Fermilab Booster Ion Profile Monitor System Using LabView

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Abstract

The new Booster Ion Profile Monitor has been implemented to simultaneously capture both horizontal and vertical profiles at a once-per-turn sample rate, through-out a Booster cycle. The system uses LabVIEW software running on a MacIntosh Quadra 650 talking to both VME and CAMAC hardware. Microchannel plate voltage is turned on just prior to making a measurement and automatically turned off when the measurement is complete. This action allows using a high gain while preserving microchannel plate lifetime. The data captured may be archived for later analysis. Current analysis available include position, emittance/sigma, 2D color intensity plot of raw data, and single turn profiles for any turn during the cycle.

INTRODUCTION

The Booster Ion Profile Monitor is the result of much previous work. Originally installed in the Fermilab Anti-Proton source,(1) the hardware has been modified and reinstalled in the Booster.(2) It has been used to make measurements of transverse profiles and emittances.(3) The current system is now operational in both horizontal and vertical planes and is interfaced to the Fermilab accelerator control system (ACNET). The system is now comprised of a cost reduced set of preamplifiers in the tunnel and new data acquisition hardware. We have used commercial hardware and software where possible to minimize development time and cost.

An amplifier is required to convert the 140 nanoamp (namp) signal to the 0 to 5 volt 50 [[Omega]] input of the A/D cards. In the Booster Ionization Profile Monitor, up to 48 anode strips with 1.5 mm spacing are used to measure the transverse profile of the proton beam. Because the profile can be measured each Booster turn, or about 1.6 usec at extraction, each strip requires a dedicated amplifier with sufficient bandwidth.

Data is acquired using 4 channel, 1 MHz OmniByte Comet digitizers that are provided a synchronous gate once per Booster revolution. They contain enough on-board memory to capture a complete Booster cycle, on the order of 20,000 turns in 33 msec. The digitizers reside in a VME chassis along with timing cards that provide gates derived from the accelerator clock system (TCLK). This chassis is controlled by a MacIntosh Quadra 650 computer running National Instruments' LabView. Programming of the system was accomplished in this graphical language to take advantage of its vast library of routines and rapid prototyping capabilities. A side benefit of this is that it is a natural way for an engineer to accomplish a measurement system without having to resort to C or assembly code for the majority of the project. Enhancements were produced within the Instrumentation Department,(4) to allow the presentation of results and control of the measurements through ACNET.

SYSTEM DESIGN

Microchannel Plates

The current gain of a microchannel plate, (MCP), can be estimated from the following equation, (5)

$$gain = \frac{I_{out}}{I_{in}} = .85\left(182 + \frac{V_{mcp}}{440}\right)^{\frac{1}{2}}\left(\frac{V_{mcp}}{440}\right)^{9.5}$$

For the Booster Ionization Profile Monitor, (IPM), a comparison of calculated and measured gain as a function of MCP voltage agrees up to about 700 volts where saturation effects become significant, fig 1. With the beam intensity at 3e12 protons, the incident current on the MCP was 0.75 namps for each 1.5x100 mm anode strip. At 720 volts, the initial gain of 1550 provided 1100 namps at the MCP output, significantly greater than the bias current of 675 namps per strip. The MCP will provide this current until the capacitance across the plate begins to discharge. This will cause a non linear gradient across the channel resulting in reduced gain and a smaller signal current.

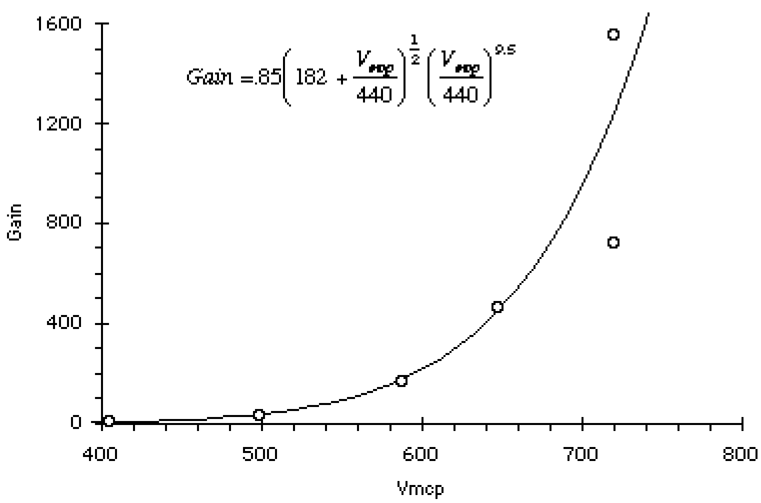


Figure 1. Measured and calculated gain of Booster MCP. The signal was beginning to saturate at the 720 volt bias, both the initial (upper point), and steady state (lower point) gain is plotted at this voltage.

Assuming a relative permitivity of 8.3 for the glass and a thickness of 1 mm, the 80 by 100 mm MCP will have 333 pf of capacitance, accounting for the size and spacing of the channels, or about 6.2 pf for each strip. At the 720 volt bias, the current in excess of the bias current, 1100-675 namps, would discharge 6.2 pf by 100 volts in 1.5 msec, consistent with the observed behavior. The 20 M[[Omega]] impedance across the MCP forms a 7 msec charging time constant.

To minimize the effects of saturation it is recommended the signal current be less than 25% of the bias current. For 3e12 protons in the Booster, a 590 volt bias provides 553 namps of current per anode strip, a current gain of 187, and a peak signal of 140 namps.

The signal to noise ratio for the MCP output can be estimated as,(5)

$$\left.\frac{S}{N}\right|_{MCP} = \sqrt{\frac{I_{in}}{e\,1.8\sqrt{\pi}\,B}}$$

I_{in} = ion current striking MCP

B = 3db bandwidth in Hz

For the Booster, the incident ion current of 0.75 namps and bandwidth of 150 kHz provides a signal to noise ratio of 100.

Detector

The time required for the signal to cascade through the MCP is only 270 psec with a 30 picosec spread.(5) Thus the MCP itself is fast enough to resolve the longitudinal profile of the 3 to 5 nsec long bunches. The Booster IPM uses an 8 kV clearing field across a 12 cm gap. The time required for an electron, initially at rest, to drift from the center of the gap to the surface of the MCP would be only 2.7 nsec, 114 nsec for a proton, and 484 nsec for a singly ionized water molecule. The polarity of the clearing field is chosen to drive positive ions into the MCP and it is believed, but not known, that the majority are ionized water molecules. With a bunch spacing of 26.4 to 18.9 nsec the spread in drift times and initial velocities should reduce the amount of energy in the anode strip signal at the bunch rate, and its harmonics. In practice, a significant amount remains but it is not clear how much is caused by ions amplified through the MCP and how much is coupling between electromagnetic fields in the detector and the strips or conductors carrying their signal.

The anode, or output, side of the MCP is shielded from the beam side with a double sided circuit card whose top and bottom are coupled through capacitors spaced around the square MCP mounting hole. The top of the board is grounded to the enclosure and the top of the MCP is connected to the bottom of the board. This was done to reduce beam coupling into the signal wires between the anode strips and the vacuum feed through connector. Typical MCP bias voltages are, 590 volts across the plate itself and 230 volts between the MCP and the anode strips.

For a total impedance of 20 M[[Omega]] across the 1.02 mm thick, 80 by 100 mm wide MCP, the volume resistivity is 160 M[[Omega]]-m making the skin depth 2e6 meters for frequencies much greater than 20 Hz. The top and bottom surfaces of the MCP are coated with nichrome or inconel and have an impedance of 200 [[Omega]]/sq. This would require a uniform thickness of 5e-9 meters of nichrome, which has a skin depth of 1.6e-5 meters at 1 Ghz. Thus, shielding the strips from the beam fields or from beam excited modes in the detector is difficult.

Preamplifiers

The signal to noise ratio of the amplifier will be proportional to the square root of the input impedance, provided the dominant noise source is the thermal noise of the impedance itself.

$$V_{signal} = R\,I_{out} \qquad (I_{out} = MCP\ output)$$

$$V_{noise} = \sqrt{RKTB} = 64 \times 10^{-12} \frac{V}{\sqrt{\Omega\ Hz}} \sqrt{RB} \qquad (at\ 300^\circ\ K)$$

$$\left.\frac{S}{N}\right|_{Amp} = \sqrt{\frac{R}{KTB}}\, I_{out}$$

For a signal of 140 namps, bandwidth of 150 kHz, and impedance of 5 k[[Omega]], the theoretical signal to noise ratio becomes 400. A good low noise op-amp will have an equivalent noise at the input about equal to that of a 1 k[[Omega]] resistor. The resulting signal to noise ratio of an op-amp and two 5 k[[Omega]] input resistors is about 200. (Note: S/N is 10 times smaller for 50 [[Omega]] than for 5 k[[Omega]].)

The signal must be transported from the anode strips in the detector to the amplifier. Transmission lines having 50 [[Omega]] impedance and velocity of 67% of the speed of light will have about 30 pf per foot of capacitance, C~1/Zo [[upsilon]]. This capacitance, in combination with the amplifier input impedance, can be used to limit the bandwidth of the signal. For cables much shorter than a wavelength, a good approximation to frequency response is simply equating the 3 dB bandwidth to 1/2[[pi]]RC, fig. 2. With 4 feet of RG-174 cable and 5 k[[Omega]] impedance the bandwidth becomes 260 kHz for the IPM. The cable is 1/4 wavelength long at 41 MHz.

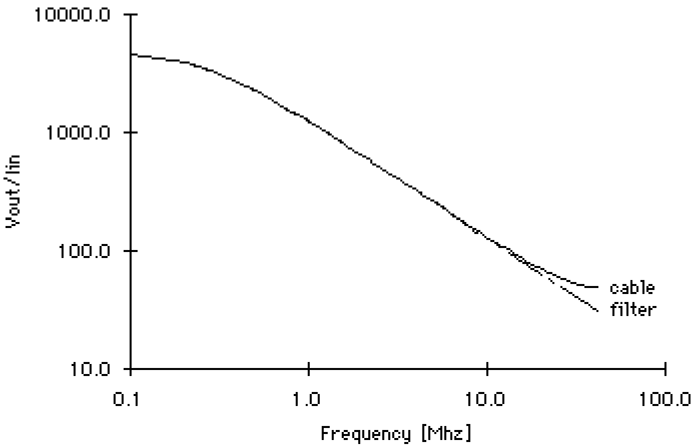


Figure 2. Comparison of output voltage from 5 k[[Omega]] resistor terminating 4 ft of cable driven with a current source to first order low pass filter, f[[omicron]] = 260kHz.

Placing the amplifiers near the detector in the beam enclosure minimizes the possible potential difference between grounds. Nearly one volt at the power line frequency and it's harmonics has been measured between the beam enclosure ground and that in the equipment galleries. The open anode strip makes the noise source impedance large compared to the amplifier input impedance at these frequencies, reducing the effect.

Several hundred millivolts of high frequency components induced by the beam have been measured on the anode strip signals. Although their amplitude was reduced with shielding inside the detector, they could not be completely removed. Because the slew rate of the op-amp was exceeded and faster in the negative direction, the presence of the high frequency components induced a substantial negative offset in the preamp output. To reduce the effect, better shielding was installed in the detector, a 1 MHz low pass filter was placed at the amplifier input, and an op-amp with very large slew rate was selected. Using all three steps significantly reduced, but did not completely eliminate, the problem. A small offset is still experienced near transition where bunches become shortest and higher harmonics are most intense.

Current feedback style amplifiers have the highest slew rate and therefore the best rejection to rf at their input. The AD844 amplifier was selected by virtue of it's low noise. The disadvantage of current feedback amplifiers is that they have significantly higher input current noise, the equivalent of 6.1 namps rms with a 150 kHz bandwidth. Combined with the 140 namp signal level, the current noise results in a signal to noise ratio of only 23. A more typical op-amp, such as the OP-37, has 30 times less current noise but has a slew rate 120 times slower, 17 V/usec compared to 2000 V/usec. Current feedback amplifiers also have larger temperature dependent voltage and current drifts. In the IPM these offsets are corrected in software by measuring them each cycle prior to beam injection.

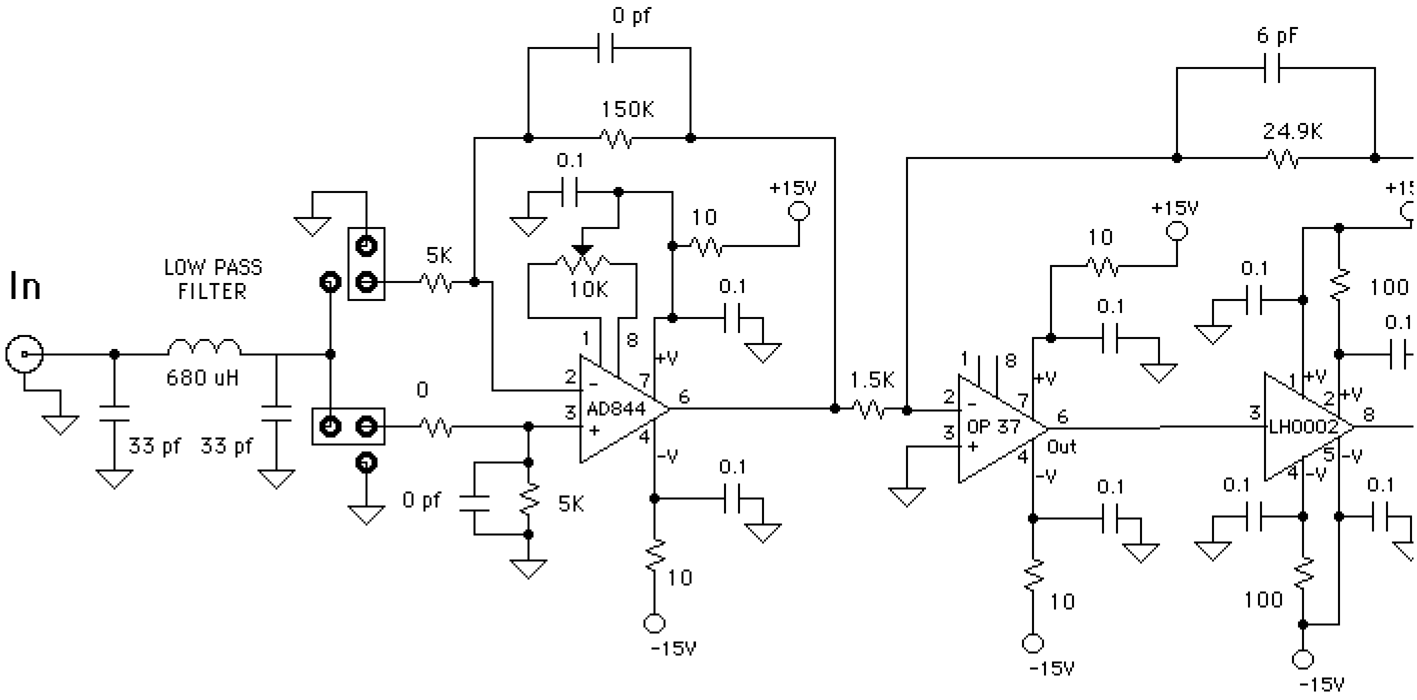
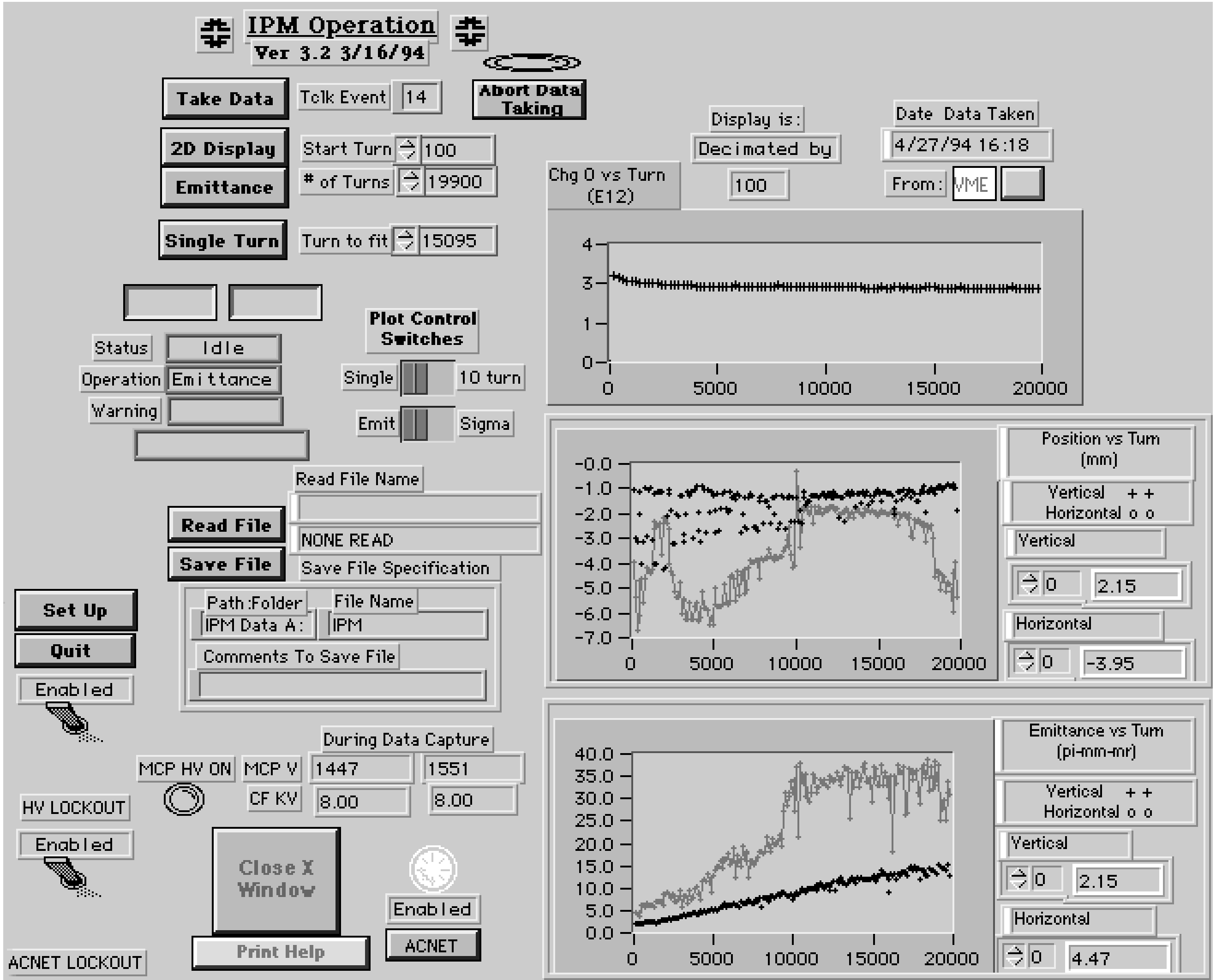


Figure 3. Booster Ionization Profile Monitor Preamp.

The amplifier is inverting so electrons collected on the anode strips produce a positive output voltage. The 150 k[[Omega]] feedback resistor on the first stage forms a 240 kHz low pass filter with the AD844 transcapacitance of 4.5 pf. Transimpedance is 2.5 M[[Omega]] . The voltage gain of 500 will affect the amplifiers response to noise which may be present at the input. The LH0002 amplifier at the output is used to drive the 50 [[Omega]] load.



User Interface

The user interface for the IPM is accomplished in 2 ways. A full graphical screen is available using commercial MacIntosh or X-Window software packages. The parameters measured, calculations performed, and settings control are also available through ACNET consoles. Measurements are initiated by determining a TCLK event on which to start data acquisition. MCP bias voltage is applied and the digitizers capture data once per revolution, 2.77-1.59 usec. 2.5 MBytes of data are transferred from the digitizers into the MacIntosh. Single turn profiles, or emittance/sigma/position vs. turn analysis, is available for the complete, or subset of, the Booster cycle. Data may be archived on an optical disk for later study.

Data Analysis

Data is presented as an array of 20000 samples for each 30 channel plane, both horizontal and vertical. Channels are separated by 1.5 mm. Each 30 channel slice provides a raw, single turn, profile from which a centroid and rms is calculated. Then these values can be used as inputs to a full Gaussian plus linear background fit. The full fit is displayed by default in "Single Turn Profile" mode. It can be turned off to speed up calculation time for "Emittance" and "Position" plotting. At the present time calculated emittance is based on measured sigma and the beta function without dispersion, which does not yield a true emittance.

Raw data includes background and offsets due to bias and drift. The timing of data collection allows the capture of samples prior to beam injection. An average of the first 8 samples are taken and used as a background subtraction for each channel. To minimize calculation time, data is decimated to a practical number of points appropriate for display, on the order of 200 points maximum. If the data of interest covers less than 200 points, then turn by turn information (un-decimated) is displayed. The process of decimating data allows for selecting each "nth" turn or averaging n turns to produce the "Nth" term.

Ions produced when the beam hits residual gas are under the influence of the clearing field and the space charge of the beam itself. This leads to a spread of the collected ions and subsequently the measured sigma is larger than that of the beam. Corrections must be applied to the raw data based on intensity and beam size during the acceleration cycle. We use Monte Carlo simulation to determine the effect of the beam induced field on drifting ions. This effect can be up to 25% to the measured sigma. The correction algorithm is a linear function of the beam intensity and beam size and is applied to data prior to plotting sigma or emittance.

Improvements

Ionization Profile Monitors are designed for the Fermilab Main Ring. The most significant change is to use the High Output Technology, microchannel plate. The impedance across these is 100 k[[Omega]] compared to the 20 M[[Omega]] of those installed in Booster. The MCP bias current increases linearly with bias voltage but the gain, and signal current, increase with the 10 th power. The maximum MCP gain is limited by the requirement that signal current be less than 25% of the bias current to avoid saturation effects. By reducing the MCP impedance the bias current is increased, allowing larger signal current and thus better signal to noise ratio at the output of the amplifiers.

A planned improvement for the Booster IPM is calculation of a true emittance which includes the dispersion. Using the charge, rf voltage, and bunch length, we can determine momentum spread which leads to the dispersion. Charge and rf voltage signals are now captured with the raw data. The calculation will be added when a true bunch length signal becomes available.

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