COMPLEMENTARY METHODS OF TRANSVERSE EMITTANCE MEASUREMENT*

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Abstract

Several complementary transverse emittance monitors have been developed and used at the Fermilab accelerator complex. These include Ionization Profile Monitors (IPM), Flying Wires, Schottky detectors and a Synchrotron Light Monitor (Synchlite). Mechanical scrapers have also been used for calibration purposes. This paper describes the various measurement devices by examining their basic features, calibration requirements, systematic uncertainties, and applications to collider operation. A comparison of results from different kinds of measurements is also presented.

SYSTEMS IN USE

Several emittance measuring systems exist across the Fermilab accelerator complex. Booster has both IPM's and Crawling Wires. Main Injector has IPM's, Flying Wires, and Multiwires. Recycler has Flying Wires and Schottky detectors. Tevatron has IPM's, Flying Wires, Schottky detectors, Synchrotron Light Monitors, and Optical Transition Radiation (OTR) [1] instruments. We will discuss the comparative measurements from only those instruments used in the normal course of stacking and storing, protons and antiprotons (pbars). Crawling Wires, Multiwires (secondary emission monitors,) and OTR are used for studies of injection and tolerate only a few turns of beam.

MAIN INJECTOR

Three types of instrumentation devices are installed in the MI10 straight section of Main Injector Ring for transverse emittance measurements; a horizontal and vertical Flying Wire, horizontal and vertical IPM[2], and one magnetic electron IPM[3]. The straight section, being of zero dispersion function by design, ensures that measurements are free from effects of longitudinal beam motion.

For collider operation, beam emittances of both horizontal and vertical plane are measured using the Flying Wire system and logged for every pbar transfer from Accumulator to Recycler Ring, Recycler Ring to Tevatron, and each proton transfer from Booster to Tevatron. In Main Injector, these measurements are taken at 8 GeV/C injection and at 150 GeV/C flat-top, before transfering beam to Tevatron.

The Flying Wire system measures beam loss profiles as a 33um carbon filament flies through the beam. Flying at 6 meters/second the wire takes about 5 milliseconds, or 450 revolutions, to traverse the entire width of beam. Quasi-stationary beam is a necessary condition for measurement to make any sense. . Unlike the flying wire system, the ion profile monitor records a complete profile from each successive turn of beam

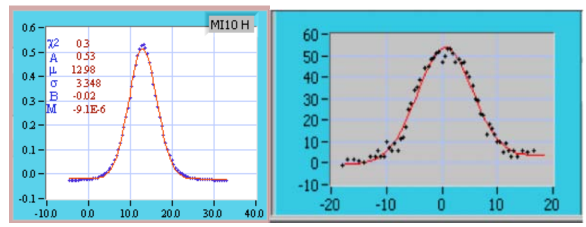

Figure 1. Main Injector Flying Wire And IPM Profile.

The IPM's are placed directly next to the flying wire system, of corresponding plane, to make comparisons more straight forward. Only one magnetic electron IPM for the horizontal plane is installed. A second unit is anticipated for the vertical plane in the near future. This is expected to be an improvement over the ion IPM for measurements at or above 120 GeV.

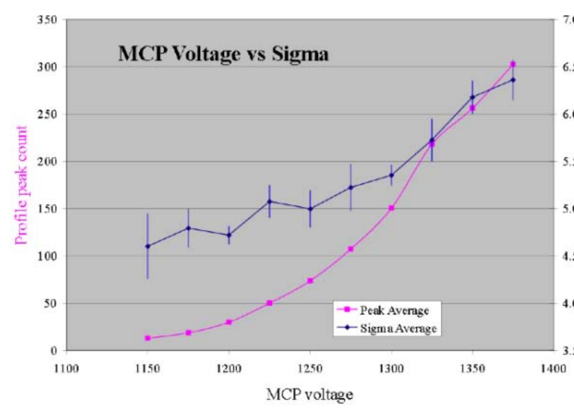

Figure 2. Sigma and peak count vs MCP Voltage

The full characterization of IPM response has so far not been completed. Figure 2 shows a measurement of beam profile sigma with varying high voltage to the Micro Channel Plate. While the increase in peak count is expected the dependency of sigma on high voltage is of concern. The best setting allows for good signal to noise measurement without saturation, or sag, at the peak of the profile. Two straight forward comparisons have been made. A simultaneous measurement of sigmas on both systems with increasing intensity and, in a separate measurement, a position bump was implemented through

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the Q102 straight section to compare the positions measured. Figure 3 shows a comparison of profile sigma from both flying wire and IPM's with varying number of Booster turns at injection for different beam intensity, and inherently varying beam width. The IPM single turn profiles show a consistently smaller sigma than the 100 turn average or the flying wire due to dilution by position oscillations.

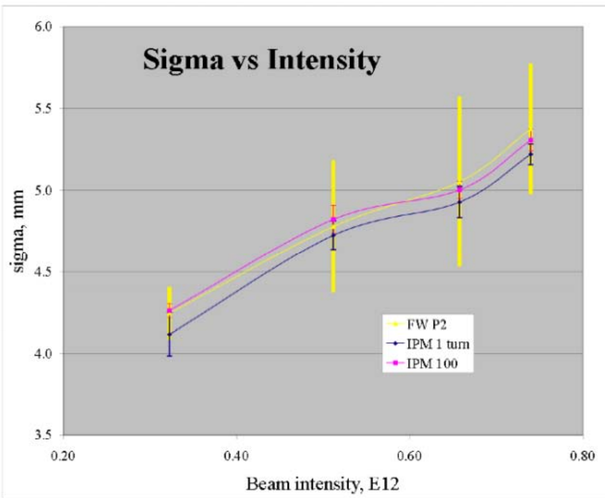

Figure 3. Sigma vs beam intensity for Flying Wire and IPM.

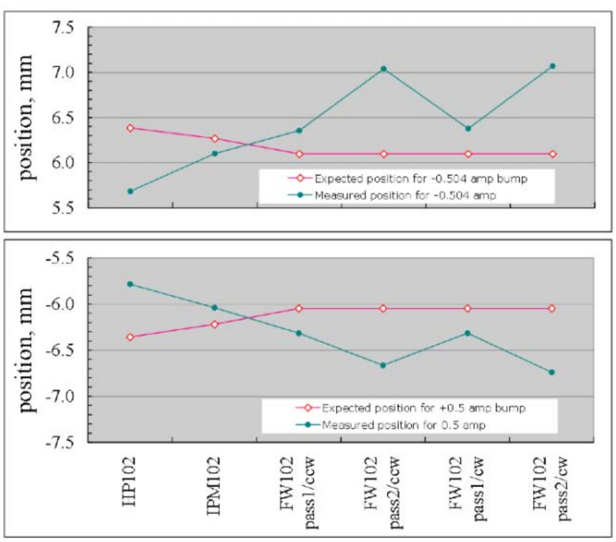

Figure 4. Position reading with known orbit bumps to verify position calibration.

RECYCLER

The Fermilab Recycler is a 3.3-km 8.9-GeV/c fixed momentum storage ring located in the Fermilab Main Injector tunnel. The Recycler has been an essential and integral part of the substantial Run II luminosity improvements since 2005. For beam stability and efficiency in generating a bright pbar beam, it is critical to have precise knowledge of the transverse emittances and beam profile. For transverse emittance monitoring, two complimentary systems are used: the flying wires, and the 1.75 GHz Schottky detectors.

Flying Wires

The Recycler Flying Wire System[4] consists of two cans (for horizontal and vertical measurements) installed at low dispersion locations. Each can is equipped with an ion pump and a TSP for vacuum maintenance. Wires were initially 33 micron monofilament carbon fiber, but the transverse emittance growth due to the wire-beam interaction is proportional to the wire diameter squared.

$$\frac{1}{\pi}\Delta\epsilon_N = 3\gamma\beta\left(\frac{fd}{v_{tr}}\right)\left(\frac{\pi d}{4}\right)\left(\frac{1}{L_{rad}}\right)\left(\frac{13.6\,MeV}{Pv}\right)^2$$

Where d is the diameter of the fiber, vtr is the transverse speed of the fiber, and Lrad is the radiation length of the fiber. The normalized emittance growth is proportional to the wire diameter squared. Emittance growths on the order of 0.5 π-mm-mr per measurement, (4 wire-beam crossings) were observed with the 33 μm wires. A system upgrade was performed in the 2006 shutdown, in which high tensile strength 5 μm Toray T1000G carbon fiber replaced the 33 μm fiber. Since the impact on emittances due to wire-beam interaction has been thus minimized, the flying wires have been employed in routine emittance monitoring of all modes (stored beam, newly injected beam and beam to be extracted).

Schottky detectors

In addition to the flying wires, a Schottky detector system is used to monitor the betatron band power, and therefore the transverse emittance, of the beam. Details about the Recycler 1.75 GHz Schottky detectors can be found in [5]. The narrow band, high impedance waveguide pickups measure sum and difference components of the beam signal. The difference components, mixed down to 2~5 MHz, are processed on a VSA (Vector Signal Analyzer) for background subtraction and band power calculation. The computed betatron power is then scaled to reflect the transverse emittance of the beam based on the constants obtained from calibration with the mechanical scrapers [6].

Comparison of the two detector systems

Flying wires measurements were compared to the measurements from the 1.75 GHz Schottky detector system. The tradition at Fermilab is to report the 95% normalized emittances. The Schottky detector measures the rms size of the beam, and converts it to the 95%

normalized emittance based on the assumption that the beam distribution is Gaussian. The Flying wires measure the time-averaged projection of the beam profile and obtain the σ from a Gaussian fit. It was verified that the two detectors agreed to within 10% when measuring a cooled pbar beam, which has a known Gaussian profile. Furthermore, it was demonstrated that the two detectors diverge when the transverse profile was known to be non-Gaussian, as when strong electron cooling is employed. The Schottky detector reports larger emittances when the distribution had a tail bias (large rms), and the Flying wires reports larger emittances when the tails of the distribution were truncated (small rms).

One of the key utilizations for the Flying wires in daily operation is the measurement of the transverse emittances when the rms momentum spread of the beam is more than 4 MeV/c, at which point the betatron and momentum bands (at h ~ 20,000) overlap and it becomes impossible to measure the betatron band power accurately due to the loss of baseline information.

Emittance measurements in a Tevatron shot

The following is an example, taken on the 19th of April, this year, of a sequence of emittance measurements for a typical set of antiproton transfers from the Recycler to the Tevatron. All emittances are 95%, normalized. Initially, recycler Schottky measurements reported 2.3 and 2.7 π-mm-mr shortly before the RF manipulation for extraction. The Recycler flying wires reported 2 π-mm-mr for the first partition of beam measured shortly before its extraction. The discrepancy has been understood to be due to a non-Gaussian distribution of the transverse beam profile of a stochastically and electronically cooled antiproton beam. The emittance measured on the horizontal Main Injector flying wire was 2 π-mm-mr at injection, before acceleration from 8 to 150 GeV, as the injection position errors are typically minimal. The horizontal Main Injector flying wire measurement made slightly later at 150 GeV showed a 25% increase in the normalized emittance. The increase can be attributed to the change in the momentum spread due to the coalescing of the bunches and the small but non-zero dispersion at the horizontal flying wire. In the Tevatron, the horizontal flying wire measurement after the first injection was 3.5 π-mm-mr, partially as a result of intended position errors made at injection on the order of 1mm to lessen beam-beam effects due to the brightness of the antiproton bunches.

In addition to distribution-dependent uncertainties, the uncertainties in the Recycler and Main Injector emittance measurements are dominated by the 15% or so uncertainty in the lattice functions used in the computation of the emittances. In the Tevatron, the field non-linearity and the orbit changes contributed to about 20% of the uncertainty in the lattice function; additionally, the uncertainty in the dispersion function at the wires was about 10%.

TEVATRON

The Fermilab Tevatron has several systems capable of measuring transverse emittance. The primary instruments used in operation are the Flying Wires, but there is also a Synchrotron Light Monitor, Ionization Profile Monitors and Microwave Schottky detectors.

Flying Wires

The Tevatron flying wire system[7] is similar in design to the other flying wires in Tevatron machines, and consists of three cans. One horizontal and one vertical system is installed at low dispersion locations, and an additional horizontal system is installed in a high dispersion location.. The idea of the high dispersion system was to independently measure the momentum spread from dispersive size of the beam but this was found to be unreliable and hence the high-dispersion system is rarely used.

Since the original 33um carbon fibers were changed to 5um, for the same reason as in the Recycler, the wires are used routinely in every stage of operation. Wires are flown following most proton injections, after each pbar injection, several times during ramp, squeeze and halo removal (scraping), and every hour during HEP stores.

Synclite

When a charged particle passes through a magnet, it undergoes acceleration perpendicular to its direction of motion and emits electromagnetic radiation. For certain energies and magnetic fields, part of this light is in the visible spectrum and can be detected with generic optical devices. Since each particle in the beam emits this light, one can point a telescope at it and produce a transverse image of the beam. The Synclite system[8] does this and thus offers a non-destructive method for measuring the transverse emittances of the Tevatron beam.

For the Tevatron, synchrotron radiation is non-negligible only when the beam energy gets above 600-700 GeV. The peak emission wavelengths are related to both the beam energy and the magnetic field ($\propto E^3 \cdot B$) and the intensity drops dramatically at shorter wavelengths. It was pointed out by [9] that there should be an enhancement of the emissions on the short wavelength side resulting from transitions into or out of magnetic fields. The Tevatron dipoles have peak wavelengths in the micron range, and as such observation would be difficult due to the lack of near infrared devices and the inherent diffraction caused by the longer wavelengths. Fortunately, the light emitted from the edge of the dipoles is enhanced in the blue optical region which helps with both of the aforementioned shortcomings.

The physical layout of the Synclite system is shown in Figure 5 and comprises a vacuum insertion mechanism to which is attached a pickoff mirror, and a light tight box containing the necessary optics for forming an image. The optical path contains a single lens for focusing, motorized mirrors for positioning the image, a 440/10 nm band pass filter (400/40 nm for pbars), and a gated, Image Intensified CID (Charge Injection Device) camera for obtaining the image. The image is retrieved from a frame grabber in a PC running Windows XP and LabVIEW.

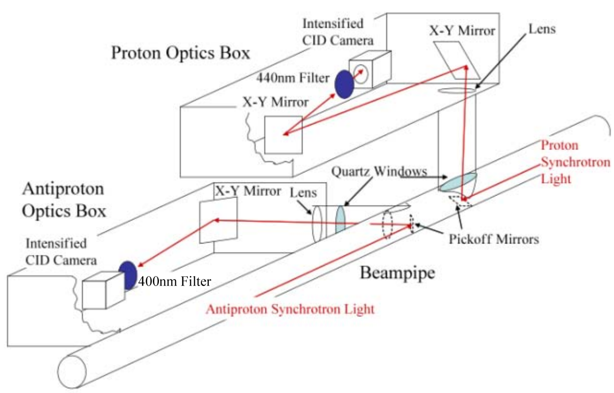

Figure 5. Synchrotron Light Monitor.

The image has its background subtracted before the beam sizes are extracted from fits to the horizontal and vertical profiles in a window around the peak. The fits are simple Gaussians with linear baselines. The values of the fits are then corrected for non-linearities in the intensified camera response and for theoretical distortions in the image. The theoretical distortions are determined via a numerical calculation [10] and contain most notably the broadening of the peak due to diffraction and the impact from the longitudinal extension of the source.

The light emitted from the accelerated particles is emitted in a cone with a half-width of roughly $1/\gamma$, which at 980 GeV is ~10^{-3} radians. This narrow cone is the optical equivalent of a circular aperture which results in a diffractive broadening of the image after propagating it through the lens. At 10^{-3} radians, the impact is 100 µm on a beam size which for pbars is in the range of 200-400 µm.

The second main effect is from the longitudinal extent of the emission source. Light is emitted along the entire body of the magnet. At the wavelengths used in Synclite, the dominant emission source is the edge of the dipole, but there is still a significant distortion from the light emitted from the body of the magnet which is neither in focus nor at the same transverse position due to the constant bending through the magnet. This effect on the image must be accounted for in determining the beam size.

Comparisons can be made with other profile measurements such as the flying wires.

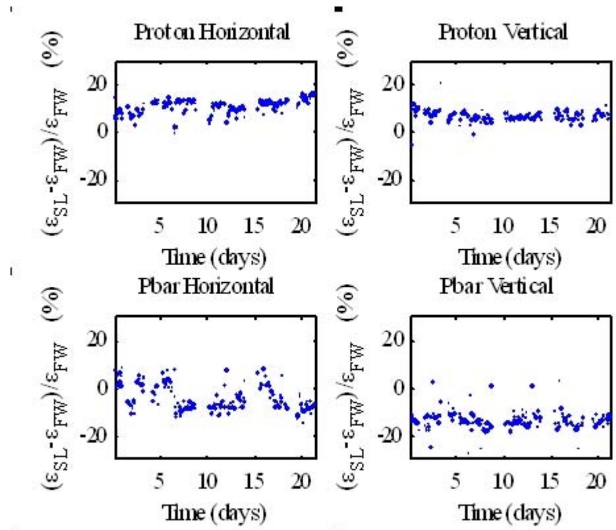

Figure 6 shows the percentage differences between the Synclite and Flying Wire emittances for a handful of beam stores.

Schottky detectors

The Tevatron has microware Schottky detectors that are identical to the ones installed in the Recycler. The acquisition electronics, software and data analysis is different, however. The Tevatron microwave Schottky is mainly used to measure tunes during stores, but the total power in the Schottky band is also reported. In the case of true incoherent Schottky signals, this signal is proportional to emittance. It has been observed, however, that during ramp and squeeze, early in stores, and sometimes for brief periods during stores, that there is significant coherent power in the Schottky spectrum. For most of the store however, this signal scales reasonably well with the Flying Wire emittance.

IPM

The Tevatron IPM's were designed to be single turn, single bunch devices, in order to resolve any turn-by-turn beam size oscillation caused by injection mismatch, and were not optimized for average emittance measurement.. However, data from multiple turns can be combined in software to create an average beam profile from which the emittance can be calculated.

The IPM measures ionization electrons collected using a parallel electric and magnetic field. A localized pressure bump obtained by controlled injection of pure N2 is required to obtain single turn sensitivity. The magnets and gas injection is left on continuously, while the high voltage sweep field is pulsed only for acquisitions. The detector granularity is 1/4 mm, and the readout uses electronics borrowed from HEP experiments, enabling close to single electron sensitivity.

Comparison of the detector systems

Both proton and pbar emittances change significantly during the course of a normal HEP store and this can be used to compare the various emittance readings. In general, the different measurements scale well within a store, but the absolute values can be off up to 10-20% In addition, the ratio between different instrument readings sometimes change up to 10% from store to store. This is the case for all the different measurement methods and is generally attributed to variations in the beta functions.

CONCLUSION

It is clear that there is more work to do and we will continue to identify and execute more complete studies. Ultimately these devices measure beam size and not emittance directly. We depend on a good knowledge of the Beta functions to convert these measurements to emittance. Additional work is on going to understand and reduce the systematic errors in the measurements of the beam size.

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