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TRANSVERSE BEAM DAMPERS FOR THE BROOKHAVEN AGS*

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ABSTRACT

A wide band damper system has been developed for the Brookhaven Alternating Gradient Synchrotron (AGS). The system consists of two sets of PUE pickups, analog and digital processing electronics, four 500 Watt wide band power amplifiers, and two pairs of strip line deflectors. The system is currently used to damp transverse coherent instabilities and injection errors, in both planes, for protons and all species of Heavy Ions. This paper discusses the system design and operation, focussing on the engineering considerations and problems encountered in the actual implementation. Operational data from both protons and Heavy Ion beams is presented.

INTRODUCTION

As more beam intensity is demanded from new or existing accelerators, there is an increasing effort to find ways to control or eliminate the instabilities that occur during acceleration. As a result, active feedback systems called "Beam Dampers" have been added to most older operating machines and are being designed into the newest ones¹⁻⁴. Dampers are used to attenuate the effect that one bunch has on the following bunches due to the image fields it induces in the beam pipe. These Wake Fields cause Coupled Bunch or Resistive Wall Instabilities. Wake Fields can effect the beam transversely and longitudinally.

The awareness of the existence of resistive wall effects in accelerators is not new, papers discussing these effects go back to the 1960's^{5,6}. The availability today of inexpensive digital electronic solutions to the wide band damping problem is what has made the construction of such devices feasible.

Sensing longitudinal motion and correcting it is a very different technical problem from the corresponding problem in the transverse direction. Since the AGS Beam Damper is a transverse damper, the rest of this paper will be concerned exclusively with the transverse case.

TRANSVERSE DAMPERS AND DAMPING

A Transverse Damper is an active feedback system consisting of one or more beam position pickups, a signal processing midsection and a power amplifier driving

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a beam deflector. The pickup measures the beam position and the processor calculates, by some algorithm, the correct deflection to apply to the deflector in order to move the beam toward the desired position. Transverse Dampers can help reduce transverse coherent oscillations in the beam motion relative to an equilibrium orbit during acceleration or due to injection errors but the implementation can be more difficult than it sounds. Some important technical issues are listed below.

First, resistive wall instabilities cause beam oscillations that grow with time. The damper deflector drivers must supply sufficient power to overcome and reverse that process.

Next, the actual sensing of transverse beam is usually accomplished by placing pickup electrodes inside the beam pipe which couple to the aggregate charges of particles contained in a bunch. These signals provide position information only, once every revolution. From this a correction signal for the deflector must be determined.

The deflector must be some distance away from the position sensor to allow for the time it will take for the system to determine the appropriate correction. But bunches undergo oscillations as they travel along the machine axis and it must be known what deflection to give the bunch at this new point under all operating conditions.

The beam equilibrium orbit will often not be on the detector center, in fact beam orbits in any accelerator are moved radially often for operational reasons. A way of establishing the equilibrium or central orbit position must be incorporated in order to keep the damper from wasting all its power in trying to drive the beam back to the detector center.

Lastly, timing must be provided which is phase locked to the beam so that the detector signals can be properly acquired and the kick properly delivered.

THE AGS BEAM

The Brookhaven Alternating Gradient synchrotron (AGS), originally constructed as a proton synchrotron, has been upgraded over the years so that it can now accelerate protons, heavy ions up to Gold $+79$, and polarized protons. Physically it is 2650 feet in circumference and the beam pipe is a 6 by 3 inch ellipse. The machine operates at a harmonic number of 12 and a nominal tune of 8.75 in both planes.

In proton operation the AGS is filled from a 1.5 GeV/c Booster Ring in four groups of three bunches each, 177 milliseconds apart, into the twelve AGS buckets by a sophisticated timing scheme. The bunch separation at injection is about 250 nanoseconds. The beam, after the filling is completed, is accelerated to 28 GeV/c where the bunches are separated by 220 nanoseconds. This represents an overall sweep in frequency from 4.0 to 4.5 Mhz. Depending on where in the cycle one looks, the bunches can occupy from 20% to 80% of a bucket's width. Present total beam intensities are up to 25×10^{12} protons. It is intended to reach 60×10^{12} by the end of 1994. Effective transverse damping in both vertical and horizontal planes is an essential part of achieving this goal.

With heavy ions, injection of beam into the AGS is accomplished from one Booster transfer of three or six bunches totaling 2×10^9 ions. The beam is then

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allowed to debunch, rebunching into twelve bunches as acceleration in the AGS begins. While the transverse dampers are not needed to damp high intensity instabilities with heavy ions they will be effective in damping injection errors. This will minimize emittance blow-up to meet the requirements for RHIC injection.

THE DAMPER SYSTEM

A simplified block diagram of the AGS Damper System is shown in figure 1. Only one plane is shown for simplicity, both planes are identical. Beam position information is obtained from a pair of capacitive pick up electrodes (PUE). The beam pickups and the stripline deflectors are contained in F20, one of 12 straight sections in the ring. The delay before any correction signal can be applied is one complete revolution of the machine, 2.6 to 3.0 microseconds.

THE FRONT END

The front end consists of the PUE and four low noise preamplifier channels, one for each plate. The PUE⁷ contains both horizontal and vertical electrodes nested together in one cylinder. The unit is about eight inches long. Coaxial cable is used to connect the PUE plates to preamplifier inputs. This provides some distance between the electronics and the high radiation environment of the beam. The lengths of the cables, about five feet each, are matched to preserve timing. A 51 Ohm resistor is added in series near the PUE end to limit reflections.

The preamplifier is the same one developed for the AGS Booster PUE's⁸. It has a bandwidth of 40 KHz to 20 MHz and provides three gain ranges, one-tenth, one and ten, which can be remotely selected. The output has a dynamic range of +/-15 Volts and the channels are matched to 0.027dB.

THE ANALOG PROCESSING ELECTRONICS

Four semi-rigid, 50 Ohm coaxial cables, about 125 feet long, connect the front end output signal to additional processing electronics located outside the AGS ring in a building known as the F18 House. The cable lengths were measured with a Time Domain Reflectometer (TDR) and cut to within a few nanoseconds of each other. The semi-rigid cable is a necessity because it has the bandwidth required to preserve the fidelity of the bunch signals over these distances.

In the F18 house, three sum and difference hybrids (North Hills Electric No. 50-212-RE) are used to create Inner minus Outer, Top minus Bottom and Total Sum signals from the four PUE plate signals. From these the usual difference divided by sum values, which are proportional to beam position, will be formed.

Next, the sum and difference signals go to a buffer/amplifier designed to provide an additional zero to 30dB of adjustable gain in both the sum and difference channels. In the final version the gain of each buffer will be set by the AGS control computer.

Following the buffers are four channels of baseline restoration and fast, gated integration. Integrating the bunch signals is a necessary step in obtaining the position data from the pulses because it allows for the measurement of the bunch centroid independent of shape. First the proper baseline for the bunch signals must be established because the original baseline information is lost in the capacitive pickup process. In order to restore the baseline, the signal is sampled at a time defined to be "between" bunches and that sample is subtracted from the signal for the entire next interval. This technique works well so long as a clearly defined null period exists between the bunches.

The sum, vertical, and horizontal difference signals are integrated over one RF period. The integrators are identical to the ones used in the Booster Damper System⁹. They use a clever scheme which multiplexes two internal integrating channels, effectively halving the bandwidth required and allowing up to half an RF period for the result of the integral to be acquired. For the proper operation of this circuit, timing is critical. A timing module provides reset and integrate timing logic synchronized with the AGS RF and locked in phase with the beam.

THE DIGITAL PROCESSING ELECTRONICS

The Digital Processor digitizes the integrated sum and difference analog signals from the PUE's with four high speed, eight bit, analog to digital converters (ADC). The values are clocked through the system by a clock signal, equal in frequency and locked in phase with the bunches. The Processor uses a programmable read only memory (PROM) acting as a look up table to generate the ratio of difference divided by sum. The quotient is sent in three different paths. On one path it is stored in an external memory for off line diagnostic analysis of bunch positions. The second path stores it to be used two revolutions, or 24 clock pulses, later. On the third path, an arithmetic unit subtracts the stored value from two revolutions ago, producing a deviation value. This technique achieves closed orbit suppression so long as the fractional tune is at or near $3/4$, the nominal AGS value.

The deviation is clocked into another PROM which acts as a correction look up table. This table contains multiple pages of different transfer functions that can be selected remotely through the AGS control computer or by specific time events. When a value is produced from the transfer function table, the determination of the correction is complete. In the final step the correction value is clocked into an eight bit analog to digital converter (DAC), converting it to an analog signal for the power amplifiers.

Since the whole process takes less than a revolution period, a delay is needed for the correction value before it is input into the DAC. This delay is accomplished using a first in first out (FIFO) memory. The FIFO is initialized with a programmed number of blank input bytes prior to strobing in the first data byte. The actual number of blank bytes can be set between zero and eight, selected by a switch on the circuit board. In the FIFO, this establishes a ripple through delay, in clock pulses, of input to output data. Since this FIFO can have separate clocks for input and output, phase and frequency of the input and output data are independent. This gives

the FIFO an the advantage over a register delay where the frequency and phase of the input and output must always be the same.

DAMPING ALGORITHMS

Within the Digital Processor transfer tables are imbedded several choices of algorithms¹⁰. They are: linear damping with several slopes, linear anti-damping, bang-bang damping and bang-bang anti-damping. The linear algorithms generate a correction signal proportional to the deviation, the bang-bang algorithm applies the maximum corrective kick that the system is capable of if the deviation is greater than some predetermined amount. The anti-damping modes are intended for diagnostics or for kicking the beam to make tune measurements.

TIMING

The proper acquisition and processing of information from the PUE's would be impossible without synchronization to the bunch signals. The availability of a low level RF signal, accurately phase locked to the beam bunches is necessary for the success of this technique. With the AGS RF upgrade project, two signals, RF sine and cosine are available. Using these two signals, and a high accuracy phase shifter developed by the RF Group, independently phased reference signals are available¹¹. The Analog Processor uses one phase to drive the baseline restoration, integration and multiplexing/demultiplexing. The Digital Processor takes three phases, adjusted appropriately, to time the ADCs, the system clock, and the output of the DACs.

One problem related to timing has to do with the inherent difference between phase and delay. Two conditions need to be met for proper functioning over the 0.5 Mhz frequency range from first turn through acceleration. The integrator clock and the bunch signal returning from the PUE's must remain in phase at the integrator location despite the fact that the bunch signals themselves are delayed by the length of the cable from PUE to F18 House. In addition the stripline drive signals must, at the F18 House, anticipate the bunch to be deflected by the same delay since it will take the same amount of time for that signal to propagate along the cable to the stripline. Fortunately the upgraded RF system, due to similar requirements elsewhere, has the provision to supply signals with what amounts to negative time delays. The RF(sine) and RF(cosine) signals at F18 have been set to effectively anticipate beam by the distance to the stripline. Local digital delay circuits then produce the clocks that contain the proper delay for the PUE integrators.

THE OUTPUT

The correction signal for each plane from the eight bit DAC is inverted and both the signal and its inverse are amplified by two wide band power amplifiers. The RF amplifier used is a commercial unit, the Model 134C, manufactured by Kalmus Engineering of Woodenville, WA. It has a 57 db gain over a bandwidth of 10 KHz to 220 MHz, and it is capable of delivering 500 Watts CW into a 50 Ohm load.

While the bandwidth is greater than required, this unit was chosen because of its low frequency cutoff. The low frequency cutoff must extend below the lowest frequency expected in the oscillations to be damped. That frequency is a function of the revolution frequency and the machine tune and, for any particular setup equals the difference between the revolution frequency and the revolution frequency multiplied by the fractional tune. In other words, it is the low frequency betatron side band. For the AGS this amounts to about 60 KHz assuming a tune of 8.75.

The stripline deflectors are located in the F20 straight section, just downstream of the PUE's. The plates are driven as a pair, in push-pull, by separate drive amplifiers. There are four strips, a horizontal pair and a vertical pair, about 36 inches long and 2 1/2 inches wide, contoured to the curvature of the vacuum pipe and spaced to maintain a 50 Ohm characteristic impedance. Feedthroughs are provided at both ends and the drive signal is connected to the downstream end. Detailed measurements have been made on these striplines to assure that the impedance of the line and the transitions at both ends maintain 50 Ohms over a wide frequency band.

The upstream end of the stripline terminates in an external, oil filled 50 Ohm load capable of dissipating up to 500 Watts. It is a commercially available unit manufactured by Bird Electronic Corp. of Cleveland Ohio. The load provides an attenuated monitor output that is brought back to the electronics with the same type semi-rigid coaxial cable used for the PUE signals. This return signal is used in the setup of the system to allow the relative timing of the drive and bunch signals to be measured.

SETTING UP WITH PROTONS

Commissioning of the AGS Damper System began in May of 1993 with protons. Because the new AGS RF System was being commissioned at this time, the availability of consistent RF was not achieved for some time. This gave us the opportunity to look in detail at the system and to resolve some unforeseen problems.

The PUE signals were clear and noise free from the start. With protons the gain setting required from the front end was one. The technique of filling the AGS with three bunches at a time proved to be an unanticipated blessing. With this signal, it was much easier to correlate signals as they propagated through the system then when all buckets were full. Combining this with the fact that the stripline can also act as a wide band beam pickup, it was easy to quickly determine if the drive signal was arriving at the stripline at the correct time.

The original implementation of central orbit subtraction was to take an average of the preceding 16 difference signals as an approximation to the correct orbit. This proved to have its limitations and so the two turn look back approach described above was implemented. This implementation, however, depends on a tune fractional tune close to 0.75 to function efficiently. During much of the setup the AGS was running with the vertical tune near 8.8 but with the horizontal tune close to 8.9 making demonstrating effective damping in the horizontal plane difficult. In the future it is expected that both tunes will be closer to the 8.75.

One feature that has proven valuable with regard to exploring various algorithms for damping and for other logic problems is that the Digital Processor is constructed largely from programmable logic devices. This makes changes in transfer tables and logic possible without hardware changes.

SETTING UP WITH HEAVY IONS

To date, damping of the heavy ion beam at injection has proven impossible due to the setup. With the present technique of transferring the beam from the Booster, when the harmonic number is six instead of three, no phase locked RF signal is available from either AGS or Booster. This is a system problem which will be changed in time. In the meantime the AGS has been accelerating heavy ion beams and so there has been ample opportunity to examine the PUE signals. The preamplifier is set to a gain of ten to see these signals and has produced some of the cleanest PUE outputs available at the AGS. This has raised the confidence that damping of the heavy ion beam will be a success once the RF is complete.

SOME RESULTS

In Figure 2 below are traces of the analog processor signals during proton running. These are taken just after the first of the four transfers of beam from the Booster where only three of the twelve AGS "buckets" contain beam. Shown in the figure are, the sum signal (top), the integrator output produced by the sum signal (center) and the integrator output from the difference signal (bottom). Notice that the actual integration cannot be seen due to the action of the internal multiplexer. The result of the integration is available in the RF or clock cycle following the actual bunch occurrence.

Figure 3 shows a dramatic example of the effect of the vertical damper during proton running. The left side shows a trace over the entire AGS cycle of the F15 normalized internal beam current transformer. The steps in the beginning are due to the filling of the 12 AGS buckets, three at a time, over four Booster cycles. The right hand trace shows the next beam current signal with the Damper disconnected. Apparently the Damper is correcting an instability during the third plateau.

THE FUTURE

The effect of the damper on machine operation is not so easy to assess. One thing we hope to do in the future is to use the AGS Ionization Profile Monitor to measure emittance through the cycle. This will allow us to compare the effect of the Damper on the emittance growth in both planes.

The AGS Damper System has the potential to perform other tasks not emphasized so far. These in a sense come free. In the anti-damp mode, the device can be used to excite low level coherent oscillations. The system then acts as a tune meter. Next, a diagnostic memory capable of storing 10000 turns per plane of bunch position data will be added and will serve as a valuable tool in machine diagnostics.

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Figure 1 - System block diagram

Figure 2

Figure 3A

Figure 3B

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