CONTROL AND PERFORMANCE OF THE AGS AND AGS BOOSTER MAIN MAGNET POWER SUPPLIES*

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SUMMARY

Techniques for precision control of the main magnet power supplies for the AGS and AGS Booster synchrotron will be discussed. Both synchrotrons are designed to operate in a Pulse-to-Pulse Modulation (PPM) environment with a Supercycle Generator defining and distributing global timing events for the AGS Facility. Details of modelling, real-time feedback and feedforward systems, generation and distribution of real time field data, operational parameters and an overview of performance for both machines are included.

FACILITY OVERVIEW

The AGS Booster synchrotron is an intermediate accelerator between the 200 MeV Linac and the AGS and operates in two modes. This machine is ¼ the radius of the AGS and its primary function is that of the source of protons for the AGS. The alternate mode is to accelerate partially stripped heavy ions to be fully stripped after extraction toward the AGS. The high vacuum nature of the Booster (10^{-11} Torr) permits very efficient injection and acceleration of these partially stripped ions to an energy sufficient to allow them to be fully stripped in the transfer line between the Booster and the AGS.

POWER SUPPLIES

The AGS Booster Main Magnet Power Supply (BMMPS) has been well documented in earlier publications [1,2]. In this description, the performance of the system will be limited to that necessary for a proton physics program. For this mode, the BMMPS operates in a rapid cycling mode (5-7.5 Hz) with a current range of 410A to 2500A and back in the repetition period. The power supply consists of six independent rectifier modules that operate in series. Depending upon the nature of the B(t) cycle defined, any one to all six of these modules can be used to power the series connected ring dipole and quadrupole magnets.

Although there are two special case modules for high current operation (6000A), the fast cycle operational limits of the power supply are 1000V per module at 3000A. When not in use for any portion of a given magnet cycle, a specific power module is automatically bypassed by triggered SCR switches.

This power supply system is connected directly to the local utility line without buffering. Of concern therefore, are the induced harmonics on the utility power grid due to the cycling of this supply. In order to be protected from damage to their system due to these "disallowed" harmonics, a circuit breaker has been installed on the 69 kV line feeding the Booster. The utility can disconnect the BMMPS from the line if the power content of any of these restricted harmonics exceeds the allowed limit as determined by the pulsed power monitoring relay, which performs repetitive Fourier transform calculations. An FFT analysis of the power waveforms is done prior to operating with a specific set of magnet functions.

The AGS Main Magnet Power Supply (AMMPS) is buffered from the utility through a motor generator set (Siemens) that has been in operation for many years. During a recent upgrade, the rectifier system, triggering circuits, feedback loops and the monitoring and controls systems have been replaced. A large number of the relay control functions are accomplished by PLCs. The new rectifiers are comprised of eight total modules, four for flattop (F) and four for pulsing (P). The F and P modules are operated in parallel as opposed to the Booster series connection. The triggering and control loops are identical to the Booster. The cycles are programmed, as in the Booster, by a set of vector function generators.

In further discussion, techniques described are applicable to both power supplies.

CORRECTION LOOPS AND AUTO-CALIBRATION SYSTEM

There are a number of correction loops that are utilized to provide the necessary tracking of the field with respect to the reference functions, and to preserve the regulation of cycles. The loops are of two types, real-time feedback and real-time feedforward. Also, field triggers derived from a Gauss Clock (GC) and a self-correction field loop provide enhanced operation. Each module (Booster = 6; AGS = 8) has a voltage feedback loop for voltage regulation and short term magnet current reproducibility due to disturbances from the AC input lines. To compensate for medium to long term current drift two systems are used; one being a real-time

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current feedback loop and the other a long term feedforward correction. The analog current loop can only play a minor role due to the long time constant in the magnet loads. The long term correction system improves the absolute output current calibration of the power supply by averaging the current error over several cycles. The present mode takes a running/updating average during the dwell portion of the cycle and holds the average current over this interval to an absolute value of about +/-0.2 Amperes.

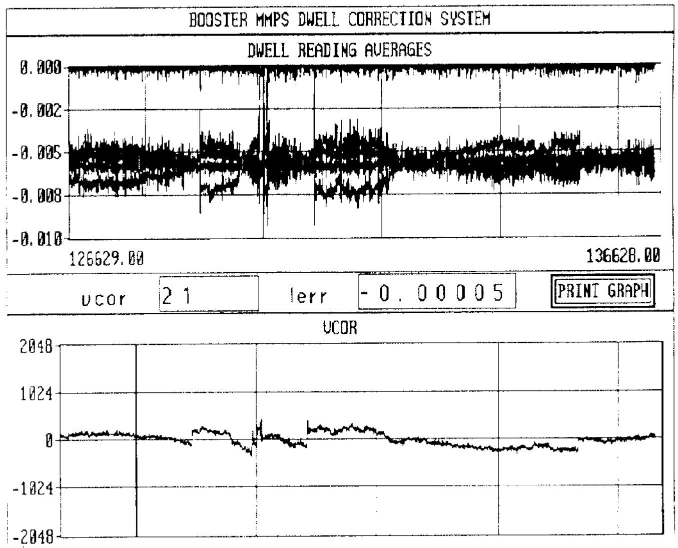

Figure 1.

The Gauss Clocks for the Booster and AGS consist of long pickup coils in a reference magnet for each machine connected to a temperature stabilized bipolar voltage-to-frequency converter; providing both Up and Down Gauss Clock counts to the Gauss Line Generator for global distribution during a magnet cycle.

Although the Gauss Clock marks the incremental (0.1G/count) field as the magnet cycle changes, it must be referenced to an absolute measurement of field to assure major events (injection, extraction) reproducibly occur at the same field from cycle to cycle and day to day. The method developed for the Booster and AGS is to sample a Hall probe installed in the reference magnets over one 60 Hz line cycle during a period in each magnet cycle when the field is changing little. The calibrate system maintains its own accumulator of Gauss Clock Up/Down counts. During each measurement, a closed loop is enabled which slews the accumulator up or down to match the reference Hall voltage. This updated GC signal is then used to reset (via a high speed (50MHz) interface) the Gauss Line Generator to the measured value immediately following this interval for each magnet cycle.

With both the long term and field auto-calibration systems in operation, all field triggers throughout the cycle have a long term reproducibility of about +/-0.5 Gauss.

TIMING

Timing for AGS Complex of accelerators is distributed for real time processes as well as B(t) timing from each machine for general use. These field markers are distributed for general use, primarily within an accelerator, to define critical events in a cycle such as injection, rf capture, extraction start and in the AGS, transition.

Fundamental to the timing, is the use of a Supercycle which operates on a line synchronized 60 Hz clock and defines the repetitive nature of the magnet functions [3]. Major machine events are globally distributed and include the primary markers, Time = 0 (TO), events to start clocking each magnet function. Several different magnet cycles can be stored and executed in sequence by defining different "Users" within the Supercycle. Up to four separate Users can operate in sequence, each with its own unique main magnet cycle.

HIGH LEVEL CONTROL

Control of guide field at the AGS facility has historically been from the engineering view where the electrical properties of the system were defined and the cycle was fixed. The new AGS distributed control system based on a workstation with remote computer environment (Apollo/HP) has allowed the user to shift control perspective to that of detailed definition of the B(t) function as required to best control beam parameters. To achieve this higher level mode, software was developed to allow the user to request a given B(t) function and then convert this request into a form the hardware could respond to using an electrical model of the power supply system as a whole. The B(t) function is derived by defining zones with specific field properties that are joined by using interpolation options within the program.

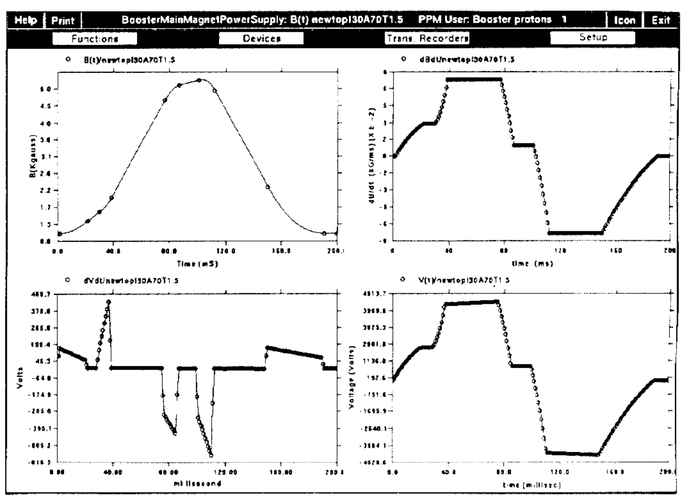

Figure 2 - MMPS program view of several B(t) related functions allows the User to verify they are as required for the cycle.

The local control hardware is driven by a family of vector functions for the system. Vector functions provide a great deal of flexibility in defining a magnet cycle. A series of linear vectors, up to 256, are fitted to the requested cycle and loaded to the hardware; a reference current function and the corresponding set of voltage functions. In the Booster, there are six voltage functions corresponding to each of the individual modules, even when the required voltage is zero. The AGS has one current and four voltage functions that are generated. Of importance to an accurate model for the system is the voltage drop across a power supply module that is bypassed for any part of a cycle. Given that at low currents or on flattops, this bypass voltage represents a significant fraction of the total voltage driving the magnet, this was first calculated, then empirically refined to image the integrated power supply - magnet system.

The conversion of a requested B(t) function into a family of electrical signals begins with a derivation of the corresponding current function from the measured B to I transfer function of the main ring magnets/power supply system. The calculation of the total voltage functions depends upon refined models of the basic R/L circuits. A time delay is included to accommodate the sampling delay of the basic rectifier circuits. A typical set of conversion parameters used in the program is shown in Figure 3.

Formula V = L*dI/dt + R*I
where L=>Inductance; R=>Resistance;
and if V < 0.0, V is scaled by NegScale

Parameter AdjustTimeV is used to compensate power supply delay.

Bypass modelling V = A + B * I + C * I * I
where A, B and C are coefficients

L in Henry:	0.148100
R in Ohm:	0.113300
AdjustTime in millisec:	1.600000
A in Volts :	1.751180
B in Ohm :	9.7100e-04
C in microOhm/Amp:	-2.5500e-02
NegScale (%):	0.986000

Figure 3 - MMPS program electrical model coefficients for a given magnet cycle.

The total voltage is divided into components according to the individual module maximum ratings. Once this function family is generated from the requested B(t), the electrical constants and function/vector fitting parameters, they can be archived for immediate use and loaded to the hardware, or saved for later recall.

SET-UP OF CONSTANTS

Although this view of a system model is sufficient for simple and/or single magnet cycles, it is not adequate when two dissimilar cycles operate within a Supercycle. The system resistance is not truly linear at high currents and the inductance also varies at these higher currents. Methods for determining these parameters experimentally have been developed. Alternately, tables of values as a function of operating current can be used.

Knowledge of the magnet cycle is most critical during the injection process given that the injected beam of fixed rigidity must be well controlled. Also, since these magnet cycles are contiguous, they must be smooth and continuous from one to the other. The DC or dwell value is this constant amplitude which is usually 10% - 15% less than the injection field. The resistance term (R) for the cycle is determined by setting the magnet to a constant dwell value from the program B(t) and measuring the resultant current and field from the Hall probe in the reference magnet. The value of R is then adjusted within the program until the current and field match that requested.

Once the resistance is fixed,the best approximation for the inductance (L) is obtained by pulsing the magnet system with a moderate current (2500A) from a defined B(t) function and adjusting the L term until the measured peak current is equal to the requested peak current. With the accounting for the individual bypass voltages throughout a magnet cycle, this should provide in principle, a sufficient power supply - magnet model. However, due to the simple modeling of the R, L and bypass voltage terms and the finite gain of the voltage feedback loops, it was found that once this process was completed for a given magnet cycle, the integral of the total voltage during the cycle from all sources was not zero and therefore the magnet field was different at the end of the cycle than from the beginning. This led to an offset injection field for the following cycle.

The offset is corrected within the high level program by introducing independent calibration constants for the positive and negative phases of the power supply voltage output. The negative calibration is empirically adjusted to give a zero net current change over a magnet cycle.

Given this present definition of main magnet cycle control, previously cumbersome changes to a magnet cycle that may be small in nature but lead to improved control of beam properties are now routinely available.

REFERENCES

[1] A. Soukas, et al., Operational Status of the AGS Booster Main Ring Power Supply, XVth International Conf. on High Energy Accelerators, Hamburg, Germany, 1992.

[2] A Soukas, et al., The AGS Booster Main Ring Power Supply System, Particle Accelerators, 1990, 29, pp. 121-126.

[3] D. Barton, private communication.