IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

TUNE CONTROL IMPROVEMENTS ON THE RAPID CYCLING SYNCHROTRON*

C. Potts, M. Faber, G. Gunderson, M. Knott, and D. Voss
Argonne National Laboratory
Argonne, IL 60439

Abstract

The as-built lattice of the Rapid Cycling Synchrotron (RCS) had two sets of correction sextupoles and two sets of quadrupoles energized by dc power supplies to control the tune and the tune tilt. With this method of powering these magnets, adjustment of tune conditions during the accelerating cycle as needed was not possible. A set of dynamically programmable power supplies has been built and operated to provide the required chromaticity adjustment. The short accelerating time (16.7 ms) of the RCS and the inductance of the magnets dictated large transistor amplifier power supplies. The required time resolution and waveform flexibility indicated the desirability of computer control. Both the amplifiers and controls are described, along with resulting improvements in the beam performance. A set of octupole magnets and programmable power supplies with similar dynamic qualities have been constructed and installed to control the anticipated high intensity transverse instability. This system will be operational in the spring of 1981.

Introduction

The RCS[1] is a six-sector 500 MeV combined function proton synchrotron. While it was originally designed as a booster for the Zero Gradient Synchrotron (ZGS), it has been used only as a proton source for bombarding a uranium target in Argonne National Laboratory's (ANL) pulsed neutron source program. Figure 1 shows the layout of the machine upon start-up in the spring of 1981. The extraction point has been moved from the L-4 straight section, the point from which beam was delivered to a prototype neutron target for about two years.

A major new facility is being constructed in one of the former ZGS experimental halls. This facility, Intense Pulsed Neutron Source (IPNS), consists of a proton transport tunnel, a well-shielded target monolith, and 12 neutron beam lines. To reach this target, the extraction point in the RCS is being moved to the L-3 straight section, as shown in Fig. 1.

The RCS, which uses H^- injection from a 50 MeV linac, is a fast cycling (30 Hz) resonant machine with a single-turn extracted pulse width of 80 ns. The design tune is 2.20 in the horizontal plane and 2.32 in the vertical. Sets of quadrupoles were located in the L-6 and L-3 straight sections and sets of sextupoles in the S-2 and S-5 straight sections. Each of the quadrupole magnets was 0.248 m long with a 0.127 m bore. They were laminated for possible pulse operation, but each has an inductance of 25 mH. A pair of these magnets yielded a maximum gradient of 1.8 T/m-m at 635 A, creating a tune shift of about 0.5 at 50 MeV. Each sextupole magnet is 0.223 m long, 6 mH inductance and can provide a gradient of 44.02 T/m^2-m at 635 A. This gradient provides over six times the theoretical correction expected[2] to properly control the chromaticity. These magnets were connected to dc power supplies

Programmable Sextupole System

When the machine tunes were first measured in 1978, a dynamic change of sign in the horizontal chromaticity was noted at about 250 MeV.[3] This, along with

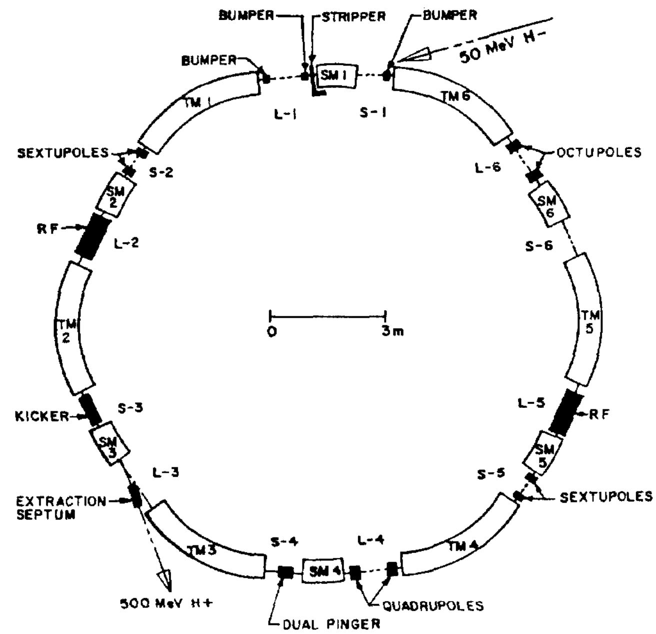

Fig. 1

normal tuning experience, pointed out the need for dynamic control of the sextupole currents. The originally planned method for dynamic control was a biased 30 Hz resonant control of the currents in which the dc level, the ac level, and the ac phase would be controlled. This apparatus was constructed and, not surprisingly, proved to be inadequate due to a lack of tuning flexibility.

Data gained from operation and machine studies indicated that one fast decay, monopolar linear transistor amplifier capable of 120 A peak current would serve well as a power supply for each of the four sextupole magnets.

Step programmability every 0.5 ms during the 16.7 ms accelerating cycle was thought to be adequate. The computer controlled function generator that was designed and constructed to provide this sort of control is described in a following section of this paper.

The rapid current changes required, the 6 mH inductance of each magnet and the high cost of high-voltage, high-power transistors indicated parallel instead of series control of magnets requiring identical currents. The availability of excess ZGS transformers and transistors were also factors in the amplifier design. Four transistor amplifiers, each capable of 7.5 kW of power dissipation, were built. Each of the two magnets for horizontal chromaticity control had its own power amplifier, but the amplifiers were driven by the same drive command. Current feedback was used to insure tracking between the two currents. The two vertical sextupole magnets for vertical control were similarly powered.

Figure 2 is a symbolic diagram of the power amplifier. The transistor, T_0, represents 48 Westinghouse

*Work supported by the U.S. Department of Energy

0018-9499/81/0600-3020$00.75©1981 IEEE

163-20 NPN silicon power transistors in parallel. A commercial noncontact current transductor with good frequency response is used as the source of the feedback signal. While somewhat expensive, its performance is far superior to that achieved using a resistive shunt. There is nothing unique about the amplifier except perhaps its protection circuits. Considerable emitter degeneration and current feedback allow the use of diode D_1 to prevent one shorted transistor from turning on all the others. Diodes D_2 and D_3 are or'd into a comparator to shutdown the amplifier if high voltage is detected on any base or any emitter.

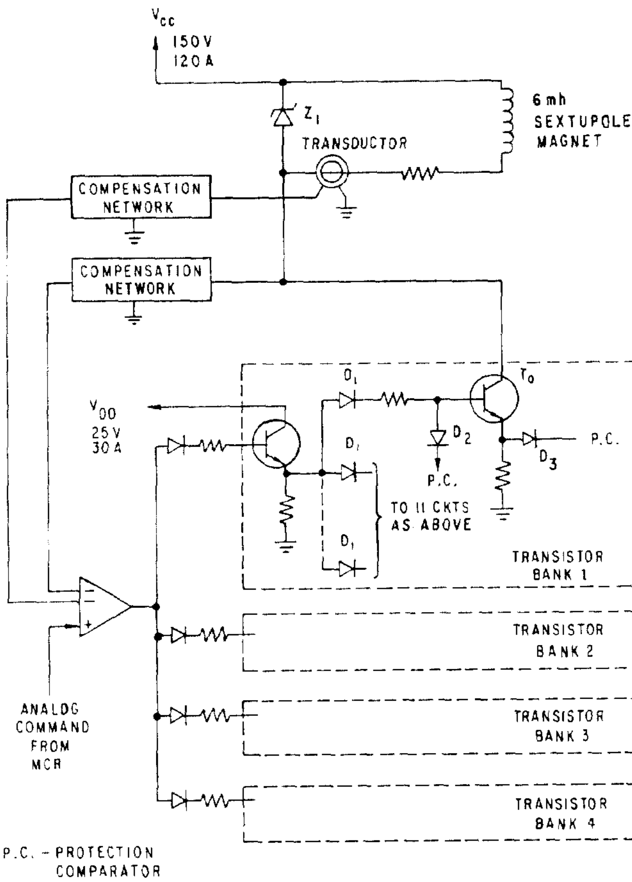

Fig. 2 Sextupole Power Amplifier

There is one driver transistor for each of 12 output transistors. All 13 are mounted on the same heat sink. The protection circuitry indicates on which heat sink a failed transistor is located to facilitate maintenance by the accelerator operating crews. Device Z_1 is 20 water-cooled diodes in series to force a rapid current-magnet-current decay when the transistors, T_0, are turned off. It is necessary in this accelerator to get ready for the next pulse in about 12 ms. A better, but prohibitively expensive, technique is to use a NPN-PNP complementary amplifier; however, the "homemade" Zener diode, Z_1 works quite well. Of course, V_{Z1} adds to Vcc when Vceo ratings of the transistor are considered.

Figure 3 shows the function generator command and resulting magnet current. A di/dt (I = 0) of 25 kA/s is achieved and a decay from 120 A to 0 A in about 10 ms is possible. The beam pipe through these magnets is about 10^{-4} m thick stainless steel. Eddy currents in this pipe cause a phase shift of the flux inside the pipe of 2° with a 30 Hz sinusoidal forcing function.

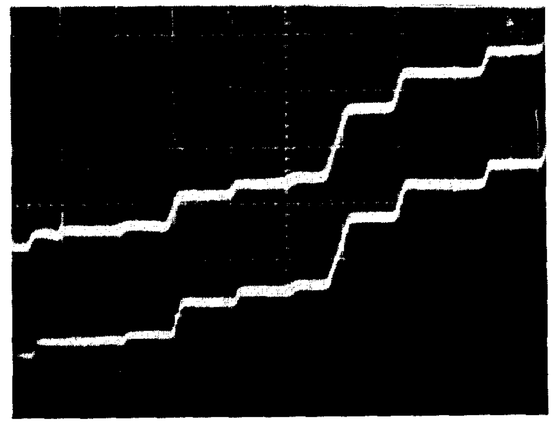

Fig. 3 Upper Trace - Computer Command Function
Lower Trace - Sextupole Power Amplifier Response
Horizontal Scale - 2 ms/cm
Vertical Scale - 10 A/cm

With big transistor amplifiers, the heat sinking is about half the job. After some unsatisfactory experiences with commercial units, a simple in-house design was chosen. Transistors are mounted every 0.035 m on a 0.6 m long x 0.075 m wide x 0.0035 m thick copper plate. One cm OD copper tubing is soft soldered to each outside edge of the plate. Large fillets maximiz. the area of heat conduction to the water from the plate. The cooling water for all the transistors is supplied in series. About 5 l/min of water has a ΔT of 8.5°C at maximum amplifier dissipation. Under these conditions, the hottest transistor junction is about 110°C, a safety margin of 65°C.

The results of operating with these programmable sextupole amplifiers has been excellent. In fact, all the concern about transistor protection seems to be for naught, since no transistors have failed in four months of operation. The proton beam is smaller and more extractable, and beam intensities of 2×10^{12} p/p have been reached. Due to the high repetition rate (30 Hz) and sextupole current sensitivity of this accelerator, badly mistuned sextupoles will cause large radiation losses inside the accelerator tunnel. Interlocks have been added to shut down the injected beam whenever the sextupole currents are not about as expected.

Programmable Octupole Magnet System

The spring 1981 start-up of the RCS will see two octupole magnets installed in the L-6 straight section of the RCS. Appropriate amplifiers will be connected with performance and protection similar to that already noted for the sextupoles. The beginnings of this project occurred about two years ago. While no definite need for octupoles was established at that time, the long delay required to get laminations stamped, coils built, etc., motivated construction based on probable future need. After considerable machine studies there is still no certainity that these magnets will cure the RCS high intensity problems, but are regarded as good insurance.

The required strength of these magnets at a beam intensity of 3×10^{12} protons was calculated to be 4.83×10^3 T/m^{3-m} at 500 MeV.[4] Limited straight section length was a significant design constraint. A 10 turn/pole coil design has resulted in a measured inductance of 2.6 mH in a completed magnet. The magnets have a laminated iron length of 0.446 m and an effective magnetic length of 0.461 m. It requires 458 A to produce the required gradient. This is some 15% above the computer prediction[5] but is within the capability of the power amplifier. The magnet coils are rated 300 A dc with 13 l/min of cooling water.

The power amplifiers have much greater capability than those for the sextupoles. There are 132 parallel-ed transistors in the output stage operating with a collector voltage of 155 V. A di/dt (I = 0) of 55 kA/s has been measured. The amplifier will deliver the required power, but the safety margin with 10 l/min is only about 25°C at the transistor junction. Of course, operation will be pulsed, not dc, and these temperatures should not be approached during normal operation.

Function Generator Design

Since it was desired to have a modular function generator design which could be used for RCS applications other than the sextupole/octupole systems, the design requirements go somewhat beyond those required for these systems. For instance, while a staircase-like output would probably be adequate for a relatively low-pass application like that described, it was desired to have a ramp-like output for applications such as beam steering and RF voltage control. Further, even though a 0.5 ms break-point spacing was adequate for the tune correction system, a 0.1 ms break-point spacing was chosen to give greater flexibility and a more curvilinear output for higher performance systems. Besides these particular requirements, there are the usual requirements of high stability, high dv/dt output capability, and high accuracy. Moreover, the function generators must be computer controlled to provide operator control flexibility, storage/retrieval, and other features.

Hardware Description

Figure 4 is a block diagram of the function generator. The essential features are a Random Access Memory (RAM) which feeds a register, Digital-to-Analog Converter (DAC), deglitcher, and integrator. The 12-bit values in memory represent the slopes of each breakpoint section. The break points occur at uniform 0.1 ms intervals synchronized to the RCS timing system. The integrator is clamped to ground at the end of the function so that a stable starting point is provided. Any overall offset required is provided by the upper register DAC and summing amplifier. The deglitcher is essentially a sample-and-hold circuit which holds the DAC output during changes of digital input, thus eliminating what would be error-producing transients. The RAM has 256 12-bit words. The first word is directed to the offset register while the remaining 255 words allow the generator to produce a 25.5 ms long function. This is, of course, adequate for the RCS's 16 ms acceleration period. The maximum dv/dt possible allows a full scale output swing of -10 V to +10 V in 40 break-point times or 4 ms.

Operator Control Features

Since the function generators are used for different applications, some of which have different performance limitations as indicated above, different computer software routines are used to interface them to the operator. For the tune correction magnet control, a list of break-point times and current values (in A) are presented on command on a display screen. The operator can add, delete, and change break-point times and current levels via a keyboard. He can also "tune" a current level by specifying a small delta current and then increase and decrease the particular level in an "eyes-off" mode.

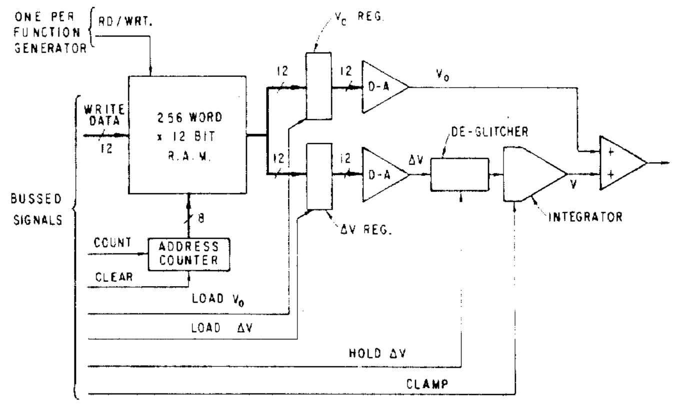

Fig. 4 Block Diagram of Digital Function Generator

Because of their interaction, the two function generators controlling each multipole system are forced by the software to have the same set of break-point times even though current changes may not occur at all points. The software also limits the maximum dv/dt for each section to correspond to 15 A per 0.5 ms (minimum break-point spacing) in order to more closely reflect the limited capability of the sextupole power supply. The software (by means of logic in the control module) also maintains a narrow pulse generated at the proper real time to show the operator where in time his latest changes are taking place. Other features allow the operator to save the function at any point for later use and to recall previously stored functions.

The flexibility of a computer based function generator such as this is evidenced by the fact that the software underwent several changes and enhancements before the tune correction system was operational and is now due for changes to add new features.

Acknowledgments

The authors gratefully acknowledge the guidance and assistance supplied by the following people: J. Simpson, Y. Cho, J. Bywater, R. Lari, T. Khoe, R. Putnam, and R. Zolecki.

References

1. A. V. Rauchas, F. R. Brumwell, G. J. Volk, "Commissioning of the Argonne Intense Pulsed Neutron Source (IPNS-I) Accelerator," IEEE Trans. on Nuclear Science, Vol. NS-26, No. 3 p. 3006 (June 1979).

2. Booster II, A 500 MeV Booster Injector for the Zero Gradient Synchrotron - A Design Report, Argonne National Laboratory, Accelerator Research Facilities Division, Internal Publication.

3. Y. Cho and A. V. Rauchas, "Observations and Cure of the Head-Tail Effect in the Argonne Rapid Cycling Synchrotron" (Proceedings of this conference).

4. T. Khoe to C. Potts, private communication Accelerator Research Facilities Division.

5. R. Lari to C. Potts, private communication, Accelerator Research Facilities Division.