ELECTRONIC INSTRUMENTATION AND CONTROL AT THE PRINCETON-PENNSYLVANIA ACCELERATOR

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Introduction

The Princeton-Pennsylvania Accelerator, a 3 BEV proton synchrotron with a 20 per second pulse rate, has been in operation for two years. The 3 BEV beam can supply an average of 10^{12} protons per second to an internal target. Construction of this machine was started in 1959. Primarily because of the high repetition rate, there were many new problems, both for the magnet and the rf system, which had to be solved. References 1 through 5 describe these problems, and the methods used to solve them.

Some of the most difficult problems were in the field of instrumentation. The radio frequency system spanned the range from 2.5 to 30 mc, and modern electronics techniques were just able to provide precision analog and digital instrumentation over this range. A precision (0.01%) frequency to voltage converter used to stabilize the master oscillator has been described in reference 2.

Digital $\dot{B}$ Integrator

This frequency meter was further improved, both in linearity and drift, and is the heart of a digital $\frac{db}{dt}$ integrator, which spews out a stream of pulses: one for each 0.07 gauss increment in the accelerator guide magnetic field. Figure 1 is a simplified schematic of this device.

The $\dot{B}$ signal is used to frequency modulate a variable oscillator in the 80-110 mc range. This modulation is feedback controlled by the analog output of the frequency meter, whose input has the swept oscillator frequency, suitably shifted down to the 2.5 to 30 mc range. This is basically the same circuit as that of the master oscillator. Long term stability of the accuracy and sensitivity is further improved by instantaneous frequency monitoring at a time when $\dot{B}$ passes through certain dc reference values. Figure 1 shows such an arrangement for dc stability control of the frequency modulation process. The maximum frequency deviation corresponding to peak $\dot{B}$ is 12.5 mc. When the output pulses are counted within a time interval, this total number is proportional to ΔB, the B field change during that time. It is in this sense this circuit is a digital integrator of $\dot{B}$.

Clock Pulses

Paralleling the $\dot{B}$ integrator, is a circuit which provides clock pulses. However, instead of using real time as a reference, the machine period is used. Thus there are always the same number of pulses per machine cycle, and as the machine frequency varies (about 5%) the real time between pulses changes. These pulses, as well as the scaled down $\dot{B}$ pulses are distributed throughout the accelerator complex and are used in preset scalers for selecting out any one of them. They are also used as clock pulses for the various pedestal type function generators and self-correcting function generators used in the rf system and elsewhere. Although these function generators have been previously described (ref. 2), recent improvements to both perhaps justify redescribing them.

Pedestal Generators

The pedestal generators are composed of multiple stage ring counters. Each stage (Figure 2) consists of three transistors which are cut off in all but one stage. Application of shift pulses causes the conducting stage to move down the counter string. The circuit is arranged so that two of the three conducting transistors clamp opposite ends of a pot to two reference voltages. The pot voltages are then summed in an operational amplifier. Different pulse widths can be generated by using standard digital techniques to form pulse trains with different spacing between pulses, or the $\frac{db}{dt}$ pulses may be used to provide pedestals at equal B intervals.

Self-Correcting Function Generators

The self-correcting function generators (SCFG) take advantage of the periodic nature of the machine to enable application of large amounts of feedback to servos by the accumulation of an error function over many machine cycles in a number of sample and hold circuits. By reading the sample and hold circuits ahead of the sample time an error function is generated which precedes the error in time sufficient to compensate for servo delays.

A string of monostable multivibrators generate successive read-out pulses A_1 to A_n (Figure 3) whose levels are arranged to switch one output transistor at a time from a reversed biased state to that of a conventional emitter follower. The output transistors share a common load resistor. A diode D_1 compensates for the emitter base stop. A second string of monostables is triggered individually from the first group through a variable delay to form the read-in pulses B_1 to B_n. The input transistor operates in the inverted (chopper) connection to minimize offset. The RC of the storage circuit is selected to limit the change in stored value due to a full scale input signal to a small fraction of full scale.

Since the effective time constant is increased by the ratio of machine cycle time to pedestal duration, large time constants are possible. Some design considerations include transistor and capacitor leakage, offset voltage and noise due to transistor switching. Large time constants require low leakage silicon pnp transistors, and tantalum capacitors. With 1 millisecond pulse widths and a 10 cycle operation frequency, a ten second time constant was achieved with less than 1% offset without matching components. Replacing D_1 with a transistor achieves an order of magnitude improvement in both time constant and offset voltage, however npn silicon transistors with the required high V_{EBO} are rare. Since SCFG's compensate for their own offset voltages when used in a loop, no effort was spent to reduce it below 1%. Matching techniques could easily hold it to .1% if desirable.

SCFG's have been built with pedestal widths as small as 2 μseconds. Here emitter to base and collector to base capacitances are important in transistor selection, with the SPAT types giving best performance.

It is difficult to overstress the value of these SCFG's for rapid cycling accelerators. One example which demonstrates their usefulness is the SCFG's used in the servo of the self-tracking rf cavity amplifiers. Previously only analog phase information was fed back, but with a 100 pedestal SCFG much improved tracking can be achieved, and the fast analog signal is unnecessary. To the extent that the magnet cycle is highly periodic, the SCFG's operate like lock-in amplifiers, and can get accurate information out of a sea of noise in the same way that they can.

A chopper stabilized amplifier is an example of a one stage SCFG, and any amplifier which needs chopper stabilization at the PPA is stabilized with a modified SCFG. The modification consist in selecting a time when the amplifier is supposed to be putting out a certain voltage, sampling and holding this voltage for one machine period and after comparing with a reference (usually zero) feeding the integral of the difference back to the amplifier input.

Precision Frequency Sampling

This principle is used to provide a very precision anti-drift signal to the master oscillator. A pulse is available which is very accurately related to a specific value of the accelerator guide magnetic field. This pulse is used to sample and hold the average value of the master oscillator frequency over a 1 μs time interval at injection time. The circuitry that accomplished this is called the F_0 circuit. The heart of it is a precision phase detector, and the frequency reference is a 2,000 ft. length of temperature regulated cable. Figure 4 is a simplified diagram of this circuit. The phase detector is a balanced arrangement, and the transformers and resistors terminate the input rf signal with a VSWR of less than 1.05 from 1 to 20 mc. The carrier levels are high (20 volts) so that variations in diode drops are minimized. The long time stability of this detector is about 0.01° at 2.5 mc, and with over $1,000^\circ$ stored in the cable provide a calculated frequency stability of 0.001%. Naturally, because of the cable delay, the two phases are being compared at times some 3 μs apart, and this imposes a limitation on the length of cable that should be used. Since the variations in this delay are the same as the variations in the magnet $\dot{B}$ at injection, it is possible to arrive at an optimum cable length which is the best compromise between errors caused by variable delay and inadequate stable sensitivity.

To meet the laboratories requirements a line of operational amplifiers has been developed. Two types are of particular interest. For general servo functions, as well as for precision low level rf peak detection, an op amp with unity gain at 100 mc is in service. For high power voltage requirements, particularly to serve as drivers for high power vacuum tubes (4CW 10,000 A's) a transistorized op amp with 600 volt swing and capable of delivering 2 amperes has been developed. This op amp is capable of surviving 20 kv surges from a three joule energy source, which is a worst case simulation of a spark in the vacuum tube. This op amp has unity gain at 1 mc.

Magnet Regulators

Passing over to the realm of experimental support, it may be of interest to describe the manner in which the PPA decided to regulate magnets. There are about 50 magnets at PPA, consuming a total power of about 8 mw. All the power supplies for these magnets are of the self saturating magnet amplifier type, and all use the laboratory standard current regulator. The regulator of a precision current monitor (10 volts per 1,000 amps), a precision zener reference with digital 5 place Kelvin Varley divider, a stable op amp and a power stage. These latter components are simply carefully engineered versions of rather standard circuits. The overall open loop transfer function has a dc gain of 5×10^5, breaks at $\omega = 5 \times 10^{-5}$/sec. and drops with a 6 db per octave slope to unity at $\omega = 60$/sec. Unity gain is at 20 cps.

The principle difference between these regulators and regulators used elsewhere lies in the current monitor. This is a 2nd harmonic detector type current transformer similar in principle to the one designed by Q. Kerns at LRL about 1949. By using good cores and a carrier of 5 kc it was possible to dispense with the complication of filters, and at the same time solve the nasty problem of a possible double error function. The error function is linear, symmetrical about zero, and clamped at ± ampere turn. Drift is less than 1 ma turn, noise and carrier feed through less than 1 ma turn and the response is flat to 100 kc.

These two latter features are of course not necessary for magnet regulation, but this monitor was developed for other applications where this criteria was important, and in any case it is always advantageous to be able to monitor well. Because of the high output voltage, no further chopper stabilized stages are necessary in the regulator chain. Performance to date of these regulators has been good and has presented a real challenge to digital voltmeter + shunt monitors to discover any drifts.

Beam Separators

Finally it might be interesting to discuss various electronic features of the crossed static field beam separators in use at PPA. Presently operating are two 5 foot units which achieve 450 kv across 2 inch gap SS electrodes at a pressure of 2×10^{-3} mm with a sparking rate of less than one per hour. The voltage is supplied by standard double power supplies and fed via a cable. At the separator a one meg resistor isolates the power supply from the separator. After considerable difficulty in trying to copy techniques used elsewhere to handle this resistor problem, an oil encapsulated unit was fabricated using 200 1 watt composition resistors in series. This has stood up well. The purpose of the above information is simply to report on present performance.

More interesting are two 10 foot beam separators which are presently being fabricated. These will use integrated Cockroft Walton power supplies built into a 3 ft. service section separating the two separators and also supply vacuum pump connections. A non-integral version of this power supply has been built and tested to determine the component failure problem. Figure 5 is a picture of this supply with the ground can removed. The PPA laboratory plans on standardizing on this type of power supply for future requirements. Both versions, the cable feed type and the integrated type can be used interchangeably on future beam separators. Figure 6 is a sketch of the physical layout of the integrated type power supply.

It is planned to monitor the output voltage by means of a vibrating 2 kc tuning fork electrometer mounted within the supply. A model of this monitor was tested using a vibrating wire and performed well. It is believed that the problems are purely mechanical, and that their successful solution should result in a complete power supply which will perform for years without failures.

Considerable effort has been expended in an effort to build a control system for the beam separators of sufficient versability such that over even very long periods of time (weeks, hopefully) the beam separators can operate unattended. This has not been fully tested as yet, but it is hoped that it can be accomplished without having to build a computer as complicated as a human being.

References

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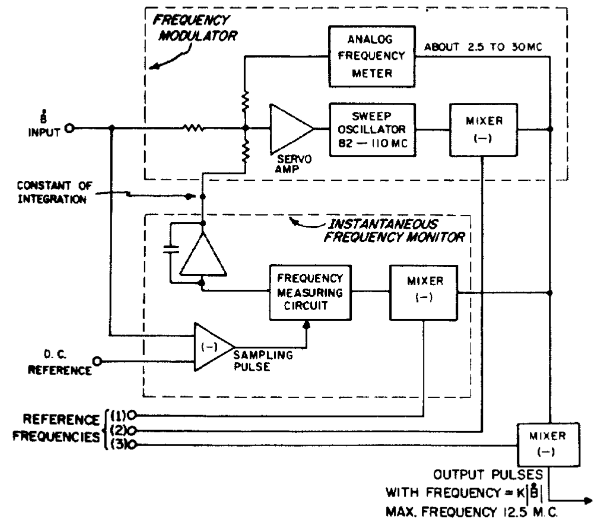

Fig. 1. Digital $\frac{db}{dt}$ Integrator.

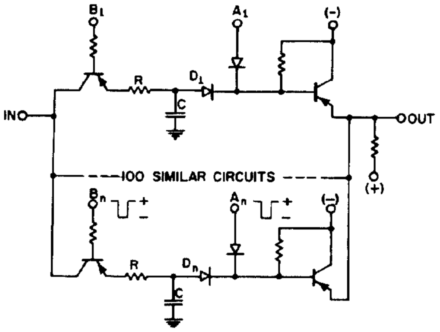

Fig. 3. Self-Correcting Function Generator Sample and Hold Circuits.

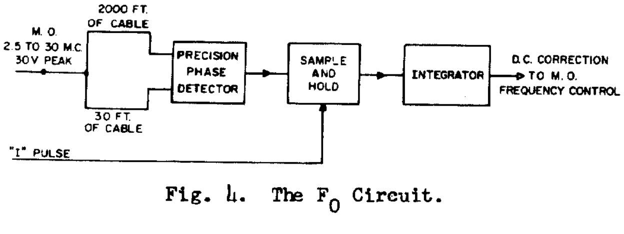

Fig. 4. The F_0 Circuit.

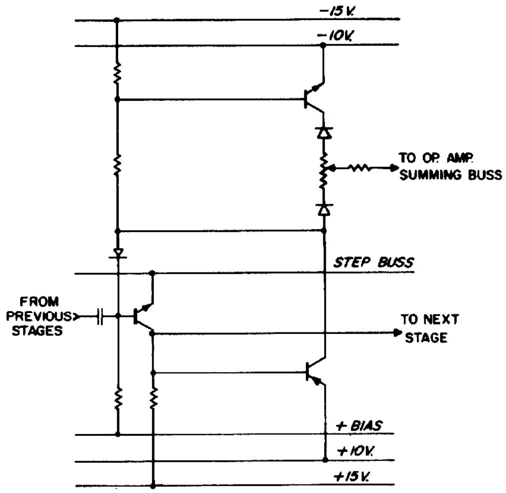

Fig. 2. One Stage of Pedestal Generator Ring Counter.

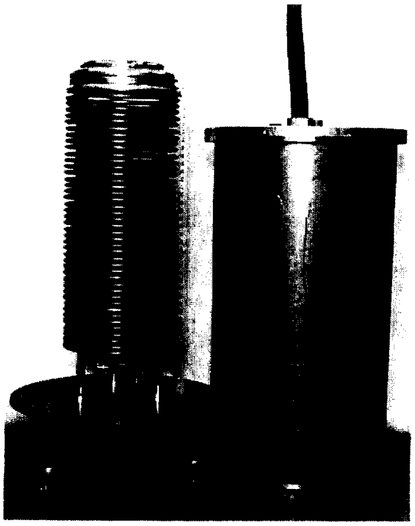

Fig. 5. Picture of 400 kv Cockroft Walton PS.

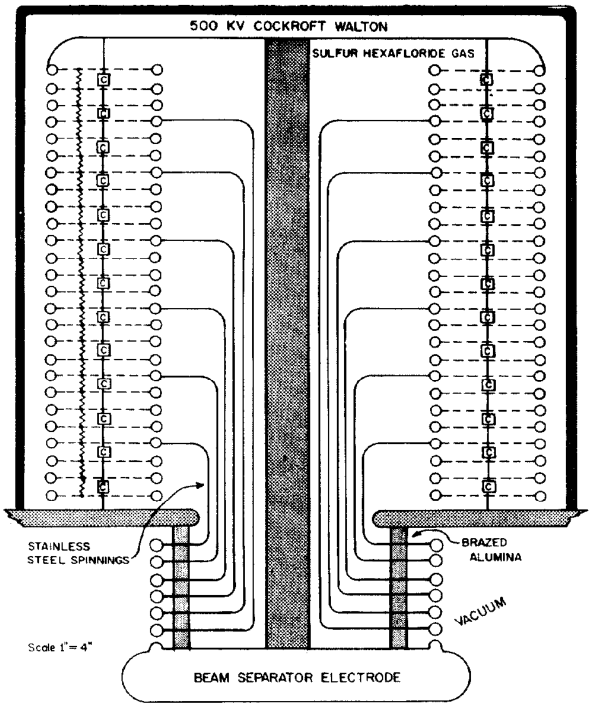

Fig. 6. Physical Layout of the Integrated Type Power Supply.