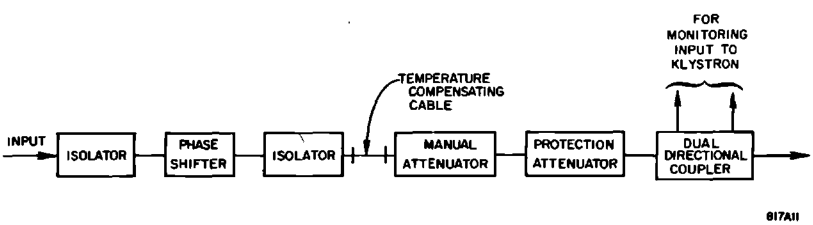
attenuator is included in the $I\phi A$ unit. The protection attenuator can remove drive in 1 to 2 sec and restore drive in 5 to 6 sec.

Isolation was required to prevent reflections from causing phase shifts in the subdrive line. Consideration of coupling ratios and cable attenuation indicated that an isolation of 30 dB was needed.

The design of the automatic phasing system required a phase shifter which could continuously and cumulatively vary in phase starting from any arbitrary setting. The phase shift had to be a linear function of mechanical setting. The Fox phase shifter,[11] of which the SLAC unit is a modification, has these characteristics. It consists of three sections: a launching section, a half-wave phase shifting section, and a receiving section. The launcher takes a coaxial TEM wave and converts it to a circularly polarized wave. The half-wave center section reverses the direction of rotation of the circularly polarized wave. The receiver section then converts it back to a TEM wave. In the launcher and receiver sections, the instantaneous time phases of the TEM waves are linearly related to the instantaneous angular positions of the field vector in the circularly polarized waves. Mechanical rotation of the half-wave center section through an angle δ increases the angle between input and output field vectors by 2δ, and, hence, increases the phase angle between input and output TEM waves by the same amount.

The isolator, the phase shifter, and the two attenuators are packaged as a unit. A block diagram and photograph of the unit are given in Figs. 9-10 and 9-11, respectively, and additional information is given in Chapter 12.

Figure 9-10 Isolator, phase shifter, and attenuator block diagram.



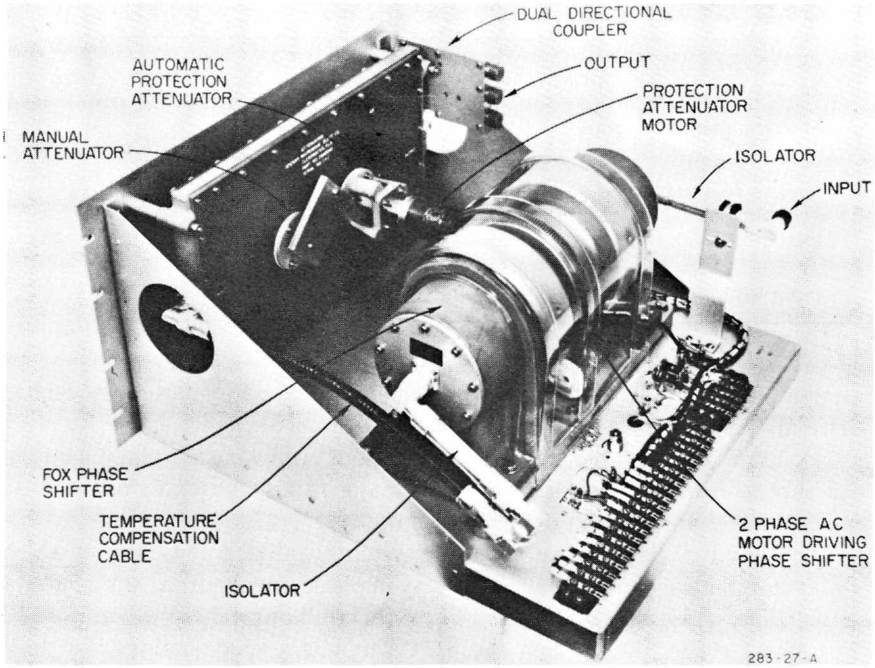


Figure 9-11 Isolator, phase shifter, and attenuator unit.

Switchable phase shifter

For purposes of positron acceleration or electron deceleration, the phase of the RF to each sector can be shifted by a preset amount within the interpulse period.

The switchable phase shifter consists of a three-port switching circulator, an adjustable short circuit, and a transistorized driver which controls the polarity of the current through the circulator control windings, and, hence, the path of the RF through the circulator. One polarity of control current causes the RF to pass directly through the circulator from Port 1 to Port 2. The opposite polarity causes the RF to pass from Port 1 to Port 3. At Port 3 the signal is reflected from an adjustable short circuit and from there out to Port 2. The phase shift of the second path can be set to any desired value by means of the adjustable short circuit. This value is normally in the vicinity of 180° to permit positron acceleration or electron deceleration for multiple beam operation at widely varying energy levels.

9-9 Dropout cables (CJK)

The so-called "dropout" cables are used to interconnect the various components of the system. Since great care was taken to ensure phase stability in all these components, the dropout cables also had to have stable characteristics.

The cables connect the main drive line to the varactor multipliers, the varactor multiplier to the sub-booster $I\phi A$, the sub-booster $I\phi A$ to the sub-booster klystron, the subdrive line to the 24-MW klystron $I\phi A$, and the $I\phi A$ to the 24-MW klystron.

The drop-out cables are semirigid $\frac{1}{2}$-in. coaxial lines having a foam dielectric. The cable has an attenuation of 7.6 dB/100 ft, and meets the following phase shift-versus-temperature specification:

Absolute (*one cable*)
$\pm 0.60°$ per foot between 60° and 100°F
$\pm 0.91°$ per foot between 100° and 130°F

Relative (*cable-to-cable*)
$\pm 0.30°$ per foot, 60° to 100°F
$\pm 0.45°$ per foot, 100° to 130°F

9-10 Standby equipment and switching (CJK, RAM)

To improve the reliability of the RF drive system, several items of equipment in the injection area and Sector 1 are backed up by standby units. One operating spare is available at all times for each of the following: master oscillator; main booster amplifier; sub-booster modulator; and frequency multiplier. For the first three of these items, automatic switching is provided in the event of failure. Manual switching is also provided, either from the Central Control Room or locally at the master oscillator rack in Sector 1.

At the output of each of the above units, RF power is sampled and detected. The detected signal is used to control switching relays through appropriate time delay circuits. Each switching unit also provides status information to the Central Control Room. In the sections immediately following, each switching circuit is described in some detail.

Master oscillator switching

Each master oscillator is coupled into its switching network and then to line or load through a 476-MHz circulator which serves to isolate the output stage of the master oscillator. With this isolation, and because the output power is only a few watts, the coaxial relay which performs the switching can be actuated while RF power is present. Switching occurs in the 2 msec or so required to operate the coaxial relay. The switching time is so short that the subsequent switching circuits for the main booster and sub-booster do not have time to initiate switching at those points erroneously.

Main booster switching

The switching unit detects the presence of RF power at the output of the main booster, and, upon loss of RF power, generates a signal which is sent to the main booster transfer switch. The logic is as follows:

1. Loss of RF power is sensed.
2. The transfer switch actuating signal is delayed a few seconds to allow for momentary failures and switching of the master oscillators.
3. The RF drive is removed from both main boosters.
4. The main booster transfer switch is actuated, placing the standby main booster in service.
5. The RF drive is restored.

Sub-booster switching

As with the other units, RF output is sampled, detected, and used to control switching. The logic is as follows:

1. Loss of RF power is sensed at the output of the sub-booster.
2. The relay actuating signal is delayed a few seconds to allow for momentary failures and switching of the master oscillators.
3. The sub-booster modulator trigger is removed.
4. The sub-booster transfer switch is actuated, placing the standby unit in service.
5. The sub-booster modulator trigger is restored.

Since switching of the main booster results in a loss of RF output from the sub-booster, a signal is derived from the main booster switching unit which inhibits sub-booster switching while the main booster is being switched.

Also, since the sub-booster output will disappear if the frequency multiplier preceding it fails, the standby sub-booster is provided with its own frequency multiplier, and failure of a frequency multiplier causes switching to occur as it would if a sub-booster had failed.

Acknowledgments

The authors of this chapter wish to thank Dr. R. B. Neal, who initiated many of the early design ideas for the drive system, and Dr. J. Dobson and Mr. W. J. Gallagher who participated in some of the early experiments. They also wish to thank Mr. J. R. Bordenave for his work on the master oscillators, frequency multipliers, and $I\phi A$ units, Mr. R. R. Hanselman for his work on the main booster amplifiers, and Mr. R. G. Wilson for his work on the drive lines.

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