# DESIGN OF THE AGS BOOSTER BEAM POSITION MONITOR SYSTEM

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The AGS Booster beam position monitor system must cover a wide range of beam intensity and bunch length for proton and heavy ion acceleration. The detector is designed to maintain 0.1 mm local tolerance following 300°C bakeout. The electronics will be located in the tunnel, communicating via fiber optic links to avoid ground loops. The design will be described and test results for prototype units presented.

## BACKGROUND

$H^-$-beams from the 200 MeV Linac, stripped to protons, and heavy ion beams from the Tandem Van de Graaff, will be accelerated in the Booster[1]. Beam intensities will range from $2x10^{10}$ polarized to $1.5x10^{13}$ unpolarized protons and from $2x10^{9}$ $O^{+8}$ to $3x10^{9}$ $Au^{+33}$ ions. The RF will sweep from 213 kHz for $Au^{+33}$ at injection, to 4.11 MHz for protons at peak momentum of 1.5 GeV/c, resulting in bunch lengths ranging from 3750 ns to 50 ns, requiring a system bandwidth of at least 25 kHz to 25 MHz. Capacitive split-plate pick-up electrodes (PUEs) were chosen as the detectors because of their good low frequency response and linearity. The single plane PUEs will be located at the betamax in each of the 48 half-cells, locked to the quadrupole on the central orbit. The absolute position will be measured to ±0.5 mm without adjustment. A precision and linearity of ±0.1 mm over 30 mm of the 76 mm radius is required. A unique feature is that the detector can be calibrated directly by a ring electrode coupling equally to the 2 plates, checking the entire system, including connection cables.

The required low frequency response and the low signal levels made it necessary to locate the electronics close to the PUEs. To reduce the radiation the electronics will be on the floor, connected by 3-meter long cables. The mean orbit is measured by integrating the signal for a number of turns to average over the betatron oscillations. This number is adjustable from a single turn to 255 turns. The integration also increases the signal and reduces the noise. Orbit measurements will be possible at an interval of 10 ms or less. Bunch signals required for applications such as the tune measurement, damper control, and RF phase and radius control loops are buffered and sent from the tunnel via wideband analog fiber-optic links.

## THE DETECTOR

Design Since the PUE will be in a $3x10^{-11}$ Torr vacuum only alumina and type 316L stainless steel were used. It will be vacuum fired at 950°C and baked to 300°C, so the design must allow for the difference in expansion rates and relax to the original position. When the calibration ring was included the simple split plate design evolved into a gimballed suspension which allowed the electrodes to be rigidly supported while being free to move radially and longitudinally. Problems in bringing the signals out and tight tolerances led to the double gimballed design shown schematically in Figure 1. The 4 inner ceramic posts are fastened to the detector plates and pass through close-fit holes in the calibrator ring. This is supported by 4 posts in close-fit holes in the vacuum shell. Due to symmetry all expansion is radial and the parts return to the original location after bake-out. Thermal cycling tests to 300°C in air have confirmed that positional accuracy is maintained to the required tolerances.

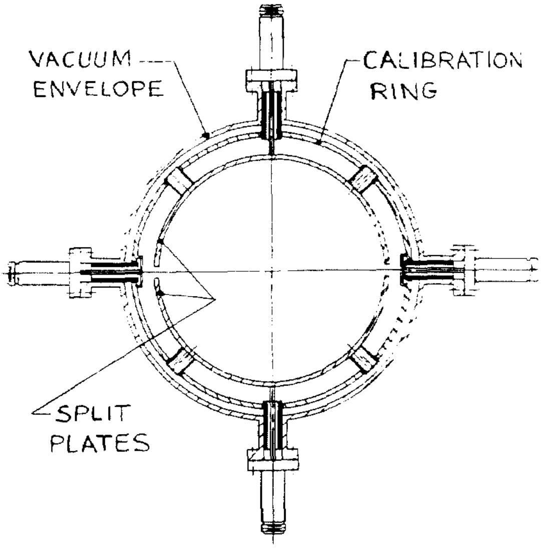

Fig. 1 Sketch of Double Gimballed PUE

The need for an overall unadjusted accuracy of ±0.5 mm led to < 0.1 mm tolerance on all components. The cylinders were machined from heavy wall tubing, then annealed with end-plugs fixing the diameter. Electric Discharge Machining was used to split the plates to prevent stress. The assembled detector is placed in the vacuum shell which is integral with the quadrupole vacuum tube. The vacuum feedthrus used are ISI type N, P/N 601B3052, which mate to the electrodes with a flexible spring collar. Measurements are made to define the electrical center with respect to an external survey mark. The endplate is then welded in place and the entire unit is vacuum fired.

Detector Measurements The large number of precision measurements made an automated test set-up necessary. The beam is simulated by an antenna driven at 10 MHz and moved within the detector aperture. An HP-9836 controls the Wavetek Model 23 Function Generator and Model 604 Signal Switcher, and HP 3458A Digital Multimeter via an IEEE-488 bus and the Techno X/Y motor driven table via an RS-232C serial link. Phase matched RG-223 cables connect each plate to the signal switcher. The plates are terminated in 50Ω at the DMM. To minimize sag and vibration the fixed wire is mounted vertically while the PUE in its vacuum shell is mounted on the motorized table by a rigid

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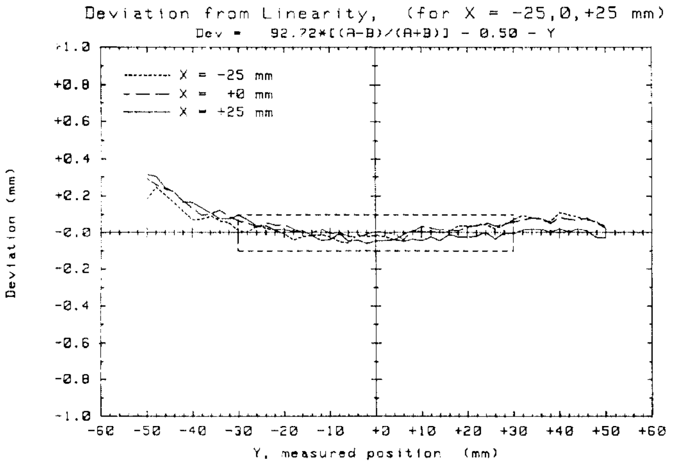

Fig. 2 Measurement of Prototype PUE

rack. The wire is tensioned on an adjustable C-frame secured to a surface plate and carefully aligned for perpendicularity and centering using a micrometer gauge. The long lever arm due to mounting the quadrupole tube on the table with the PUE at the top, magnified imperfections (<0.001") in the drive mechanism. This produces a cusp-like modulation of the response but it is still within the requirements. The mounting fixture is being redesigned for the production testing. Figure 2 shows a typical measurement with the deviation from a linear fit plotted for three scan locations. The dotted box is the specified precision of the detector, ±0.1mm, over the aperture of interest (±30 mm).

## THE ELECTRONICS

A block diagram of the average orbit circuitry is shown in Figure 3. Each block will be described below. The electronics perform sum and difference processing with the normalization done in software.

The Compensation Circuit The compensation circuit matches the cable at high frequencies but has high impedance at low frequencies to extend the bandwidth. It also provides attenuation at higher intensities. At low frequencies the capacitively coupled termination resistor does not contribute, and the electrode and cable capacitances form a voltage divider which determines the sensitivity. To maximize this, 93 ohm cable was chosen. At the upper end the capacitive reactances are small and the resistors form the voltage divider. The cable resonates as a damped capacitively loaded quarter-wave line but is compensated by an adjustable series LC. The resonance of this inductance with the input capacitance of the buffer is also damped. The transfer characteristic from the electrodes to the buffer is flat to ±1.5 dB from 10 kHz to 30 MHz.

The Buffer/Gain Block The buffer/gain block uses an AD9610 trans-impedance amplifier with low input noise voltage (0.7 nV/$\sqrt{\text{Hz}}$), high non-inverting input impedance and low capacitance (200 KΩ 2 pF), and stable bandwidth versus gain (G=+1,>100 MHz; G=+10, >70 MHz) characteristic. Gain may be switched between 1 and 10. Signals to the Fast Analog Optical Link are taken from the output of this stage.

The Sum and Difference Stage The sum and difference function is realized with a broadband hybrid transformer. This passive device eliminates degradation due to radiation effects and the drift of an active element. For position resolution of 0.1 mm, the common mode rejection required is >60 dB, from 30 KHz to 20 MHz. Since no such commercial devices were available, a 4-port transmission line transformer using trifilar windings was successfully designed, based on a 7-port hybrid used at the CERN PS[2]. The signals from the two electrodes are applied to the primary winding, with the center tap becoming the Sum Port. The secondary winding provides a voltage proportional to the difference signal. Commercial 1:4 impedance transformers provide noiseless voltage gain before being buffered by the next stage. Variable shunt capacitors adjust the circuit balance.

The Baseline Restorer The sum and difference signals must be integrated to get the average orbit. Since the capacitively coupled signals have zero average value, the baseline must be restored before integration. A diode bridge matched for both capacitance and forward voltage drop (HP 5082-2813) is configured as a switch[3] It is biased to present a high impedance during the bunch signal and low impedance to ground between bunches and restores the baseline to zero. In the high impedance state a 1:16 balun provides the sym-metric drive necessary to insure that the reverse bias voltage is large enough to prevent forward biasing by any bunch signals. The diode bridge clamp is capable of switching within 12 ns with an offset of 5 mV, which can be compensated if required.

Bunch Timing Circuitry The 48 PUE locations are equally spaced around the Booster Ring. Since the harmonic number is three, 16 RF phases are sufficient to time the arrival of a bunch at a PUE and synchronize the baseline restorer, integrator and ADC functions. These will be provided by a centralized timing circuit phase locked to the beam (Figure 4).

The Gauss-clock derived frequency from the LLRF system is offset by a fixed frequency and mixed with the PUE Sum signal. The IF output of the mixer, i.e.,

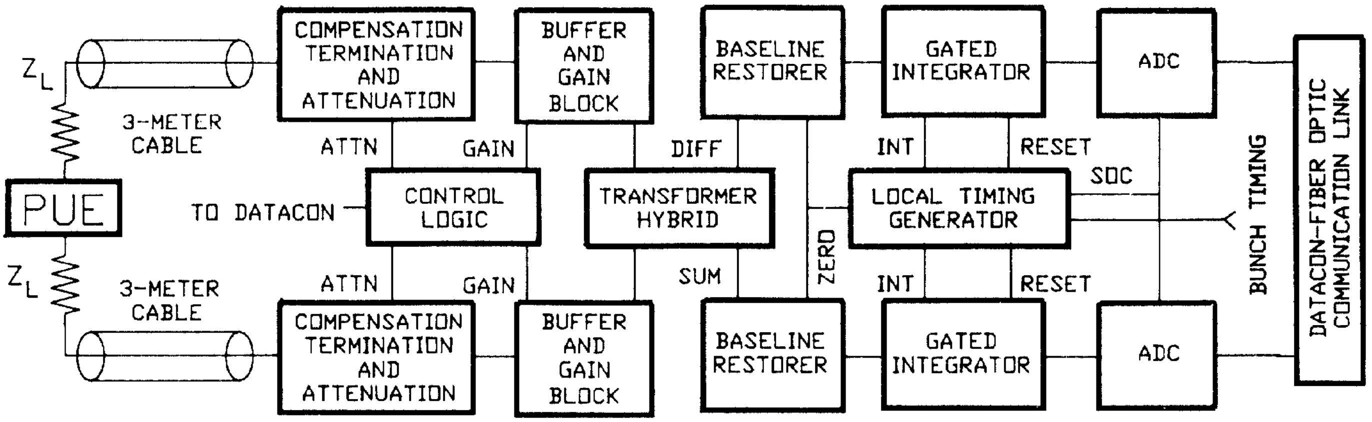

Fig. 3 Average Orbit Electronics Block Diagram

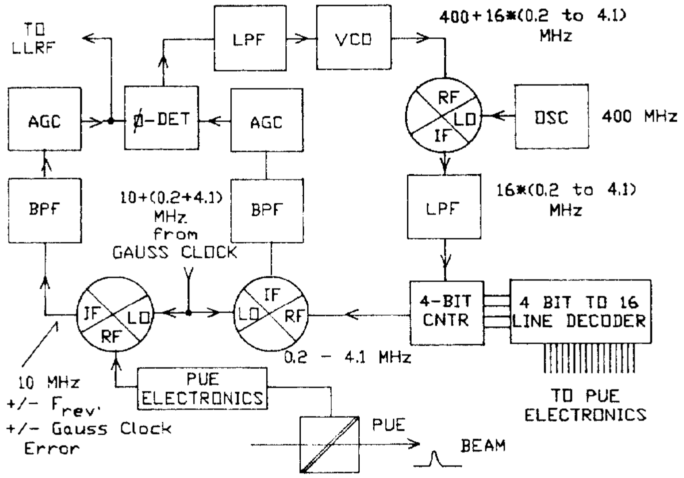

Fig. 4 Block Diagram of Bunch Timing Circuitry

the offset frequency, is put through a filter of bandwidth $f_{offset} \pm f_{rev}$. The resulting sinusoid is used as the reference in one leg of the phase detector. The detector output passes through the loop filter to drive a voltage controlled oscillator (VCO) which must have linear frequency variation over a range 16 times the RF(3.2 MHz to 65.7 MHz). A UHF VCO will be used to make the tuning range a fraction of the center frequency. This is heterodyned and low pass filtered to achieve the desired linearity. The VCO output is digitally divided with the 4 output bits decoded into sixteen different phases locked to the LLRF. The VCO/16 signal is offset, filtered and limited in the same manner as the original signal to provide the second input for the phase detector.

**The Integrator** The integrator used to average over the betatron oscillations consists of a precision operational amplifier with FET gated input and reset. It must process the signals from a single turn (< 1 $\mu$s) as well as 100 turns at the lowest frequency (1.5 ms). Opamps with sufficient bandwidth to integrate a single bunch have large offset voltages and currents, causing excessive drift for the longer integrate times. The OP-97 opamp has 10 $\mu$V offset voltage and 30 pA offset current, but the unity gain bandwidth is less than $10^6$, making it necessary to "pre-integrate" the signals with a low pass filter immediately preceding the op amp. This compromise results in negligible drift and error in the integral.

**System Calibration** The PUE includes a calibration ring which couples equally to both electrodes, providing a simulation of the electrical zero position. This allows a complete system check, including the cables which connect the electrodes to the electronics. The calibration signals must simulate the wide range of bunch lengths and frequencies of the actual beam. It is important to simulate different intensities since the gain balance of the various ranges must also be checked, but testing at the equivalent of full intensity will not be practical due to the large signal required. Selection of the gain settings, simulation pulse type and calibration mode will be done through the control system. The position sensitivity of the PUE can be verified by disconnecting one of the electrode signals, providing a check of the relative gain of the sum and difference signal channels.

## DATA TRANSMISSION

**Requirements** The data flow consists of commands, bunch timing, digitized sum and difference readbacks, status bits and analog bunch signals. The commands include the number of turns over which to integrate and the gain and calibration settings. The position data will be read at intervals of 10 ms or less during the pulse. The proposed LAN will use the DATACON[4] standard, but add the provision for broadcasting commands which would be recognized by an address universal to all units. In readback mode the units will be polled individually, responding with address, status bits, gain setting and sum and difference data (12-bit). The bunch timing will be sent via a fiber-optic line independent of DATACON. The bunch signals will be transmitted on wideband analog fiber-optic links.

**Digital Optical Isolation** The PUE electronics are electrically connected to the beam pipe, making maximum electrical isolation critical for low level measurements. The approach taken uses digital fiber optic links to the DATACON interfaces. Radiation effects have been considered. The estimated typical level of gamma radiation and neutron fluence at floor level is 5.4 krads/yr and 3.4 x $10^{12}$ respectively[5]. It is desired to obtain at least a 5 year lifetime for the optical components. Low-cost commercial GaAlAs photo-diodes operating at 820 nm, (HP HFBR-14X4), with less than 10 m of radiation resistant optical cable, were selected because of the radiation resistance of GaAs compared to Si types. Testing at the AGS showed no degradation at a dose of 28 krads(Si). The proposed cables will use a hard clad silica fiber (Ensign-Bickford HCR series) selected because of its low initial attenuation, large numerical aperature, wide core diameter, and excellent rad-hardness. The manufacturer has indicated that over the system lifetime, the radiation induced attenuation will most likely be negligible compared to standard loss considerations.

**Fast Analog Optical Isolation** The transmission requirements for the analog bunch data are a low pass bandwidth of 30 MHz, minimum group delay variations, 26 db instantaneous dynamic range, and linearity to within 3 %. The commercial analog fiber optic modules (Meret Inc., MDL288TV) with a bandwidth from 6 Hz to 35 MHz, which are being evaluated, use PIN GaAlAs photodiodes. The high DC bias level of 100 $\mu$W aids fiber recovery from long term effects of radiation through photobleaching. In bench tests the system has shown sufficient bandwidth, linearity, and sensitivity. Further radiation tests are planned.

## Acknowledgements

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