OPERATIONAL USE OF IONIZATION PROFILE MONITORS AT FERMILAB*

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Abstract

Ionization profile monitors (IPMs) are installed in the Fermilab Booster, Main Injector and Tevatron. They are used routinely for injection matching measurements. For emittance measurements the IPMs have played a secondary role to the Flying Wires, with the exception of the Booster (where it is the only profile diagnostics). As Fermilab is refocusing its attention on the intensity frontier, non-intercepting diagnostics such as IPMs are expected to become even more important. This paper gives an overview of the operational use of IPMs for emittance and injection matching measurements at Fermilab, and summarizes the future plans.

INSTALLATION LOCATIONS AND OPERATING CONDITIONS

IPMs are used in three accelerators at Fermilab. Booster and Main Injector IPMs are designed to collect a data sample once per machine revolution. The Booster has two electrostatic units that collect ions using an 8 KV clearing field. These units collect data in the Booster throughout its complete operating cycle of about 20,000 turns. At injection (400 MeV) the revolution period is 2.25 μsec. At extraction (8 GeV) this period drops to 1.5 μsec. The Main Injector has two electrostatic units, one horizontal and one vertical, operating at 28 KV, collecting ions and producing data each 11.1 μsec. An additional horizontal unit was installed with a 1 KGauss magnetic field, and 10 KV clearing field which allows the collection of electrons,. The magnetic field confines liberated electrons to orbits smaller than the anode pick-up strips which minimizes the deleterious effect of space charge from the beam. The Main Injector IPMs are limited to the 65K samples of the current digitizer, however by skipping turns during acquisition, the full cycle can be measured. The Tevatron has two magnetic units of 1KGauss and a 10 KV clearing field. As explained later, these units are capable of sampling 36 proton and 36 antiprotons (pbars) bunches, turn by turn, for up to 1000 turns.

FRONT END INTERFACE

LabVIEW was chosen as the environment for the front end program because of its facilities for easily tying together different types of hardware (GPIB, VME, Ethernet) and software (Accelerator Control Network (ACNET), .dlls). The LabVIEW built-in graphical environment has also proved to be a significant help in debugging and commissioning the IPM systems. In normal operation, the system is controlled remotely through ACNET, but the front-end program provides complete functionality for running the system locally. Beam measurements are configured with a set of file based measurement specifications that include trigger and event types, timing delays, high voltage settings, analysis parameters, and logging preference. Measurements are initiated by activating a specification number through ACNET to the front end, which then configures the system hardware and waits for the specified trigger clock event. The triggering phase occurs in two parts. A pre-trigger is generated which initiates the hardware setup. and turns on the micro channel plate high voltage, This is followed by the event trigger, which starts the data acquisition. Data is collected using a beam synchronous clock. After acquisition, the front end analyzes the data using the selected parameters (turn by turn, averaging, start turn for analysis, and number of turns to analyze), and then returns the selected data and measurement parameters through ACNET. Raw data and measurement conditions are saved in binary files on the front end, and can be recalled into the front end program and reanalyzed.

The front-end code makes use of parallelism to take advantage of multi-core processors. There are three major tasks running: an event loop to detect front panel activity and handle ACNET commands, a monitor loop to track high voltage and receive remote commands, and a state machine to execute measurements and all other program functions. State machine functions are driven by a dynamically created command queue which can contain single or multiple commands. After the queued commands are executed, the state machine returns to an idle state. A second state machine was added to one of the IPM systems that does frequent measurements so that the front end could respond to select remote commands while it is waiting for a pre-trigger or trigger. The queue driven state machine design pattern has proved to be very flexible and efficient in operation, as well as easy to diagnose and debug system issues.

A significant benefit of using commercial PC's running LabVIEW is that it has enabled us to retain the front end hardware unchanged while being able to realize overall system performance improvements as faster PCs have become available.

ACNET CONSOLE INTERFACE

The ACNET user interface is comprised of two distinct parts, the console application page, and the pre-existing data collection engines.

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The application page for the IPMs, as well as for most LabVIEW front-ends, is largely an attempt at duplicating the format and function of the LabVIEW front-end's own interface. From this application you can modify typical measurement parameters such as the start event, number of skipped turns per sample, and micro-channel plate high voltage levels for normal operations.

The ACNET console raw data plot, Fig.1, is a read back of the front-end data for a single Main Injector cycle measurement. It uses the Y axis to show intensity dots instead of false color used on the front-end. This results in a mountain range plot, which is more easily readable. A green dot marking the calculated center and red dots marking the sigma are added for clarity.

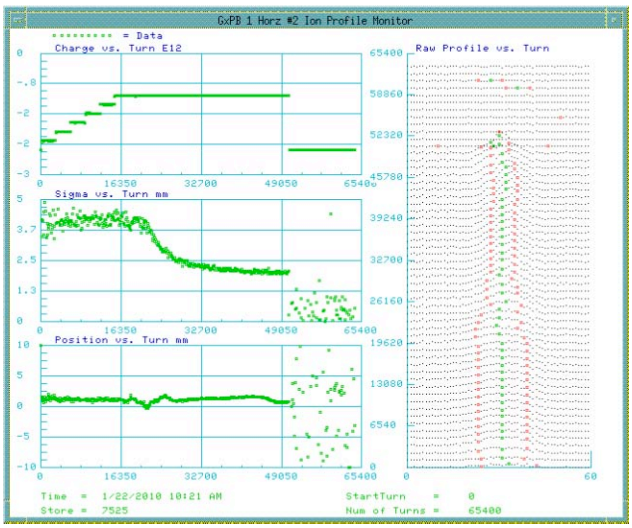

Figure 1: IPM application page plot showing (from top left) beam intensity, beam sigma vs. turn, beam position vs. turn, and on the right, the raw data vs. turn. Beam is extracted at turn ~50,000.

This plot shows sigma and position data during an 8 GeV to 120 GeV MI cycle. The reduction in sigma corresponds to the acceleration of the particles. Measurements are taken for each pbar transfer from the Accumulator to the Recycler Ring, and for each proton and pbar injection into the Tevatron. Fig. 2 shows a typical front end interface, albeit this one for Booster.

There are two types of logging engines, Shot Data Analysis (SDA), and the data logger called the Lumberjack. The SDA and Lumberjack systems are used to collect scalar data in four different situations:

- On a regular interval (once/minute)
- At some accelerator clock event plus delay
- At an accelerator sequence point i.e. HEP shot setup or pbar transfer
- On a state change generated by the front-end itself. (data ready)

These data collection engines allow the recall of any stored data, to be plotted over any time period of interest, for debugging of accelerator issues and system performance.

BOOSTER

The Fermilab Booster is a rapid cycling, 15Hz alternating gradient synchrotron accelerating 400MeV proton beam to 8GeV. Typically High Energy Physics (HEP) requires 4-5e12 particles per pulse. The practical minimum for a good measurement is 1e12.

The Booster IPM [1] is the only non-destructive tool for measuring its transverse beam profiles. The width of the distribution is determined from a fit to a Gaussian plus a linear background, and was calibrated to the crawling wire on the injection girder [2].

A typical beam width display measured throughout the entire Booster cycle is shown in Fig. 2, Fig. 3, and Fig. 4.

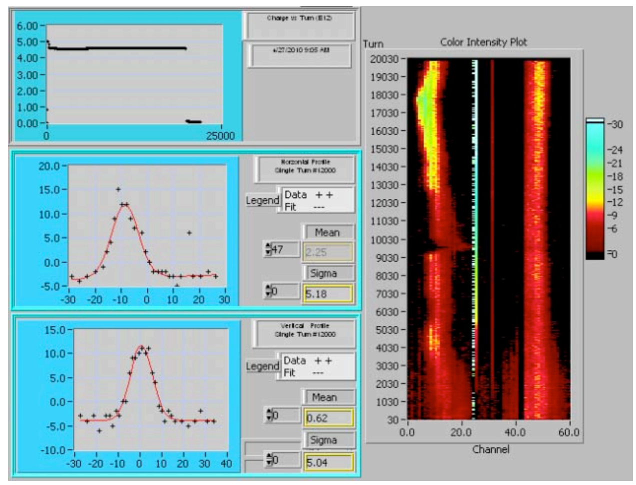

Figure 2: Front End interface to operate Booster IPM.

This data is a useful reference tool when comparing good running periods with changing efficiencies and/or beam intensities. Once a good reference set of beam profiles is taken, they are compared to the current conditions to observe if any changes have taken place. If the profiles differ during the current running period this leads to investigating what machine parameters may have changed. By comparing magnet settings and ramps during these periods of change a problem can be corrected.

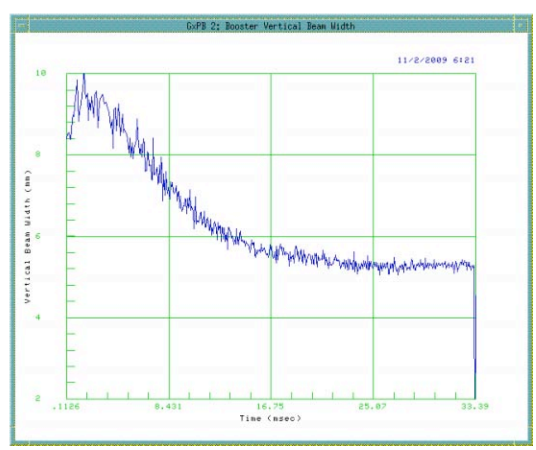

Figure 3: Booster beam Vertical Sigma vs Turn.

The IPM is used to better understand the increase in transverse emittance with its relation to beam intensity. The emittance growth is thought to be due to space charge effects [4]. The IPM is limited by beam variations that can make interpreting the data inconsistent from day-to-day. Some of this disparity can be caused by position changes in the beam due to tuning the beam or cycle-to-cycle variations. The beam can undergo RF manipulations on different beam cycles and in some cases the same beam cycle.

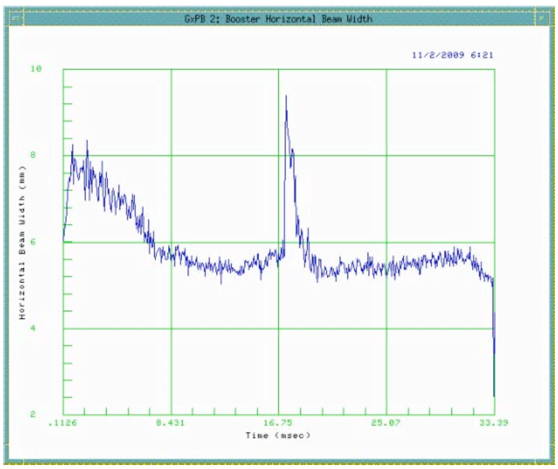

Figure 4: Booster beam Horizontal Sigma vs Turn. The spike is due to transition at about 5.2 GeV.

MAIN INJECTOR

The Fermilab Main Injector (MI) is a very dynamic machine used to accelerate both protons and pbars from 8 GeV to 120 GeV or 150 GeV with intensities from $5x10^{8}$ to $5x10^{10}$ particles per bunch and a peak total intensity of $5x10^{13}$ particles in the ring. At the current peak intensities the flying wires would be damaged if used so the IPM system[4] is the only method to measure sigma parameters in the Main Injector on high intensity cycles.

The injected 8 GeV protons and pbars can come from either the Proton Source via the MI-8 transfer line, the Accumulator storage ring via the P1 injection line, or from the Recycler Ring via the RR800 transfer line.

To monitor the lattice matching between the various transfer lines and the MI ring, the MI IPMs are configured to acquire data on the various transfer events associated with each type of transfer. The data is logged on every transfer and recorded in the SDA system described earlier.

With the data from the IPM we are able to track changes in the sigma/emittance and measure oscillations in the sigma, which is indicative of a lattice mismatch.

In November 2009 the MI IPMs showed an oscillation of ~1.3 mm on the sigma for protons injected into MI from the Booster, via the MI-8 line. Fig. 5 shows how increasing the quad magnet current by 9 Amps (5%) improved the lattice match resulting in sigma oscillations being reduced to less than 0.4 mm.

Correcting the match between the MI-8 injection line and the MI lattice reduced the beam spot size on the NUMI target after extraction at 120 GeV by almost 5%.

Automated data collected from the pbar injections into the MI from the Accumulator ring showed similar oscillations on the injected sigma which led us to adjust one of the transfer line quadruple magnet power supply currents by 3 Amps (0.8%). This reduced the sigma oscillations from 1.3 mm to 0.5 mm and resulted in a slightly smaller sigma and a 1% increase in pbar transfer efficiency.

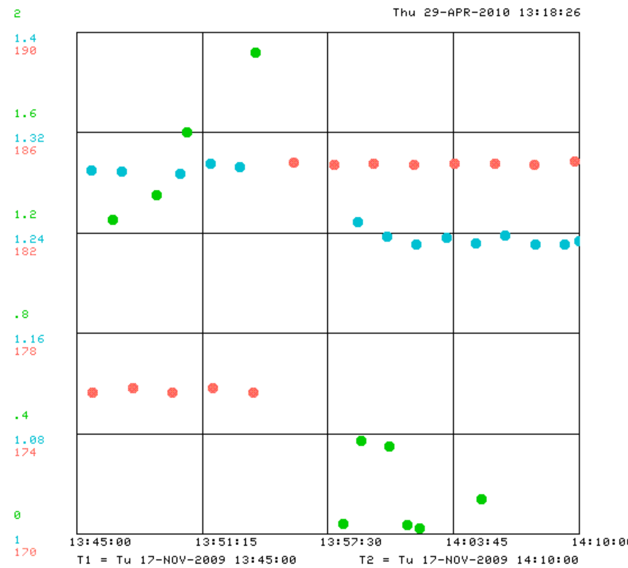

Figure 5: I:Q847 current (red data points) optimization reduces the sigma oscillations (green data points) at injection and results in smaller beam spot size on the NUMI target (cyan data points) after extraction at 120 GeV.

In addition to the automated monitoring of the injected beam, the IPMs are used to measure beam parameters for studies and to diagnose transverse beam instabilities. They can be configured to do a detailed analysis of 500 turns of the collected data, at any point in the cycle.

The IPM systems provide sigma data independent of our flying wires and can be used to verify suspect measurements at intensities low enough to use the wire system without damage.

Table 1: Listing results of simultaneous measurements from both Flying-wire and IPM, with a 25 turn average.

	Flying wire		IPM	
	sigma	Emittance	sigma	Emittance
8-GeV Pbar from Accumulator	2.37	6.6	2.25	5.4
8-GeV Pbar from RR	1.22	1.7	1.3	1.8
150 GeV Pbar to TEV	0.37	3.1	0.6	5.7
8-GeV Proton from Booster	3.75	16.4	4.2	18.8
150 GeV proton to TEV	0.81	15.0	1.2	22.8

IPM and Flying-wire data have been taken consistently for beam monitoring and diagnostics. Table 1 lists results from various modes of MI operation for both instruments. Fig. 6 shows the IPM measured sigma compared to expected sigma, i.e. sigma from Flying-wire adjusted for differences in lattice beta function. Fig. 7 shows the comparison of their measured normalized emittances. The results for 8 GeV beam are very comparable. At 150 GeV we see higher measured emittances from the IPM, for both proton and pbar. This may be signaling the limitation of IPM sensitivity for small beam size.

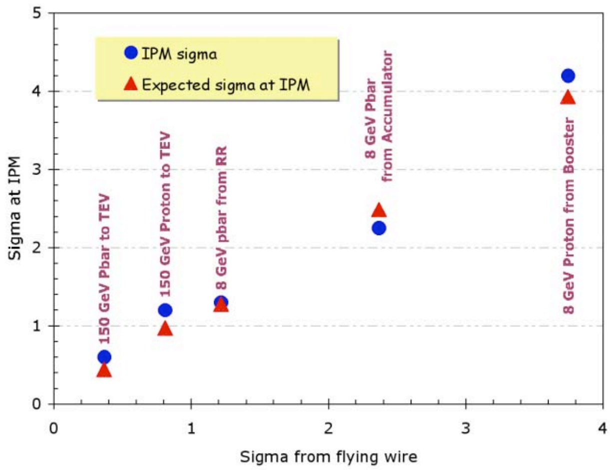

Figure 6: Comparing measured IPM profile sigma to that of Flying-wire. Blue dots are IPM sigmas. The red triangles are sigmas calculated from Flying-wire data with adjustment for difference in lattice beta function between the instrument locations.

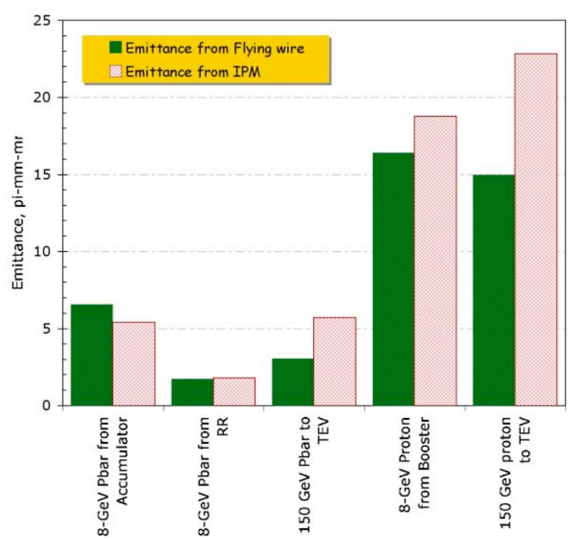

Figure 7: Comparison of measured normalized emittance from Flying-wire and IPM for different beams.

TEVATRON

The Tevatron IPMs [5,6] were developed primarily to measure injection beam size oscillations due to mismatch, in particular for pbars. Early in the Tevatron Run II there were indications of relatively large antiproton emittance blow-up between the Main Injector and Tevatron, The IPMs were installed as part of a campaign to eliminate any such sources of Luminosity loss.

To measure antiproton injections in the presence of a circulating proton beam, the Tevatron DAQ system is significantly different from the other machines. Instead of using a low pass filter with a time constant of the order of a turn followed by a regular ADC, the signal of each anode strip is continuously integrated in intervals of approximately 60 ns using a chip developed for the CMS experiment. One full revolution corresponds to 318 such intervals. The location of the IPMs and the integration interval (3.5 T_{rf}) were chosen in such a way that proton and pbar signal end up in separate integration intervals. Fig. 8 shows one turn of Tevatron IPM data, where proton and pbar bunches can be clearly identified. The measured profile for each bunch can be analyzed either turn-by-turn for injection measurements, or averaged over many turns in order to improve the signals for coasting beam.

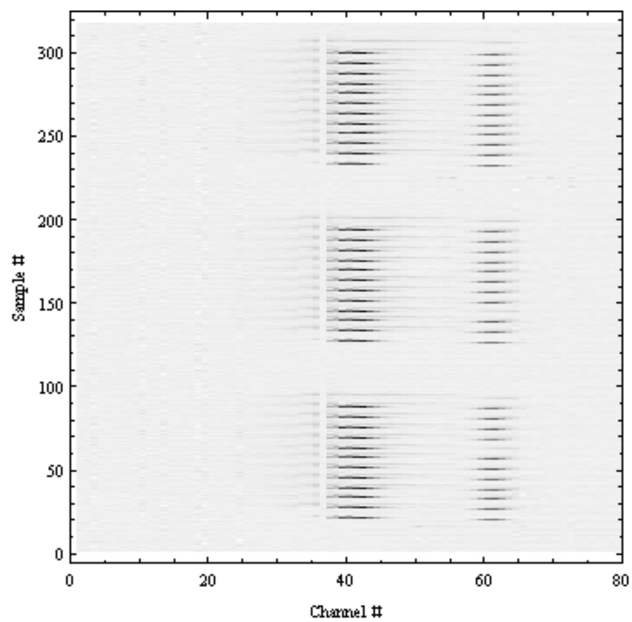

Figure 8: One machine revolution (318 samples) of Tevatron IPM data, showing the 36 protons (center) and 36 pbar (right) bunches. Proton and pbar separation due to the open helix orbit. (Channel 36 is a dead channel that is ignored by fitting routines.)

With the incorporation of the Recycler as an intermediate storage ring for pbars, and the routine operational use of high-energy electron cooling, antiproton emittance blow-up due to injection mismatch is no longer a concern. In fact, it has been found that too small a pbar emittance has an adverse effect on proton lifetime and losses. Therefore, the pbars delivered by the Recycler are typically first injected into the Tevatron with an intentional offset in order to increase its emittance, and then further blown up at flat top by injecting noise through a directional coupler (pbar jacking.)

The IPMs are used to monitor the process of blowing up the pbar emittance at flat top. For this, the system is run at the maximum measurement rate, which is a bit less than 1 Hz. This rate is limited by the time it takes to turn the HV voltage on/off. Fig. 9 shows an example of such a measurement.

Despite the decreased focus on injection matching, the

IPMs are set to monitor every injection event. They are also used to measure the coasting beam at regular intervals during HEP stores. Figure 10 shows the evolution of the beam sizes as measured by IPM and Flying Wires.

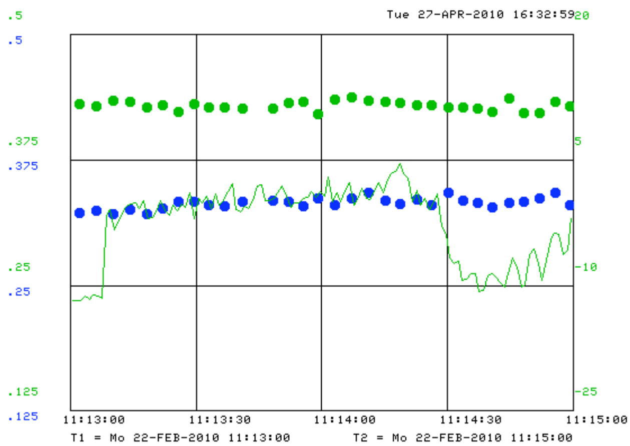

Figure 9: Tevatron IPM pbar beam size measurement during 'jacking' (intentional increase of pbar emittance at flat-top to improve proton lifetime and limit losses in the low beta squeeze). Green dots indicate vertical proton sigma, and blue dots vertical pbar sigma. The green solid line shows the Schottky power, which increases during jacking.

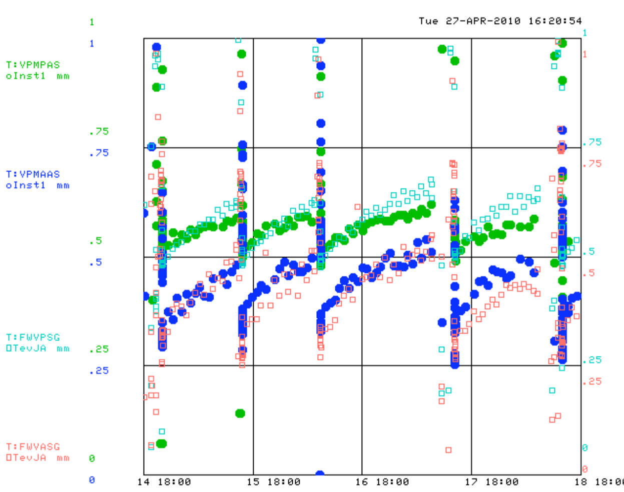

Figure 10: Tevatron IPM and Flying Wire beam size measurement during 4 typical stores. Green and blue dots are proton and pbar IPM measurements, while blue and red squares are the corresponding Flying Wire measurements. All measurements are in the vertical plane.

MICROCHANNEL PLATE LIFETIME

The MI IPMs are taking data for each pbar transfer that occur about every 40 minutes and typically include 3 batches each. Tevatron shots occur approximately once per day and include about 100 proton injections, and exactly 9 pbar injections. This results in about 220 measurements per day plus any physics study measurements. The micro-channel plates show signal degradation that can be compensated for only slightly by increasing gain or using another position on the plate. Eventual replacement on at least a yearly basis is required.

SUMMARY - THE INTENSITY FRONTIER

The IPMs are incorporated into the daily operations of the Fermilab Accelerators. They provide direct measurements of sigma oscillations during normal operation. As particle intensity increases, traditional intercepting profile monitors cannot be used. IPMs will certainly fill this need. Micro-channel plates do require regular replacement to maintain good signal integrity due to lifetime issues.

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