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BEAM CURRENT MONITORING IN THE AGS BOOSTER AND ITS TRANSFER LINES*

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ABSTRACT

The new AGS Booster is designed to accelerate low intensity polarized protons and heavy ions, and high intensity protons. The wide range of beam parameters and the vacuum, thermal and radiation environment, presented challenges in the instrumentation design. This paper describes the problems and solutions for the beam current monitors in the Booster and its transport lines. Where available, results of the initial operation will be presented.

INTRODUCTION

The AGS, with a long history as a proton machine, also accelerates polarized protons[1] and ions,[2] up to S^{+14}. The Booster, a multi-function machine with instrumentation to cover a wide range of beams, will enhance all of these operating modes. AGS proton intensity will be increased by injecting 4 pulses of 1.5×10^{13} protons at a 7.5 Hz rate. The 1.5 GeV proton energy will reduce space charge effects in the AGS at low momentum and allow it to accept ions up to Au^{+33} for delivery to RHIC. Polarized beam intensity will be increased by accumulating 20 Linac pulses at 2×10^{10} each. The Booster circumference is 201.8 meters, one-quarter that of the AGS. The rf duration for protons will be 60 msec, and 620 msec for heavy ions. Protons (H-minus) are injected in the Linac-to-Booster (LTB) line, while ions from the Tandem Van de Graaff are injected from the HITL-to-Booster (HTB) line. The Booster-to-AGS (BTA) line carries the beam to the AGS.

This flexibility causes many problems. The LTB beam current monitors require three orders of magnitude in range (10 μA to 25 mA) and at least two in resolution. The Linac beam can be as short as 300 nsec (one Booster bunch) or as long as 400 μsec. The HTB ion beams range from 10 μA to over 100 μA, with pulse widths from five to several hundred microseconds. DC beams used for tuning vary from 10 nA to over 100 nA. The BTA line will carry 2×10^{10} to 1.5×10^{13} charges in three bunches as narrow as 50 nsec. Booster current can vary from 10 μA for single turn polarized protons or heavy ions to 2.9 A at full intensity. Injection stacking requires a rise time of under 1 μsec, but polarized proton accumulation can last 3 seconds. The electronics for low intensity beams must be in the tunnel to maintain low noise wideband signals. Here they risk radiation damage from the high intensity beam which can be interleaved with low intensity. The vacuum will be 3×10^{-11} Torr in the ring and 10^{-10} in the transport lines. While most of the current monitors are external to the vacuum, they must tolerate bakeout at 150 to 300° C, depending on location. The various types of monitors employed will be described. Fast bunch intensity measurements made with the beam position monitors in the LTB line[3] and in the Booster Ring,[4] and the wall current monitors in the Ring will not be described here.

TRANSPORT LINE CURRENT TRANSFORMERS

The beam current transformers used in LTB and HTB are similar to those in the BTA line. They are improved versions of the HITL units,[5] which were derived from a LANL design.[6] The new transformers have 4-inch and 6-inch IDs and much faster rise times for the detectors and the electronics than earlier designs. The droop of the LTB and HTB signals had to be less than 1% for a 500 μsec beam. The time constant (L/R) of the winding inductance (L) and the input resistance (R) "passively" integrates the differentiated beam current. High permeability Supermalloy 2-mil tape cores[7] of 0.5 by 0.5 inch cross-section were used. A larger core would give a higher inductance but at much higher cost. Increasing the number of turns (N) causes L to go up as N^2 but the signal goes down and the rise time gets slower. The LTB and HTB units have a 200-turn winding which gives L = 0.5 H. The usable rise time was improved to 20 nsec by putting 1 kOhm resistors from every 20th turn to a copper foil around the core.[8] This damped the ringing of the turn-to-turn capacitance and the coil inductance, but about 25 % of the signal was lost. The BTA units had only 40 turns since the beam lasts < 1 μsec and a larger signal was needed. With fewer turns, it achieved the same rise time without damping resistors.

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MASTER

Each core is mounted in a Mu-metal shield inside a 0.5 inch soft iron (1006) housing. This assembly sits on a three-point spring suspension isolating it from acoustic noise. The signals are carried differentially to the amplifier in the tunnel on RG-22 double shielded high frequency twinax cable. Units near the Booster have water cooling of the aluminum core casing to maintain it below 80° C during the 300° C bakeout.

Two separate amplifier chains are used to cover the three-decade intensity range, digitally selected by switches at the input and output of the board. Relays were chosen for their low contact resistance rather than FET analog switches which would have increased the droop rate. One amplifier chain was designed for high speed and low gain. Coupled to the standard 200-turn transformer it has a gain of 10 mA/V and a bandwidth of 5 MHz for a 70 nsec rise time. The slew rate of high speed AD848 op-amp is 225 V/μsec and not a factor in the rise time. Noise at the output is equivalent to 50 μA beam current. A differential input stage provides low frequency common mode rejection. The current boosted output stage has an output resistor for back-termination of long cables.

The other amplifier chain is designed for high gain with reduced bandwidth: 100 μA/V or 10 μA/V and a 1 μsec rise time when used with a 200-turn transformer. An OP37EZ was used for the first stages for its low noise and moderate speed. The final stage uses a high speed OP42EZ. A gain bit drives an FET analog switch to switch the gain of 10 stage in or out. The current equivalent noise for this amplifier chain is less than 1 μA for either gain. The input amplifier is differential with both high and low frequency common mode adjustments. Preceding the input is a "hum-bucker" transformer to further suppress high frequency common-mode noise. The final stage is current boosted and shares the output resistor with the faster amplifier.

A Base Line Restorer circuit located outside the tunnel is used to reduce the effect of 60 Hz pickup by the beam current transformer. The base line is sampled, using an AD582, just prior to beam time and subtracted from the pulse by a differential unity gain amplifier (OP27EZ), reducing the base line offset to 10 mV. An Elantec 2003 provides output drive capability.

The beam current monitors are calibrated by sending a current pulse to a single turn winding on the transformer core. The Calibrator Board provides a 50 mA, 500 μA, or 50 μA (± 0.1 %), 500 μsec (nominal) wide current pulse selected using the same bits that control the Beam Current Transformer Amplifier Board gain.

The BTA beam consists of three bunches as narrow as 50 nsec, extracted over 729 to 980 nsec, so total charge rather than current is of interest. To cover the range from 2×10^{10} to 1.5×10^{13} the circuit was designed with four gain states. The input signal is switched by an array of three rf relays (Aromat RF1E-DC5V) with 80 dB isolation at 250 MHz. This is critical to prevent coupling of the high intensity signal through the disconnected low intensity inputs. An amplifier stage (AD849) allows bunch viewing and optimization of the input resistance of the integrator stage (AD843). Charge injection and offset voltage adjustments are provided. A peak reader/hold circuit follows the fast bunch integral and retains the maximum, preventing the transformer backswing from causing a noticeable error. Drift is < 0.1 % in 10 msec. Tests indicate the area of simulated bunches to correct to within 0.1%.

FARADAY CUPS FOR THE HEAVY ION BEAMS

Beam current is monitored at eight locations in the HTB line using Faraday Cups mechanically identical to that in the HITL line.[9] Though destructive, they are necessary to monitor the DC beam used for tuning the line. The all stainless steel and ceramic design allows the units to be baked to 150° C. A -600 V bias suppresses secondary emission. The new amplifier design consists of separate relay selectable DC and pulse circuits each with two gain states. Mode selection (DC or pulse) and gain selection (X1 or X10) is available computer or locally. The DC circuit uses the stable OP97EZ to provide a gain of 1 or 10 nA/V (jumper selectable) in the high gain state and 100 nA/V in low gain. The bandwidth is kept to 350 Hz to limit noise. The pulse circuit uses an OP37EZ and an OP42EZ to provides a gain of 1 or 10 uA/V (jumper selectable) in the high gain state and 100 uA/V in the low gain. The bandwidth is 300 KHz. Both circuits use an Elantec 2003 as an output driver.

RING BEAM CURRENT TRANSFORMERS

The beam current measurement in the ring was specified to be from 10 μA to 10 A with a rise time of under 1 μsec and a droop time of at least 3000 sec. Two separate units, a fast injection beam monitor (BIBM) and a slower circulating beam monitor (BCBM) were installed to meet these requirements. The BIBM and the BCBM are mounted in a 0.5 inch thick, 1006 steel magnetic shield mounted on vibration isolators. A water cooled copper sheet between the transformers and the heater blanket keeps the temperature under 80° C during 300° C bakeout. A ceramic break in the beam pipe diverts the image current outside of the transformers. The electronics are mounted near the floor with steel conduit shielding the cables to the transformers.

The BIBM uses a beam current toroid[10] which provides 0.1 V/A into 50 Ohms with a bandwidth of 0.5 Hz to 8 MHz. The core is enclosed in a 170 mm ID aluminum shield. The circuitry is similar to that in the LTB but with gains of 100 μA/V, 1 mA/V and 1 A/V. The rise time is 70 nsec for the high and 1 μsec for the low intensity range.

The BCBM uses magnetic modulation with synchronous second harmonic detection to measure current. This commercial unit[11] uses metal glass tape cores modulated at 6.928 kHz to obtain a DC to 15 kHz bandwidth. The Front End Electronics (FEE) must be within 3 meters of the detector while the Back End Electronics (BEE) can be 300 m away. With ranges of 1 A/V and 10 mA/V, it produced only 1 mV for a 10 μA beam, so a switchable amplifier (X 10) was put between the FEE and BEE.

The transformers were tested in the AGS. The BCBM showed RF sensitivity, both from pick-up and the beam, in the 3-4 MHz range. The circuits were modified by the vendor and are waiting to be tested with high intensity beam. An AGS dipole produced about 1 Gauss at the housing, causing pick up equal to 50 μA. Modulation noise equivalent to ± 150 μA was observed. See Figure 1. Since this was crystal generated, a filter with -40 dB notches at the fundamental and 3rd harmonic was able to reduce it to ± 10 μA of 5th harmonic. A 4th order 21 kHz low pass filter left only random noise of a similar level. Figure 2 shows a 50 μA test pulse measured with the BCBM. The BIBM reacts strongly to RF after 40 msec in the AGS cycle at highest gain. The high intensity range bandwidth overlaps that of the bunched beam. Rolling off the response at 1 MHz eliminated the problem while leaving enough bandwidth to observe stacking. Figure 3 shows a partial turn of 45 μA of O^{+8} spiraling in the AGS as seen with the BIBM. During LTB commissioning, the two beam transformers performed well and met the design requirements.

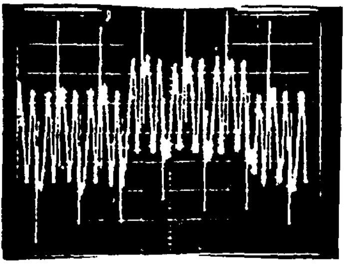

Fig. 1. Modulation noise of DCCT. 50 μA test pulse. 50 μA/div., 100 μsec/div.

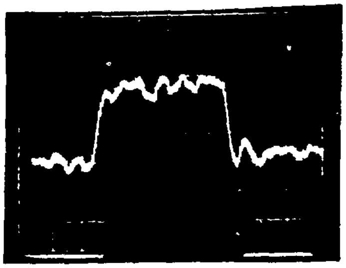

Fig. 2. 50 μA test pulse in DCCT after notch filter. 20 μA/div., 100 μsec/div.

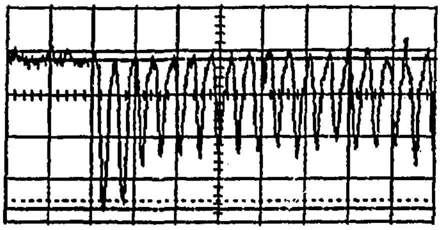

Fig. 3. Partial turn of 45 μA of O^{+8} in AGS viewed by BIBM. 50 μsec/div.

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