THE RF SYSTEM FOR THE PRINCETON-PENNSYLVANIA ACCELERATOR*

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(Presented by M. G. WHITE)

Construction of the Princeton-Pennsylvania Accelerator was begun in 1957, and a 3 GeV beam was achieved in April 1963. The machine proper is described in various reports [1, 2, 3]. Basically it is similar to the Brookhaven Cosmotron, but with the aperture greatly reduced, and the repetition rate increased by a factor of 100. These two factors created many difficulties for the RF system. The smallness of the aperture made it necessary to operate on a high harmonic of the particle rotation frequency and hold very close tolerances on frequency, amplitude and phase. The high repetition rate meant that high RF accelerating voltages were necessary.

SPECIFICATIONS

Operating on the 8th harmonic of the synchronous frequency, the RF accelerating frequency must cover the range 2.5 to 30 MHz and not depart from the 8th multiple of the synchronous frequency by more than 0.02%. A 0.1% error will cause half the beam to strike the vacuum chamber. The synchrotron oscillation frequency varies between 12 and 50 kHz. The acceleration voltage is proportional to $\dot{B}$ and for a 30° phase angle has a peak value of 120 kV/turn. Fig. 1 is a plot of frequency, and voltage per turn vs. time.

The acceleration is to occur at each of four 1.6 m straight sections. After the 10 turn injection time the RF must be turned on to

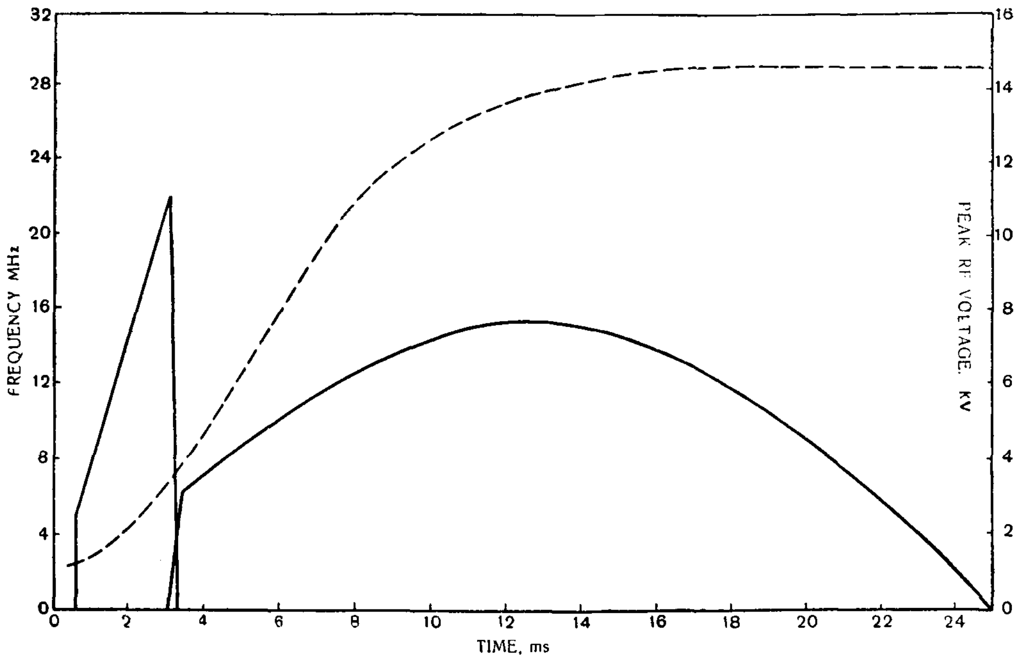

Fig. 1. Frequency and voltage per turn vs. time. Drift tube voltage appears four times and cavity voltage appears sixteen times per revolution (right scale). Frequency vs. time (left scale).

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full amplitude in 10 μs, after which time the RF phase, with respect to the phase of the synchronous particle, must be held constant to better than 3 degrees. Also, after 10 μs, the amplitude should not vary by more than a few percent from the value necessary to keep the synchronous particle at a phase angle of 40 degrees. Another complication is that the equipment near the magnet must be capable of reliable operation after being subjected to a flux of 5×10^8 Rads. of neutron radiation.

GENERAL DESIGN CONSIDERATIONS

Because of the large accelerating voltages required it is necessary to use high Q cavities, and high Q ferrites cannot be varied over large RF permeability ranges. For this reason the 12 to 1 frequency range is split into two parts. Furthermore, to minimize the amplitude of RF driven radial betatron oscillations the acceleration must occur at each of the four available straight sections. The combination drift tube plus cavity acceleration station solves this problem. Fig. 2 is a block diagram of the RF system. The output of the master oscillator is fed to the two separate RF accelerating systems, each of which drives four accelerating stations.

THE ACCELERATING STATION

An accelerating station, of which there are four, consists of a drift tube inserted within a double cavity. The double cavity is, in principle, similar to the double cavities used on the Brookhaven AGS. 750 kg of Ferroxcube 4C are used to resonate a double cavity over the frequency range 6 to 30 MHz. The power dissipated by the ferrite at maximum $\dot{B}$, when a double cavity is providing 30 kV of accelerating voltage, is 32 kW per station. The RF flux density is 20 Gs, and the dissipated power density is 0.25 W/cm³. A pair of 10 kW tetrode amplifier tubes at each station supply this power, and the power is removed from the ferrite by circulating 100 l/min of oil over the surfaces of the ferrite. This limits the temperature rise in the center of the ferrite toroids to 5° C.

The ferrite bias is supplied with a single turn winding, which provides 14000 A, and varies the RF permeability between 150 and 3.5. A coaxial, single turn secondary, transformer, mounted immediately below the cavity supplies this current, and at maximum $\frac{d\varphi}{dt}$ the bias voltage required is 18 V. The current is in opposite directions on alternate cycles, so that no dc component is necessary. The vacuum chamber which fits inside the cavities constitutes the drift tube. This vacuum chamber is a 20 cm i. d. stainless steel pipe broken at four places where 7.5 cm long alumina insulators are brazed to it. Two of these insulators are between the cavity gaps, and the cavity RF appears across them. The other two insulators are at the drift tube ends, and the drift tube RF voltage appears across them. Fig. 7 on p. 167 shows how the three metal sections of the drift tube are connected to the ferrite inductor in such a way as not to interfere with the cavity.

The net coupling between the drift tube and the cavity modes is low. When the cavity and drift tube are tuned to the same frequency at about 7 MHz, the coupling energy is less than 10% of the driving energy for either system. Since the drift tube accelerates by virtue of $\frac{dV}{dt}$ and the cavity by V, they must operate in quadrature, and any coupling energy must be dissipated in the plates of the power tubes. The ratio of coupling energy to circulating energy is ordinarily about 0.002 and can be adjusted to be less than this by moving the drift tube azimuthally within the cavity by a few millimeters.

Tying the drift tube ends together introduces two resonant modes at 18 and 24 MHz. The upper mode is moved up to 32 MHz and the lower down to 2 MHz by placing a center tapped inductance at the tie point in the manner shown in Fig. 7 on p. 167. The capacity of the drift tube (about 600 pF) is resonated from 2.5 to 7 MHz with a ferrite inductance of 4 turn Fig. 8 construction. A single power tetrode delivers 50 kW peak to each drift tube inductor, which operates at an RF flux density of 200 Gs. The drift tube is electrically 60° long, and therefore the peak net accelerating voltage exactly equals the peak applied voltage, which at 7 MHz is 11 kV. The voltage holding limit of certain elements in the drift tube feed system is only 13 kV and to prevent damage due to accidently increasing the voltage to this level, lucite light pipes pick up possible corona light from three places in each station and transfer it to a photomultiplier tube. The output provides alarm signals in the control room so that operators can reduce the voltage before damage is

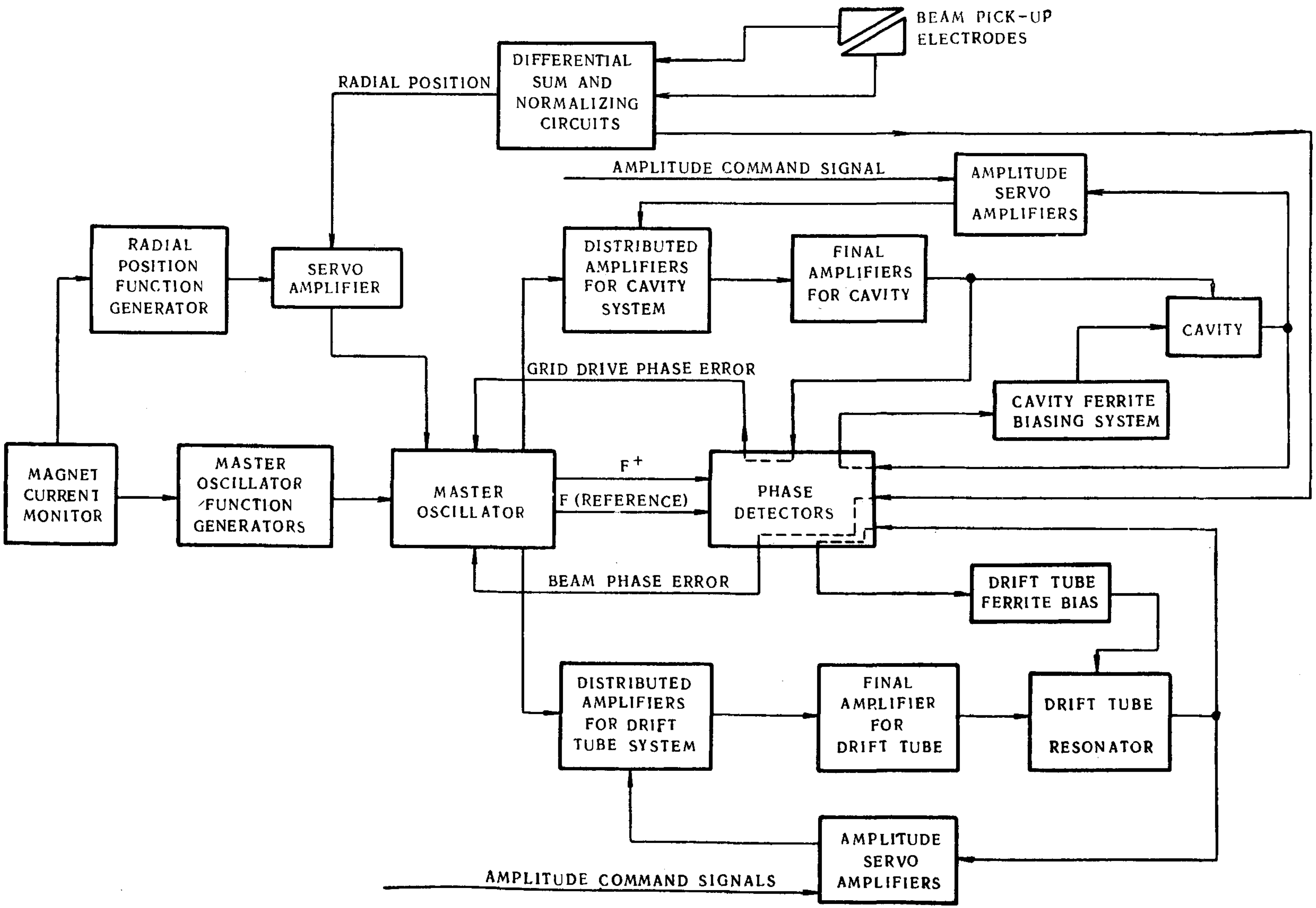

Fig. 2. Princeton-Pennsylvania Accelerator RF system block diagram.

done. The 6000 A turns of ferrite biasing current for the drift tube inductor, necessary to vary the RF permeability between 150 and 8, is supplied directly from a 1000 turn winding on the ferrite tank driven by a pair of tetrode tubes. 2500 V is necessary to achieve the desired rate of change of current.

THE DRIFT TUBE SYSTEM

The output of the master oscillator is amplified by conventional techniques and fed to the grid of the final amplifier at a 700 V 200 Ω level. The problem of turning on the RF in 10 μs with no overshoot or ringing has proven to be quite difficult. The RF amplitude servo loop, asking for an amplitude proportional to $\dot{B}$, controls the grid bias of the driver amplifier. The frequency response of this loop is only 50 kHz. For fast turn on the screen voltage is applied in a programmed manner. So far, smooth turn on has only been accomplished when the turn on rate has been 10 μs or greater. Analysis of the capture process shows that perhaps 30% more beam could be captured if the RF could be turned on in one cycle.

The bias current is servoed from phase detectors which measure the phase difference between the drift tube RF and a master oscillator reference RF, which is assumed to be 40° out of phase with the 8th harmonic of the synchronous particle. The frequency response of this loop is about 10 kHz, not nearly enough to keept the phase errors less than 5°. Advantage is taken of the fact that the magnet is short time stably periodic at 19 Hz, and a form of adaptive control, called self correcting function generators, is used to augment the high frequency gain of the phase servos. A phase error existing over a 50 μs interval of time is sampled on a given machine cycle, stored, and gated into the phase loop for 50 μs at a slightly earlier time during the next machine cycle. This earlier time is the delay, or time constant of the «fast» phase loop, about 100 μs. There is a weighting factor on the ability of an error during a given cycle to change the stored error associated with that particular time interval, more recent errors weighing more heavily, and characterized by a time constant of about one second. These circuits act as anticipators of error and for stable periodic devices can achieve high frequency response control with intrinsically slow systems.

The four, 50 pedestal, sample, hold, and gate, self correcting function generators used in the drift tube RF system require 1400 transistors. With the aid of these circuits, the drift tube RF system can work essentially unattended, and hold phase errors to within a few degrees. During the time when the cavity RF is building up, and before there is enough cavity voltage for the cavity phase servoes to regulate the phase properly, the drift tube system must regulate the net accelerating phase and amplitude. RF divider monitors, involving the use of 90° phase shifters, provide a net accelerating RF voltage signal for each station's amplitude and phase servoes. The crossover period between drift tube and cavity mode of acceleration is 0.5 ms (6.5 to 7 MHz).

MASTER OSCILLATOR

The master oscillator, which gets its frequency information from magnet current and beam radial position, provides four outputs. One, to the drift tube system; another, 90° phase shifted from the first, to the cavity system; a third, which is the reference RF previously referred to; and a fourth, designated F^+, which is 500 kHz higher in frequency than the third and is used in 10 phase detectors described below. Outputs one and two can be phase shifted with respect to the reference by ± 60° at up to a 500 kHz rate.

The F^+ signal is used in the ten phase detectors to permit phase detection to be done at a constant 500 kHz. Four phase detectors measure the net accelerating phase and control the drift tube phases. One detector measures the net phase at the grids of the cavity amplifiers and compensates for the 10° of variable phase shift due to mistermination of the grid feed cables. Four phase detectors are used to regulate the cavity phases; the tenth is used to measure the phase of the beam with respect to the reference and is fed into the master oscillator phase servo.

The oscillator frequency is slaved to be a linear (0.05%) function of its various inputs by virtue of an analog frequency transducer (0.01%) and a high gain servo loop. Magnet current information is obtained from a 2nd harmonic current transducer, and operated on with an essentially passive, temperature regulated, array of varistors and biased diodes to produce a voltage stably (0.01%) proportional (± 2%) to the calculated frequency vs. current relationship. A 50 knob periodic pedestal generator and a 25 knob independent adjustment analog function generator, operating on current input, provide additional program inputs to the master oscillator. Acceleration to final energy has been achieved with only these program inputs.

Pick up electrodes mounted in the short straight sections of the accelerator vacuum chamber provide beam sum and difference signals. The difference signal is amplified by a 100 MHz bandwidth amplifier to a 10 V level and a difference is taken between the positive and negative peak detected outputs. This voltage is divided by the peak detected sum signal to provide a normalized radial position signal. The division is accomplished with a field effect transistor. Overall frequency response is about 100 kHz.

The injected beam gets bunched within a few RF cycles, but the radial position signal is not useful for frequency control until about a quarter of a synchrotron period. Therefore, a second field effect transistor is used to slowly gate the radial position signal into the radial position servo. Within 50 μs the radial position loop corrects the master oscillator frequency to force the beam to stay in the center of the vacuum chamber. This loop reduces coherent radial motion of the beam from 5.2 to 1 cm.

However, the beam becomes unstable unless the derivative of the radial position signal is fed into the master oscillator phase shifter. This latter loop damps out coherent phase oscillations within a few cycles. The magnitude of permissible phase oscillations is only a few degrees, and, so far, signal to noise problems have prevented the effective use of beam derived phase information other than that obtained from the derivative of the radial position.

THE CAVITY SYSTEM

The master oscillator output is amplified with 100 MHz bandwidth distributed amplifiers and fed to the grids of the eight cavity final amplifier tubes via 30 Ω terminated transmission lines. The total peak drive power is 40 kW. The details are described in a PPA report [4]. The problem of ferrite biasing of the cavities has proven to be far more difficult than RF generation. This would not be true if efficiency were no consideration, but then the total power necessary for biasing would be about 1.5 MW. A perfectly efficient system would only have to provide for 20 kW of I^2R losses and 1000 J of reactive energy to be thrown away 20 times a second (another 20 kW). The switching transformer scheme which is used at the Princeton-Pennsylvania Accelerator [5] consumes 200 kW of power to accomplish ferrite biasing, and so is 20% efficient.

As with the drift tube system, phase detectors are employed to force resonant tracking of the cavities. When the master oscillator frequency reaches 6.5 MHz (20 MeV) the cavity RF is slowly turned on in a programmed way. Between 6.5 to 7 MHz both the drift tube and the cavity are accelerating the beam, with the drift tube servo controlling the magnitude of the net accelerating voltage. After 7 MHz the drift tube RF is shut off and the cavity accelerates the beam the rest of the way. During the time when the biasing transformer taps are being switched (about 1 GeV) no disturbance is noted in either the bias current or the phase signals.

The full beam can be accelerated with only three cavities operative, each one being capable of operating at 30% more than its design voltage. However, due to adiabatic damping of incoherent synchrotron oscillations, by the time maximum voltage is called for, a phase angle of 50°, from 1 GeV on, seems to be adequate for accelerating all the beam, and three station operation can be employed with the use of only slightly more maximum voltage per station than was designed for.

At the present time an operator must be in continual attendance on the bias system to adjust the various programs that aid the phase servoes. More gain in the phase servoes will not help, because the most critical adjustments involve presetting the ferrites in the proper place in their B—H loop to have the right values of both RF permeability and dc permeability at cavity turn on time. Self correcting function generators are presently being constructed to solve this problem. Complications in their design arise from the requirement that the RF system's performance should be independent of the value of the final energy. It is anticipated that many experiments will require a long beam spill out at reduced final energy. With the very high $\dot{B}$ at the Princeton-Pennsylvania Accelerator it is difficult to make the RF system B dependent only. At the present time several hours would be required to readjust the various programs to permit operation at reduced final energy.

PERFORMANCE

Operating experience to date has demonstrated that the RF system is particularly critical at only two places: RF turn on, or beam capture, time, and crossover time between drift tube and cavity. Stability of capture has been one of our more vexing problems; but so far it has been difficult to determine the relative magnitudes of the contributions to beam fluctuations from the injection system and the RF system. However, it is quite clear that $\pm$ 0.05% jitter in the RF frequency at turn on will lead to very significant fluctuations, and even $\pm$ 0.02% jitter in frequency is noticeable. Injection with zero radial betatron oscillations seems essential, and 2 cm of coherent radial betatron amplitude significantly reduces the amount of captured beam, and imposes even more stringent accuracy requirements on the RF system. Best performance to date has been about $\pm$10% cycle to cycle capture intensity fluctuation.

The capture process is further complicated when the cavity system is on because some of the magnetic field from the cavity bias current leaks into the vacuum chamber with about a 20 ms lag. Thus at injection time there exists a vertical component of magnetic field capable of giving a 1 to 2 mrad radial deflection to the beam as it passes through a cavity. This kick is in opposite directions at alternate cavities, and at a given cavity is in opposite direction on alternate cycles. This effect can be almost entirely compensated for by programming a 10 cycle current into a magnetic «kicker» placed just before the inflector electrodes. Calculations show that this kicker can reduce free betatron oscillations to zero amplitude, leaving only a 1 cm amplitude 2nd harmonic forced betatron amplitude.

The total amount of beam picked up at injection is very sensitive to the amplitude of the drift tube RF voltage. The peak amplitude of the sum pick up electrode signal is relatively independent of the RF voltage, but the area is maximized when larger phase angles (less voltage) are used. An initial phase angle of 60° to 65° seems best. About 80% of the beam picked up by the RF system is accelerated to the end of the drift tube range. The frequency and amplitude programs must be adjusted very carefully to avoid beam loss at the time of crossover between drift tube and cavity modes of acceleration. However, when proper adjustments are made, and when radial position feedback is used, all of the beam that is accelerated to the end of the drift tube range is successfully accelerated to its full energy.

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