ZERO GRADIENT SYNCHROTRON RF SYSTEM

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Introduction

As accelerators are developed to extend the frontiers of high energy physics, the complexity of their nature presents technological problems that need to be solved by extensive programs of research and development. The following reports on the results of one such program, the design and construction of the radio frequency accelerating system of the Argonne Zero Gradient Synchrotron. It describes the system requirements, the equipment that has been developed to fulfill these requirements, and the present performance of the system.

System Parameters

The basic radio frequency system parameters are determined by a synchrotron's final energy, injection energy, and magnet design. In the case of the Argonne ZGS these parameters are a final energy of 12.5 BeV ($\beta = 0.995$), an injection energy of 50 MeV ($\beta = 0.3$), a radius of approximately 1000 in. for the weak-focusing magnet and a radial aperture of 26 in. at injection. This gives a range of particle revolution frequencies extending from 550 to 1750 kc/sec. The nominal rate of rise of the guide field is 21.5 kG/sec so that the energy gain per turn is $\Delta E = 8.3$ KeV. In practice, the guide field can increase at a rate as high as 26 kG/sec so that ΔE can be as high as 10 KeV per turn. To operate with the equilibrium particle at a phase angle of 150°, and thus with a 180° stable range of phase, requires that the accelerating cavity produces a peak voltage of twice this. Figure 1 shows the sensitivity of radial position to accelerating frequency. This varies from 0.04%/in. at injection to 0.1%/in. at full energy. Reproducibility to 1 in. is adequate for accelerating the protons, but the requirements for targeting the beam are much more stringent (of the order of 0.001 in.).[1]

The above parameters of the rf system are determined by the basic machine parameters. Choosing the harmonic number $n = \omega_{rf}/\omega_{orbit} = 8$ gave a frequency range from 4.4 to 14 Mc/sec. The larger the harmonic number, the smaller the radial amplitude of the synchrotron oscillations (in the ZGS the amplitude is about 5 in. for $n = 8$). Also, for some experiments the rf structure on the targeted beam becomes less objectionable as the harmonic number is increased. However, there are technical problems in making n too large: higher n requires broader bandwidth in any equipment that reproduces the bunch shape; and in a weak-focusing machine, the induction pickup electrodes are long in the radial direction and the beam can induce ringing on these electrodes at the frequency at which the structure resonates. In the case of the ZGS, the lowest such frequency is about 90 Mc/sec. With $n = 8$, the highest observable harmonic of the bunch frequency is therefore the sixth. This harmonic number of 8 was chosen as a compromise between these factors.

Accelerating Cavity

Figure 2 shows a block diagram of the basic accelerating system. The accelerating structure is a three-gap, ferrite-loaded, resonant cavity tuned by a bias magnetic field in the ferrite (Fig. 3). Each gap is associated with a cell and each cell is resonant at the operating frequency. The three-cell cavity, chosen over the one-cell configuration in order to reduce the rf magnetic fields in the ferrite and thus ferrite heating, gives an rf flux density of 61 gauss peak at 4.4 Mc/sec and 19 gauss peak at 14 Mc/sec with a ferrite cross section of 1200 cm^2. The ferrite is divided into 4 cm thick frames separated by water-cooled copper laminates.

To obtain 20 kV peak accelerated voltage, 6.7 kV peak is needed at the driving point. The driving point impedance varies from 300 Ω at 4.4 Mc/sec to 355 Ω at 14 Mc/sec giving an input power varying from 75 kW to 65 kW. The beam loading is 2.3 kW max. for 10^{12} protons/pulse which is negligible compared to the losses in the rf cavity.

Power Amplifier

The cavity is driven (Fig. 4) by a pair of ML 7560 tubes operating in push-pull with grounded grids. These tubes operate with a plate voltage of 10 kV and a cathode current of 10 A per tube. The drive to this stage is

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transformer-coupled from a pair of 4W20000 tubes operating with grounded cathodes. This stage is driven by a pair of 7213 tetrodes which are driven by a conventional push-pull transformer-coupled amplifier. All these stages are operating as linear amplifiers class AB and are broadband, except for the 7560 triodes which operate into the tuned cavity. The dc operating voltages on these stages are held constant and the rf envelope is controlled by modulating at low level. There is a closed loop to control the amplitude of the rf signal on the cavity which operates with a 100 kc/sec bandwidth. There also is a phase lock system that compares the cathode and anode signals from the final amplifier and adjusts the cavity tuning to keep them in phase.

RF Source

The signal used to accelerate the protons comes from a master oscillator controlled by the guide magnetic field. An oscillator that tunes the limited range required for targeting (± 1% in the ZGS) is employed in conjunction with the master oscillator to give reproducible radial control of the beam during beam spills. This targeting oscillator controls the beam position with an order of magnitude greater precision than direct measurements can be obtained using induction electrodes. The accuracy of such direct measurements is limited by the large aperture.

The master oscillator gives a well-controlled rf signal in the absence of any induction electrode signals. This allows the rf system to be used in beam spill techniques[2] where the beam becomes debunched as seen by an induction electrode.

Master Oscillator

The ZGS rf signal is generated in an oscillator that is both permeability tuned and dielectric tuned. The permeability tuning approximates the desired tuning curve by using a ferrite whose curve of μ_i = dB/dH vs. H comes close to the needed frequency program. This can be accomplished within ± 10% with a long-term reproducibility of 0.03%. Fine tuning is accomplished by changing the back bias on silicon diodes to change their incremental capacitance. These diodes have additional inputs which are used for the control of the frequency by external signals. The frequency response of these inputs is from dc to 100 kc/sec.

The command signal for the oscillator is derived from the magnetic field by using an analog integrator[3] to integrate the induced voltage on a coil in the guide magnet. The integrator is unclamped at 433 gauss by a pulse from an electron-paramagnetic-resonance detector also situated in the guide magnet. Its output is processed in a two-slope function generator to drive the bias field in the oscillator ferrite. This gives the correct frequency vs. machine magnetic field, B, within ± 10% (depending mainly upon the ferrite characteristics). The integrator output is processed in a standard analog computer diode function generator to produce the fine-tuning signal. This function generator can generate a voltage function of B consisting of thirty straight line segments, each of which has an adjustable starting point (in B) and an adjustable slope.

The long-term drift in the frequency of the master oscillator is less than 0.1%/day and the short-term noise (in a band from dc to 1 kc/sec) is less than 0.03%.

Targeting Oscillator

The targeting oscillator is a precision oscillator tuning over the range 12 to 14 Mc/sec. At about 1/2 the maximum energy, the master oscillator is phase locked to the targeting oscillator to allow the targeting oscillator to have complete control. To avoid a sudden jump in frequency, the phase lock-loop is turned on slowly by the use of a light-sensitive resistor illuminated by an incandescent bulb as a switch.

The targeting oscillator is tuned by a voltage variable capacitor and is placed in a temperature-controlled oven. The long-term stability of the frequency is one part in 10^5 and the noise four parts in 10^5.

Frequency Shifter

The frequency shifter[4] is used to obtain a signal 1 Mc/sec higher in frequency than the master oscillator. In precision measurements of phase and amplitude, this signal is used to translate signals to a standard 1 Mc/sec.

To obtain this 5-15 Mc/sec signal, an oscillator similar to the master oscillator (except that its command comes from the master oscillator through a frequency-to-voltage converter instead of directly from the magnetic field) is tuned roughly 1 Mc/sec higher than the master oscillator. The outputs of these two oscillators are mixed to produce a 1 Mc/sec signal. To ensure that this is 1 Mc/sec, the mixer output is phase locked to a 1 Mc/sec crystal oscillator by feeding back to the voltage variable capacitors of the 5-15 Mc/sec oscillator.

Cavity Bias System

To tune the accelerating cavity, a bias current ranging from 30-650 A is passed through a bias winding that has been arranged in a figure-8 configuration bias signal from the rf fields of the cavity. This current comes from an amplifier whose final stage comprises 190 MP1547 transistors in parallel. This stage is located along with the power amplifier power supplies in the basement of the injector building approximately 100 ft. from the accelerating cavity. This allows access during operation and also keeps the power transistors away from high radiation fluxes.

The command signal for rf cavity tuning comes from a diode function generator operating on the output from a frequency-to-voltage converter. This converter receives its signal from the master oscillator. As mentioned before, an additional signal from a phase detector associated with the power amplifier is added to the approximate tuning described above. This phase signal forms a closed loop that keeps the accelerating cavity in tune within $\pm 1^\circ$.

The bias system has a 14 kc/sec small signal bandwidth.

Phase Detector

The cathode and anode signals of the 7560 triodes are sampled with voltage dividers and are mixed with the output of the frequency shifter to give two 1 Mc/sec signals. The phase between these signals is detected and filtered to give a bandwidth from dc to 6 kc. Only a small amount of rf limiting is employed so that the phase detector transfer function gain (volts output/degree) varies with accelerating voltage amplitude. This allows the phase control on the cavity to come on smoothly with the rising rf voltage amplitude.

Beam Phase Detector

At low frequencies (below the synchrotron oscillation frequency, approximately 4 kc/sec in the ZGS) the normal phase stability keeps the center of gravity of the beam at the equilibrium phase. Low frequency modulation noises on the master oscillator, therefore, merely move the beam radially. On the other hand, high-frequency noise on the oscillator can cause beam to wander out of the region of stable phase. The beam phase detector senses these noises by comparing the phase of the fundamental component of the beam bunch structure with the phase of the voltage on the accelerating cavity. The beam signal is obtained from a triaxial wideband induction electrode and amplified in a limiting amplifier. The output of this amplifier is constant for beam intensities from 1×10^7 to 5×10^{13} protons/pulse without range switching. The signal from the accelerating cavity is similarily limited over a 200:1 range. These two signals are mixed with the output of the frequency shifter and filtered giving two 1 Mc/sec signals. The phase between these signals is detected and filtered giving an output from dc to 230 kc/sec. The signal is then passed through a high pass filter and fed back to the master oscillator.[5]

At normal accelerating voltages and beam intensities, the high limiting ratio suppresses the noise in the system. This system has an accuracy of $\pm 1^\circ$ and it is self-calibrating.

Radial Position Detector

There are two sets of split electrodes to locate the radial position of the beam. Two are needed since the ZGS has four short straight sections with a dc bending magnet in each and four long straight sections without dc bending magnets. The radial position of the beam changes with B in the two different types of sections.

Figure 5 shows a block diagram of the radial-position detecting equipment. The signal from each half of the electrode is mixed with the output of the frequency shifter and filtered to get a 1 Mc/sec signal whose amplitude is proportional to the fundamental component of the induced signal on that half of the electrode.

After mixing, the amplitudes of the two 1 Mc/sec signals are proportional to Q and radial position giving:

$$v_A = K_1 Q \left(1 + K_2 X\right)$$

$$v_B = K_1 Q \left(1 - K_2 X\right)$$

where Q is the charge in the machine, X is the radial position of beam (measured from the center of the chamber,) and K_1 and K_2 measured constants. Detecting the 1 Mc/sec signals and adding gives:

$$\left(v_A + v_B\right)_{\text{detected}} = v_{\text{sum}} = 2K_1 Q.$$

Dividing v_A by v_{sum} and subtracting 1/2 gives:

$$\frac{v_A}{v_{\text{sum}}} - 1/2 = \frac{K_2}{2} X$$

This is an analog voltage proportional to the radial position of the beam.

To divide v_A by v_{sum} electronically, v_A is applied to the deflection plates of a 7360 beam deflection tube and a voltage representing $1/v_{sum}$ is formed in a diode function generator. When the tube current is held equal to this voltage with a closed loop, the output signal from this tube is proportional to v_A/v_{sum}

This system has a dynamic range of 20 dB in beam and the 1 Mc/sec amplification can be stepped in 10 dB steps. The radial position detector system senses the beam position with an uncertainty of ± 0.5 in.

The signals from the electrodes can also be observed directly to monitor the radial position of a coasting beam occupying less than one turn of the synchrotron.

Charge Measuring System

The structure of the beam bunches is observed by the use of a broadband amplifier system on an induction electrode. As mentioned above, the bandwidth of this system is limited by the radial aperture of the machine. In the ZGS, the lowest resonant frequency of the electrode occurs at about 90 Mc/sec. The frequency response of this system has been attenuated above a frequency of 75 Mc/sec.

The average value of the induction electrode signal is detected to obtain a slow (dc to 10 kc/sec) indication of the beam in the machine. This slow signal is sampled and digitized for the use of the experimenters.

The sensitivity of the electrode was determined by the use of an electron beam technique. A modulated electron beam was passed through the electrode and collected in a Faraday cup. Known capacitance was added to the Faraday cup until its signal equaled the electrode signal. Knowing this capacitance and the configuration of the electrode in the machine gives a sensitivity of 3.88×10^{-12} V/proton.

The gain of this system can be remotely switched in 10 dB steps and is automatically calibrated between machine pulses. The gain of the system is accurate within ± 1%. Because of questions about frequency response, the overall charge measuring system has an uncertainty of absolute calibration of ± 15%.

System Performance

The rf system of the ZGS has now been in operation for over a year and some comments can be made as to its general performance.

It has been demonstrated that little can be gained in raising the accelerating voltage higher than 20 kV peak (the nominal operating point). The system noise is such that without feedback approximately 70% of the captured beam is lost during the accelerating cycle. With beam phase feedback, there is negligible loss. The long-term drift of the oscillator is such that it is now standard practice to retune that system about once a month. The frequency shifter rarely needs retuning. The normalizing function generator of the radial position detector system presently needs to be retuned weekly to maintain the accuracy of the system. The accelerating cavity needs to be retuned about once a month.

The entire system tracks the guide magnetic field well enough that changes in flat-top length or slope (or changes in peak field) do not require retuning.

During the last quarter of 1964, the ZGS downtime attributable to the rf system was 4.6% of the scheduled operating time. The total downtime was 26.4%.

Acknowledgements

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[*] Hughes Aircraft Corporation, Fullerton, Calif.

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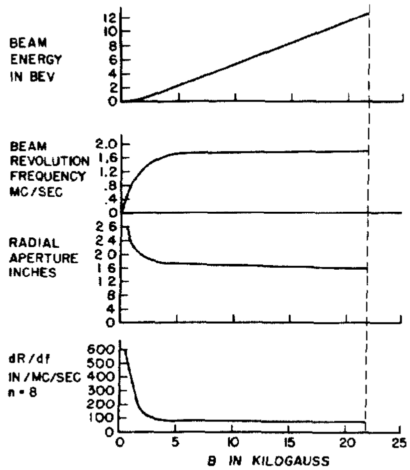

Fig. 1. ZGS Machine Parameters.

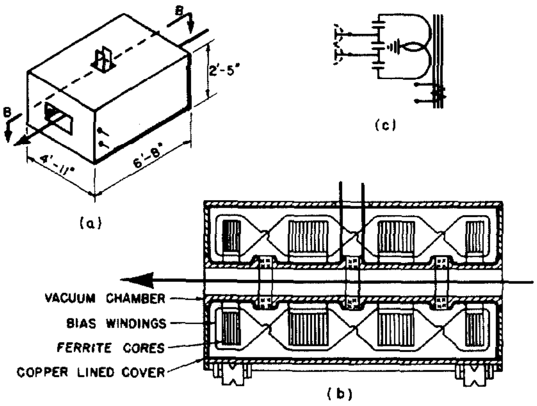

Fig. 3. ZGS Accelerating Cavity.

(a) Full View

(b) Cross Section

(c) Equivalent Circuit

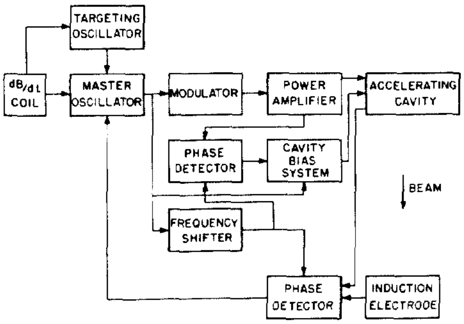

Fig. 2. ZGS Radio Frequency System Block Diagram.

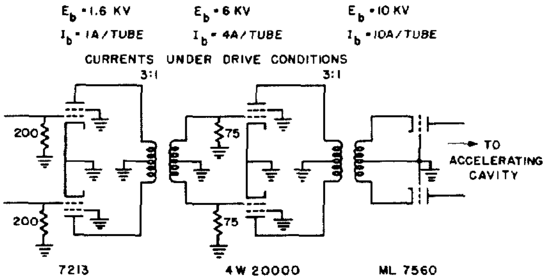

Fig. 4. ZGS Radio Frequency Power Amplifier.

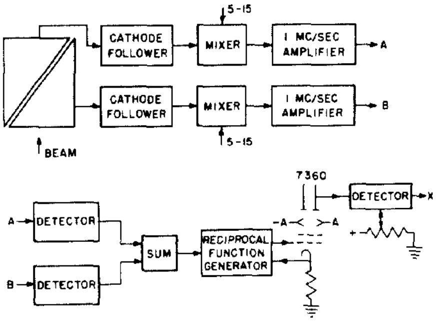

Fig. 5. ZGS Beam Radial Position Detector Block Diagram.