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TEVATRON IONIZATION PROFILE MONITOR

-CONCEPTUAL DESIGN REPORT

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Abstract

There are strong indications that the Tevatron transverse emittance is blowing up at injection and during the ramp. To diagnose this in particular, and complement existing emittance diagnostics in general, an ionization profile monitor (IPM) is being developed for the Tevatron. To resolve the dynamics of the injection process, single turn resolution is required. For pbar studies with protons in the machine, this effectively implies single bunch resolution.This report proposes a conceptual design for such a device, capable of single bunch resolution. It consists of a sensor part largely based on the existing Main Injector prototype IPM, and uses an electromagnet to focus the ionization electrons. Since the signal from a single bunch is very weak, the signals are then digitized directly in the tunnel, to minimize cable losses. The front-end electronics is based on a prototype board built by PPD for the CKM experiment, using the charge integrator encoder (QIE) chip designed at Fermilab (Previous versions of this chip has been used in KTev and CDF, and the latest version will be used by CMS). The data is then sent on optical fiber to a buffer card in a PC located in a nearby surface building. The proposed card is an adaptation of a card being developed by the Computing Division (CD) for the BTev experiment. The data on the card is read out over PCI bus for analysis locally in the PC.The estimated total cost of two IPM units is about $350.000, which includes a rather large (40%) contingency.

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Specification and requirements

Motivation

A relatively large emittance increase has been observed at beam transfer from the Main Injector to the Tevatron. Currently, no instrumentation exists to directly diagnose this blow-up. An ionization profile monitor providing turn-by-turn profiles of both protons and pbars would be a useful tool to understand and eliminate this effect. Moreover, such a device could provide an additional measurement of emittance at other points in the Tevatron cycle, in particular during the ramp where significant emittance growth is also observed (and sync lite, the only continuous emittance device, it not yet working).

Requirements

The instruments should be able to:

- Measure the transverse size of injected proton bunches (3.5 10^{10} - 3.5 10^{11}/bunch, nominal value 2.7 10^{11}/bunch) and pbar batches/bunches (1 10^{10} - 1 10^{11}/bunch, current nominal value 2.7 10^{10}/bunch) turn-by-turn following injection with a relative accuracy of 10%. The number of turns acquired should be at least 100, but preferably larger (1000 or more). This will allow detection of betatron mismatch in the order of 20%, which gives a negligible emittance blow-up. A controlled local pressure increase to the order of a few 10^{-8} Torr may be permitted to achieve sufficient signal (e.g. for pbars or low intensity proton beams).
- Measure the transverse size of the stable (nominal intensity) proton and pbar beams up the ramp to an accuracy of 3% at nominal vacuum. Turn by turn resolution is not required in this mode of operation. However, the refresh rate should be high (<1 Hz) to resolve emittance growth on the ramp.
- Measure both planes (using two separate systems).

Also

- The presence of protons should not impede measurements of antiprotons, and vice versa. However, simultaneous measurement of protons and pbars is not required (The instrument could cycle thru the bunches, changing settings depending on the particle type/intensity. Also, at injection the time between injections is of the order of a minute or more).
- The instrument should be fitted with a calibration system to enable in-situ verification of proper functioning of all subsystems.
- Any magnetic field used to confine the ionization electrons must be corrected so that it introduces less than 0.1 mm rms orbit distortion around the ring.

Theoretical considerations

Introduction

The purpose of this section is to discuss the feasibility of using ionization electrons to measure beam size in the Tevatron. Since the nominal intensity values for protons and pbars are close to the extremes (pbar intensities are projected to rise), calculations in this document are typically done for the nominal values rather than the entire intensity ranges. In most calculations and simulations, it is assumed that the beam size is 1.7 mm at injection and 0.5 mm at flat top. It should be remembered that these theoretical estimates have a relatively large error bar, since some input parameters (e.g. vacuum properties) are not so well known.

Estimation of primary ionization

The main issue to answer is: Is there enough signal from the ionization in order to detect single bunches. RGA scans in the E0 sector, performed by the Tevatron vacuum group, indicate that the residual gas consists of approximately 42 % H_2, 42 % H_20 and 16 % N_2. The number of electron-ion pairs caused by minimum ionizing particles in different gases has been published by Sauli (see Fig n). The values are 5.9 cm^{-1} for H_2, 10 cm^{-1} for N_2. For H_20, an estimated value of 15 cm^{-1} can be obtained by extrapolating the data given in the published graph. The weighted average is thus about 10 electron-ion pairs per centimeter. These values are given for atmospheric pressure. Scaling to vacuum pressures yields about 1.3×10^{-2} electrons/proton/cm/torr.

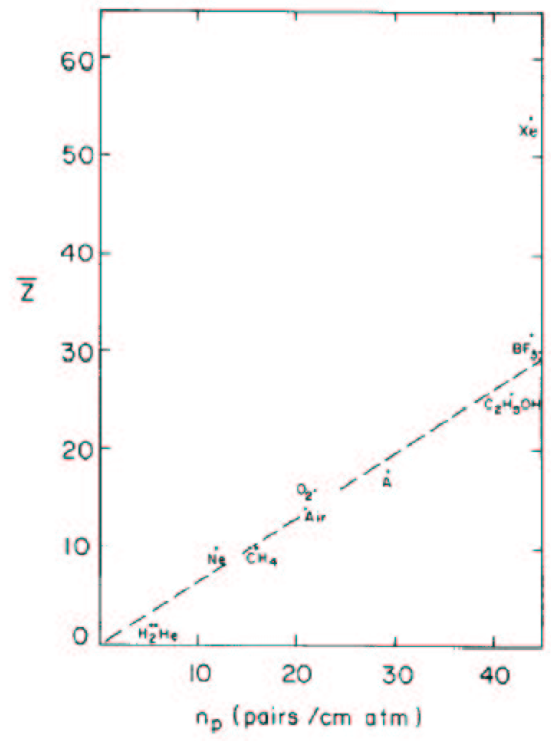

Fig. 7

Primary ionizing events produced by fast particles per unit length at normal conditions for several gases, as a function of their average atomic number (from Table 1). With the exception of xenon, all experimental points lie around a straight line. The plot may be used to estimate the number of primary pairs in other gases.

Figure N. Measured primary ionization from F. Sauli (CERN Yellow Report 77-09).

Assuming a vacuum of 3 10^{-8} torr and a detector length of 10 cm gives a total primary signal of about 1000 electrons per typical proton bunch (2.7 10^{11}). There are 36 bunches

in the machine, and the revolution time is about 21 us, so this corresponds to a total signal current of 0.3 nA.
If the transverse beam distribution is assumed to be Gaussian, the peak current density is 80 pA/cm^2 at injection. At flat-top, the size is three times smaller, and the peak signal density about 240 pA/cm^2.
There is of course a relatively high degree of uncertainty in this prediction. This uncertainty is dominated by the accuracy to which the measure the properties of the vacuum can be measured.

How to separate protons from pbars?

The protons and antiprotons circulate on two different helical orbits. The spatial separation of these orbits, expressed in units of the local beam size, varies around the ring. In addition, the direction (phase) of this separation in xy-space varies as the proton and pbar orbits "corkscrew" around each other. This means that in a given plane, the separation may be very small in certain locations. Recent work on improving the helix has increased the overall separation. This work is still ongoing. In the available locations, however, the current helix is barely enough to separate protons from pbars in both planes, using spatial separation alone. In addition, future helix work may change the projected separation at any selected IPM location. It is therefore not wise to expect to separate protons from pbars using only spatial distance. However, if the monitor is positioned in a good location, the time difference can be used to enhance separation. Since bunches are injected into the Tevatron one by one (or four by four in the case of pbars), time gating would anyway be required to separate the injected bunch from the circulating beam.

Several ways to gate on single bunches have been considered. One way would be to gate the micro-channel plate (MCP) by pulsing the voltage. However, the large area MCPs have a relatively long recharge time (100 us, according to Burle), making them unsuitable for single bunch gating (slow gating could still be an option to reduce the exposure of the plate, and increase its lifetime).

The other option would be to use a gating grid to shut off incoming electrons before they reach the MCP. However, unless the drift field is completely reversed and the electrons collected in the opposite end (which would require a gating pulse of several thousand volts) the effect will just be to collect electrons in an electro-magnetic trap. The trapped unwanted electrons would return to the MCP as soon as the grid voltage is dropped. Therefore, this solution does not appear to be feasible.

Hence, it seems like time gating must be based on fast readout electronics.

Is there enough signal for bunch-by-bunch resolution?

The question whether there is enough signal can be split in two sub-questions. Are there enough primary electrons to accurately reconstruct a profile in the first place, and is the signal to noise ratio sufficiently high to detect this profile. The textbook answer to the first question is that the relative uncertainty on a width determined from N samples is $1/\sqrt{2N}$. In other words, about 50 electrons would ideally be sufficient to determine the beam width to 10%. This idealized formula does not take into account detection efficiency, detector resolution, quantization noise, and many other effects. It is, though, an indication that the number of primary electrons does not have to be huge for the width measurement to work. However, when dealing with low-statistics samples, a ‘standard’ Gaussian least-squares fit will not perform well. It is better to use a maximum-likelihood fit, since it handles statistical fluctuations of the primary signal better (a least squares fit works best for ‘white’ noise on top of a well defined signal). Such a fit algorithm should therefore be implemented in the IPM software.

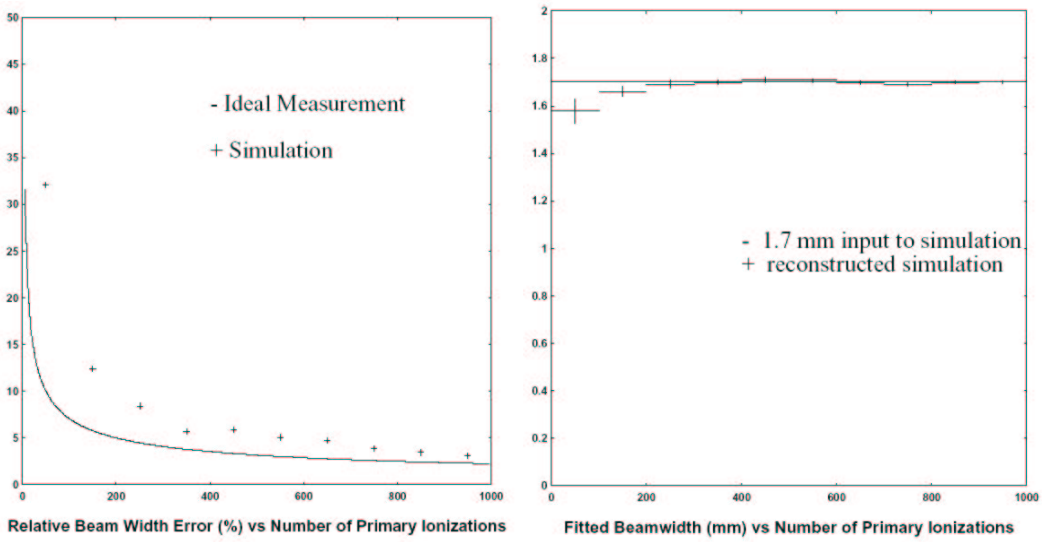

FIG. Simulation of reconstructed beam size error. The left plot shows the statistical fluctuations (rms) and the right plot shows the systematics of the mean value. About 200 primary electrons are needed to reconstruct the beam size to 10%, and avoid systematic errors. An MCP gain of 10000 and a noise of 6000electrons/sample was assumed.

As mentioned above the expected signal for a proton bunch is about 1000 electrons per nominal proton bunch, and 100 electrons per nominal pbar bunch. In terms of primary statistics, there is no problem for the protons, whereas the pbars are on the limit. However, pbars are injected four by four, so one can improve the situation at injection somewhat by making an average over these four bunches. For a circulating beam, this average could be done over multiple turns, since single turn resolution is not required.

Obviously, the signal levels scale directly with the vacuum pressure. If the vacuum would improve, the primary signal would decrease accordingly. Hence, to ensure reliable operation, it is necessary to incorporate a means to control the local vacuum pressure in the vicinity of the IPM, to make sure that the primary signal is adequate even if the vacuum system is upgraded.

Therefore the IPMs should be equipped with a controllable gas leak to increase signal if needed. The preferred gas is N_2 since it is has a large ionization cross-section and is relatively easy to pump. Adding adequate pumping capability, the 'pressure bump' can be contained to a few meters. Also, sector valves are required on either side of the IPM(s), to facilitate maintenance.

The second question, whether enough gain can be provided while keeping the noise low, will be discussed in more detail later on. It turns out that, although very high gains (10^6) can in principle be achieved using e.g. micro-channel plates, the gain is effectively limited to ~10^4 by the total amount of beam in the machine. Therefore, low noise detection electronics is called for.

Detector Design

Choice of location

Ideally, the IPMs should be placed next to another device measuring beam width, such as the flying wires (In fact, it would be ideal to have all emittance devices next to each other to facilitate cross-calibration). However, due to the limited space available in the Tevatron, this is not possible. Of the available locations, the optimum one for installing IPMs was found to be in the E0 straight section, where there is a relatively long free straight section. This is relatively close to the E11 flying wires (measuring beam size in both planes) as well as the new high-frequency schottky pick-ups in E17. The proximity simplifies comparative measurements. Also, there are scrapers nearby that could be used for calibration. Furthermore, a trim quad have recently been installed there to measure the local beta function. Recent optics work has also indicated that there are no major optics distortions in this sector.

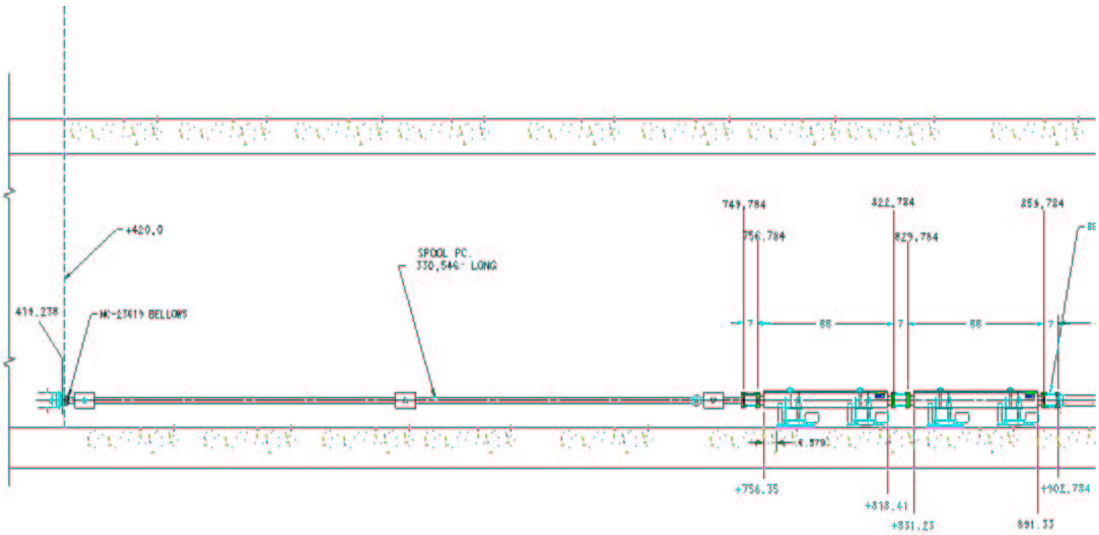

FIG. Layout of the free space in the E0 sector.

The total free space is about 10m, of which some is now taken up by an the trim quadrupole. Also, part of the free space is underneath an old main ring dipole. However, only about 3.25 m will be required for the IPM.

The radiation level at the location of choice was measured using a “scarecrow’ detector on a vertically movable stand. The levels were found to be reasonable, especially a few feet away from the beam pipe. The average radiation levels during stores at 4-5 feet above the beam was found to be less than 0.5 rad/h. Furthermore, the current duty cycle of the machine, defined as the time when radiation levels above background are measured, was found to be 60%. Hence the expected annual dose, under current running conditions, is about 2500 rads/year.

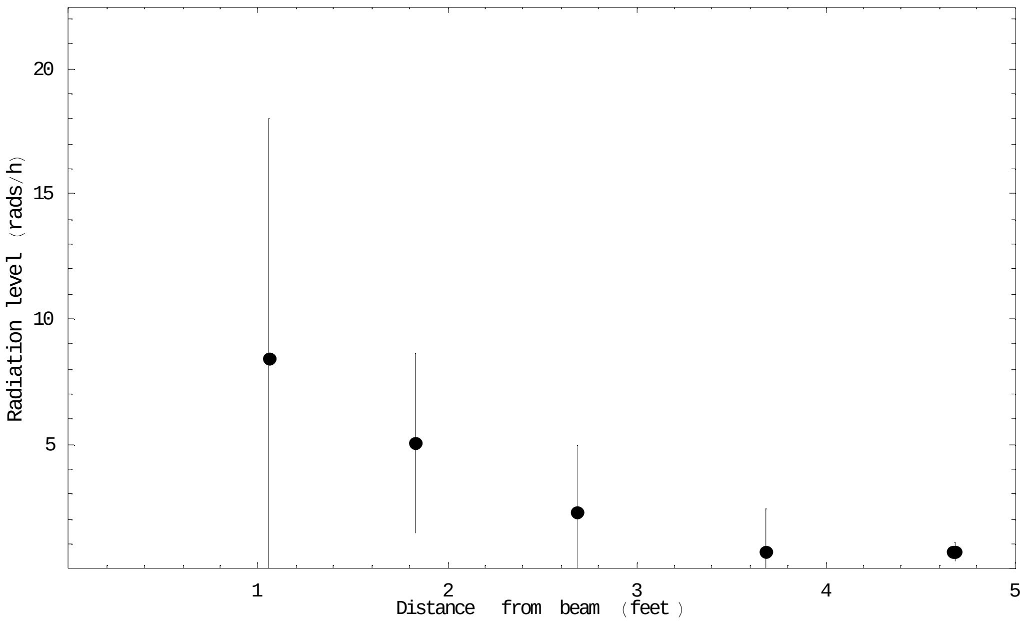

FIG. Radiation levels during stores versus distance (up) from beam. The error bar shows the variation (standard deviation) between and within stores.

The beta function in the straight section is about 90 m horizontally and 60 m vertically and the current helix amplitude is about 4.5 mm in the horizontal plane and 3.5 in the vertical. The recent helix work has changed the helix slightly at E0. Assuming an emittance of 30 π mm mrad, the amplitude is now a little less than 4σ horizontally and a little less than 3σ vertically. At flattop, the amplitude is less than 2σ horizontally, and 4σ vertically. These numbers vary somewhat along the ~10m long free section. The minimum time separation between protons and pbars correspond to 6-9 RF cycles at injection and 4-7 RF cycles at collision (depending on position within the straight section).

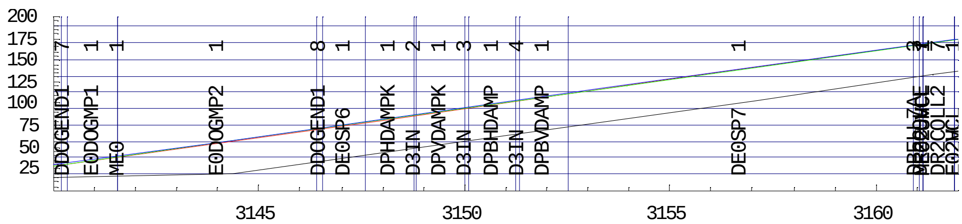

FIG. Minimum time separation between protons and pbars, as a function of position. Blue is injection cogging, black collision cogging. The DE0SP7 is the straight section chosen for installation. The vertical grid lines are separated by one RF period.

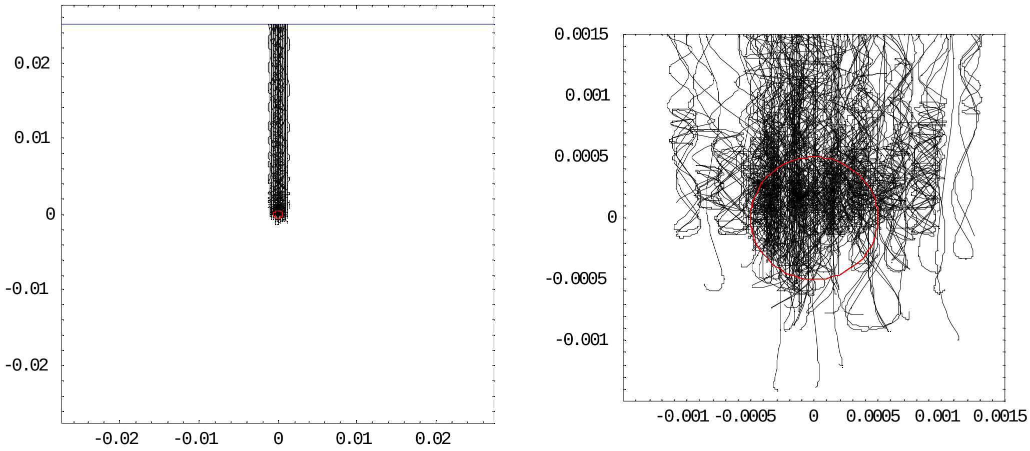

FIG. Simulation of protons at flat top. Here, detector is assumed to be above the beam. The cyclotron motion can be clearly seen in the individual tracks. Also, some signs of space charge capture (returning tracks) can be seen.

Transport and focusing of the primary electrons

Most IPMs at the lab detect ions. The ions are accelerated towards the detector by an electric field. These IPMs tend to have problems due to the slow drift of the ions, combined with the strong electric field of the beam, that tend to cause a spreading of the detected distribution. In the Tevatron, the ionization electrons will be detected instead.

The advantage of electrons is that a magnetic field (parallel to the electric field) can be used for focusing. Electrons are captured on the field lines and confined to their cyclotron radius, p/eB. This is essentially given by the initial velocity of the electrons (plus some effects from the electric field of the beam). Most of the electrons have an initial kinetic energy below 50 eV. Simulations show that a 0.2T field is sufficient to keep the transverse spread of the distribution negligible (The cyclotron radius for 50eV electrons is about 100 um at 0.2 T). The simulation code was adapted from a LabView program written by Alan Hahn.

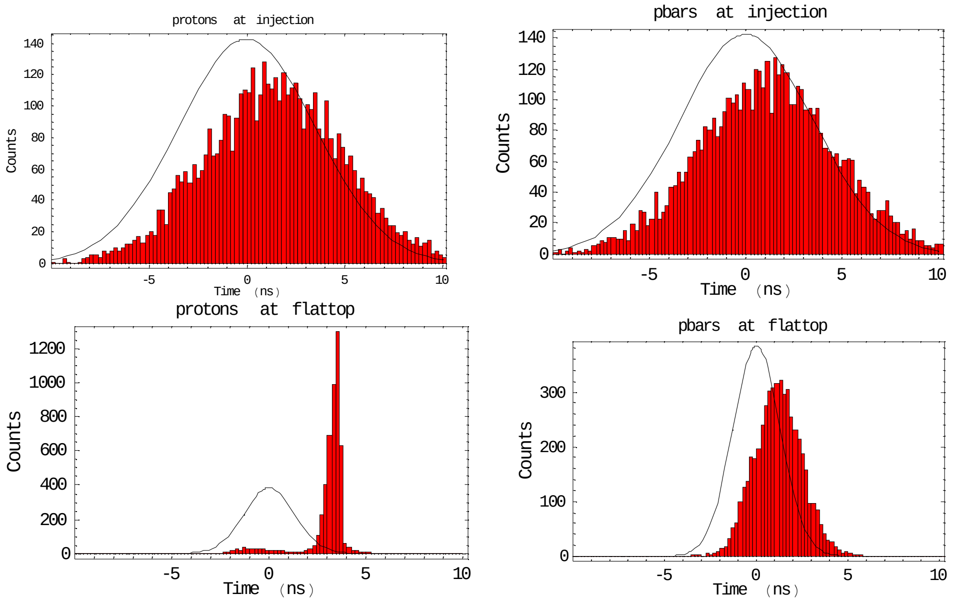

FIG. Time distribution of the detected signal. The black line is the bunch shape (assumed to be Gaussian for simplicity), and the red bars the detected electrons. Typical drift time is about 1ns, except for the case of protons at flat top, where about 75% of the electrons get captured in a "space charge penning trap" formed by the external magnetic field and the electric field of the beam. These electrons get released in a short intense burst, once the electric field of the beam (proportional to the instantaneous beam current) falls below a certain value.

These simulations also indicate that electrons typically reach the detector within nanoseconds of being generated. However, for high intensity and small beam size (protons at flat top) a large portion of the electrons (about 75%) of the electrons get caught by the space charge potential of the beam, and are only released once the bunch has passed. The transit time is, however, so short that no electrons are caught permanently, even for a modest sweep field.
The ions on the other hand, move much slower. Hence, the minimum field should be estimated so that the average potential does not capture ions indefinitely. This requires only a very modest field. When the ions hit the collector, they produce secondary electrons, which would normally get accelerated back towards he electron detector together with the primary signal electrons. It is therefore necessary to use a suppression grid to make sure these electrons do not affect the measurement.

There are two ways of producing the required magnetic field: using permanent magnets and electromagnets. The latter is preferred by the Tevatron Department, since it can be turned off to verify that it does not affect the beam, and also seem considerably cheaper (at least in terms of purchase price, maintenance will be higher).
The transverse kick given to the beam by the magnetic field must be corrected for. For this reason a two-bump consisting of two identical C-type electro-magnets will be used. The residual orbit distortion from single 0.2 T dipole magnet with a magnetic length of 0.4 m, would be about 8 mm in the arcs and 16 mm in the interaction regions (at

injection, the effect is smaller at flat-top). Using a second magnet with opposite polarity reduces this by a factor ~L/β_0 , where L is the distance between the magnets. This brings the residual orbit distortion down to 30 um in the arcs, and 60 um in the IRs. Splitting the correction magnet in two half-magnets, placed symmetrically around the main magnet (three-bump) would give a theoretical reduction of ~1/2 $(L/\beta_0)^2$., which would give a completely immeasurable orbit distortion. However, there are practical limitations to this approach, since there are tolerances on magnet manufacturing. An alternative using a three-bump permanent magnet (one piece) was studied. Although the three-bump is theoretically superior, tolerances on field matching dominate the residual error. The integrated field from this magnet would have caused a larger residual orbit distortion than using two electro-magnets.

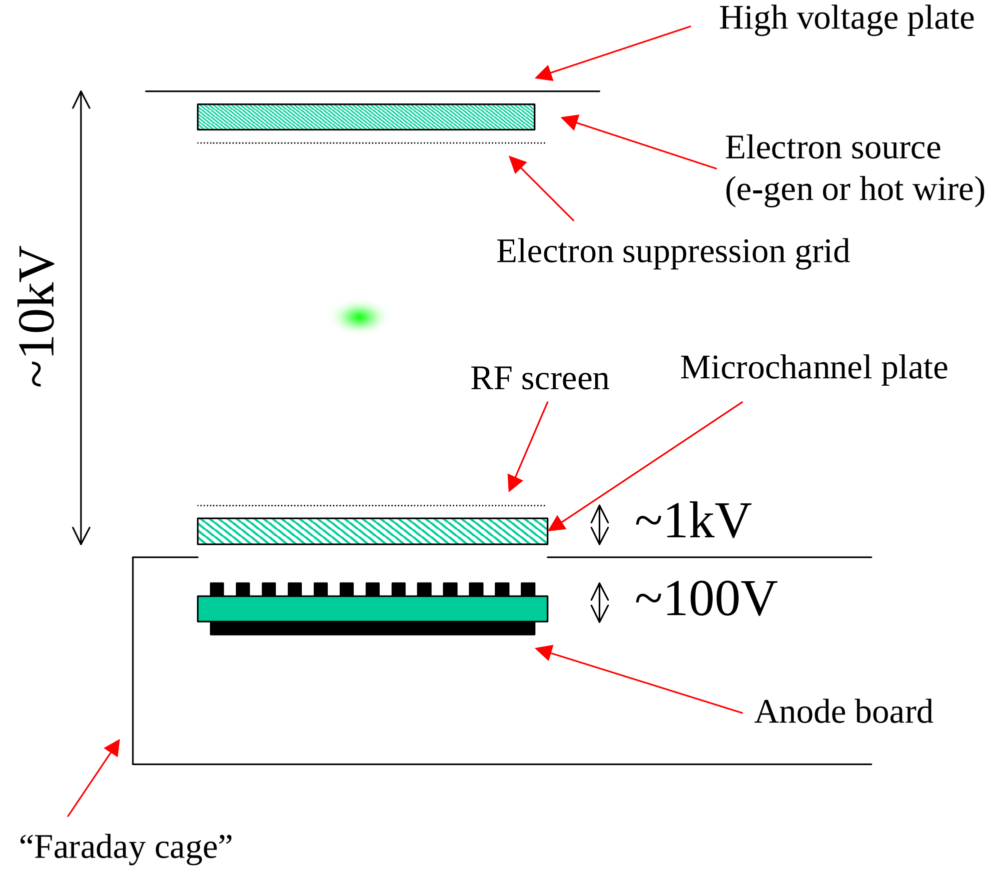

FIG. Schematic layout of the detector components and required voltages.

The alignment of the electrical and magnetic field is not supercritical, as long as the fields themselves are uniform. Any angle between the two fields will generate a constant drift velocity of v=E×B. In the case of uniform fields, this velocity is common to all particles, and therefore only generates a spread through the difference in drift time. However, the bulk of all particles have very similar drift times, so this spread is small.
The space charge of the beam does produce a strong E×B component (E-field from beam and B-field from magnet). Since these fields are transverse, the result is a longitudinal

spread of the particles, which can be of the order of millimeters. This, however, does not affect the measurement of the transverse width.

The field quality also has an influence on the result. Since the electrons follow the field lines blindly, if the field lines are not parallel the image will be distorted. For this reason, the field quality for the magnets was specified to have better than 1% field uniformity in the drift region.

Amplification of the primary signal

The primary signal must be amplified before it can be detected. The amplification will be obtained by using a micro-channel plate (MCP). An MCP is a glass plate with microscopic pores acting as miniature photo-multiplier tubes (PMTs). These devices are used in all IPMs, and are often blamed for ambiguities in the measurement result.

It is well known that MCPs suffer from aging, i.e. the gain is reduced as a function of total charge extracted, such that the plate develops “dead spots” in extensively used areas. In beam diagnostics applications, this typically leads to a broadening of the measured beam width, since the center of the measured profile is depressed. This can be detected for example by moving the beam to an unused area of the MCP, or by employing a system to measure the gain uniformity *in situ*. Both methods will be used in the Tevatron IPM.

However, there are other more subtle effects that may affect the measurement result. In particular, there is a limit to how much current can be drawn from an MCP. Each pore in the plate acts as an individual mini-PMT, with a relatively long recharge time (typically longer than the revolution time in the Tevatron). If the average time between hits is smaller that the recharge time, the gain will be reduced for the second pulse. This is referred to as field distortion saturation.

There are no good predictive models for MCP saturation known to the authors. Parametric models exist, but require measurements to match the parameters to each individual MCP. Hence, it is difficult to make hard prediction based on published MCP parameters. A test stand is being set up for this purpose.

However, since the recharge time of the MCP pores is much longer than the bunch separation, the primary signal can be approximated as DC. As a rule-of-thumb, in DC mode the signal current should be kept less than 10% of the MCP bias current in order to avoid saturation. It is therefore desirable to use plates with very high bias current. High bias current (low resistance) MCPs typically have values of 4-14 $\mu A/cm^2$ (at maximum voltage). The highest expected primary signal current density for 1.7 mm (injection) and 0.5 mm (flat top) proton beams are around 0.1 nA/cm^2 and 0.4 nA/cm^2, respectively (based on 36 bunches of 3 10^{11} with a revolution time of 21 us), so the gain will be limited to a few thousands for low-end plates and around 10000 for high end plates. A single plate typically has a gain of 10.000 or more, which would be adequate (but not excessive) for this purpose.

The maximum allowed output signal integrated over a ¼ mm wide by 10 cm long anode strip is 0.4-1.3 10^6 electrons per bunch (assuming uniform primary signal). It is important to understand that, disregarding the fact that the bias current varies with gain (voltage), this is independent of the primary signal level.

The higher the bias current, the more signal current can be drawn from the MCP without saturating. Obviously, the bias current increases linearly with the MCP voltage. Previous implementations of IPMs at the lab have used two plates in series (so-called Chevron configuration). For a given total gain, a chevron configuration has a lower voltage on the individual MCPs, and hence a lower saturation limit (Studies of the effect of MCP voltage on the reported emittance in the MI IPMs have confirmed that there are indeed strong signs of MCP saturation). Since a single plate can provide adequate gain for protons in the Tevatron, it therefore appears advantageous to abandon the Chevron.

A potential disadvantage of using a single plate, however, is that the pulse height (gain) distribution has a rather long tail (negative exponential), whereas in a Chevron the gain distribution is narrower, at least at high gain. Simulations have shown that this has very little practical effect in our application.

The main disadvantage is that the gain with a single plate is limited. This could be a problem if the primary signal level turns out to be much lower than expected. However, gain can compensate for a low primary signal only as long as the primary statistics is high enough. The largest useful gain, defined as the ratio between the saturation limit output, and the smallest primary signal that is still useful from a statistics point of view, is therefore less than a factor ten of what a single plate can deliver (unless the bias current can be further increased). This is for protons. Since the pbar intensity is only about 10% of the protons, if the primary signal is significantly smaller than expected, single bunch resolution will not be possible. To ensure that there is enough signal, it is therefore

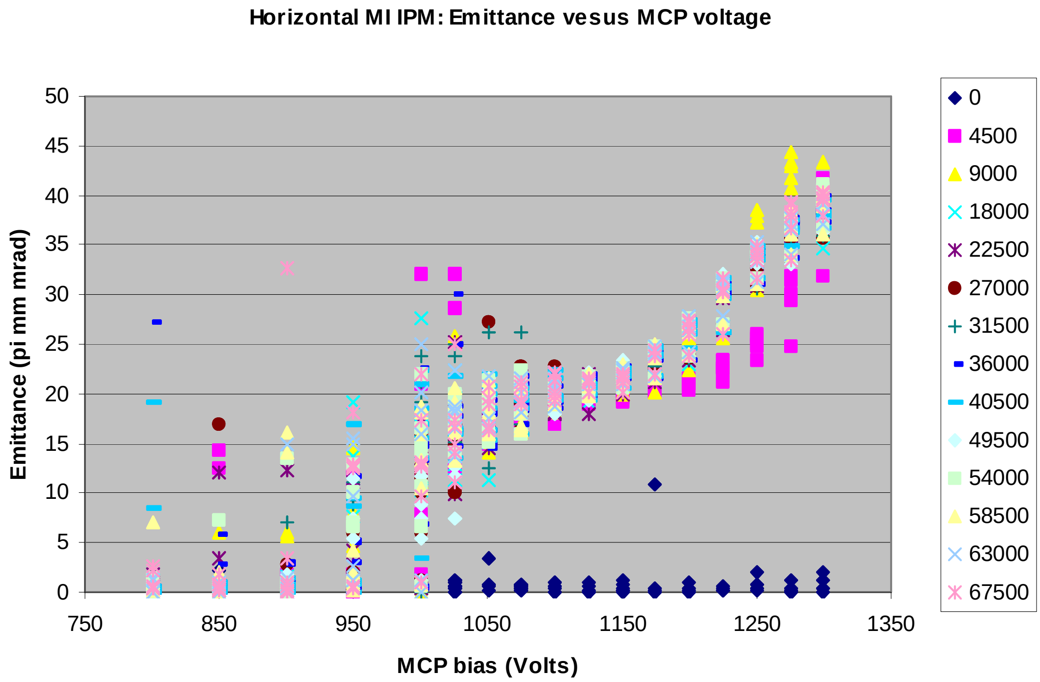

FIG. Measured emittance versus MCP voltage for the main injector IPM. The different dot colors represent different turn numbers. For low gain values, the signal is too noisy, and at high values the emittance increase as a function of MCP gain This is a clear sign of saturation. The two regions (noise dominated and saturation dominated) almost overlap, with an indication of an optimum gain around 1150V. However, it is not clear that there is no saturation at this gain setting.

foreseen to be able to increase the primary signal using a controllable leak valve.

An informal market survey and discussion with vendors have shown that there is a very limited choice of large area MCPs. Burle sell 8×10 cm plates in two qualities, standard and extended dynamic range (EDR).
In addition, they could produce special EDR plates with 50% smaller and 50% longer pores. These would have about the same characteristics as the EDR plates, but about 5x higher gain. There may be some advantage in using such plates, but they would be more expensive. The best choice therefore seem to be to use common EDR plates, but to select only those with a very high bias current.

The final decision will be made based on the outcome of tests performed in the MCP test stand.

Screening of unwanted signals

Since the signal charge deposited on the anode strips is very small, any parasitic coupling between the beam and the anode board must be kept under control. For this reason, the anode board will be essentially be enclosed in a Faraday cage. The MCP will be covered with a thin metal mesh, to screen the RF signals. The optimal design of this Faraday cage is still being studied. However, tests show that it is possible to significantly reduce the parasitic coupling between the beam and the anode strips. In addition, it is clear that the signal cabling from the anode strips to the amplifier are important. Care must be taken to avoid resonances due to the connections, since these can enhance the parasitic signals by 30dB or more. Tests on a spare Booster can showed signifincat resonances, that could be traced back to the physical separation between signal and signal return acting as an inductor. The Booster IPM was, however, never designed for high-frequency signals. In the Tevatron IPMs, reflections and resonances will be suppressed by keeping the signal path from the anodes strip a matched transmission line.

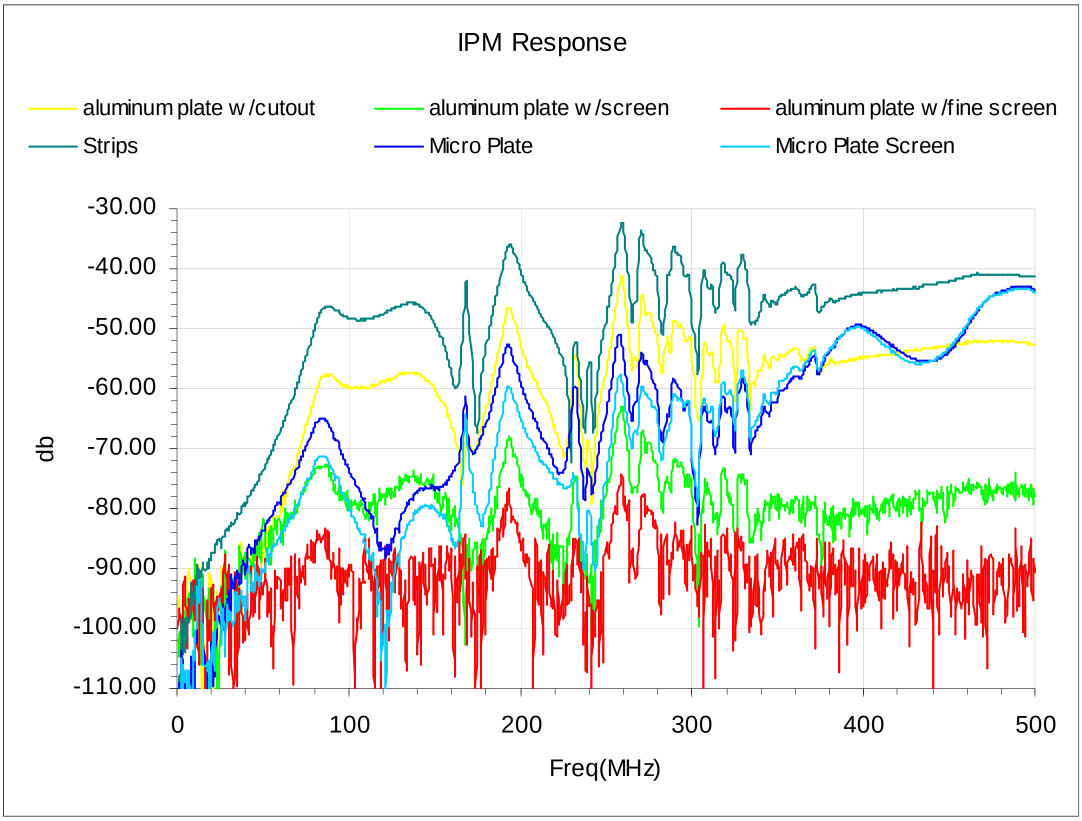

FIG. Test of different schemes to suppress the capacitive coupling between beam and anode strips. The enclosing the anode board in a faraday cage yields about 20dB, and the screen another 10-20dB.

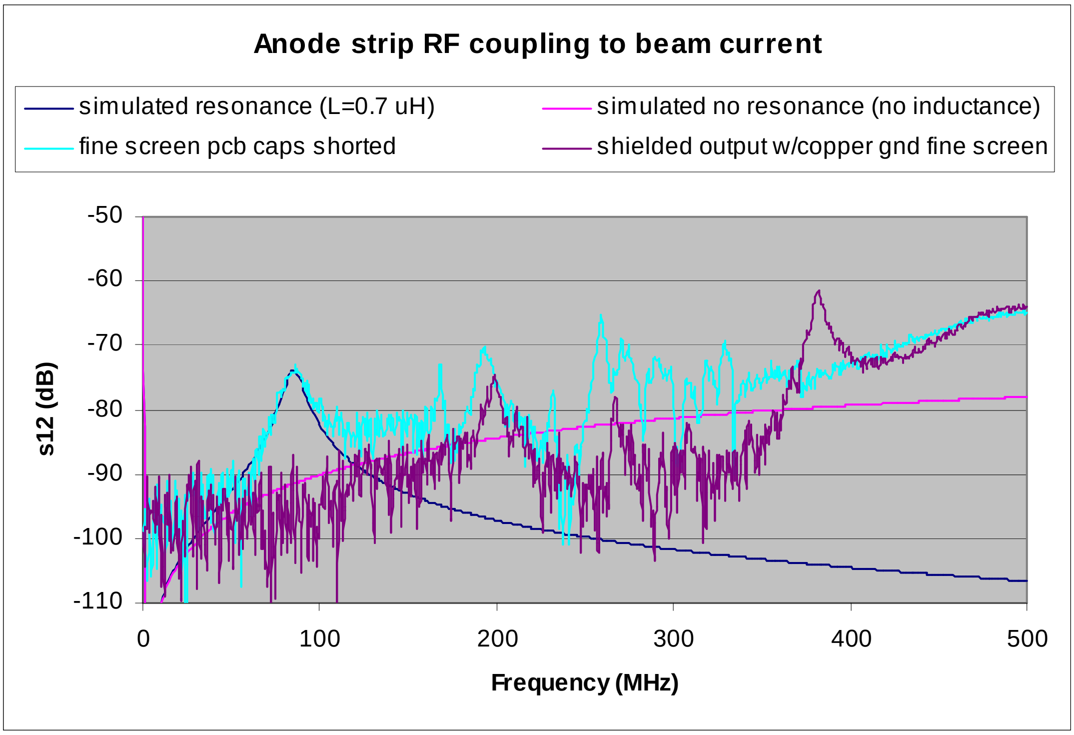

FIG. Measured strip response (cyan). The first resonance was modeled as a 0.7 uH inductance in series with the anode capacitance and out cable impedance. Reducing this inductance by screening the cables removed the resonace. Also shown is the model response with no inductance.

Detection of the amplified signal

The electrons generated by the MCP will be detected using anode strips parallel to the beam. Due to the small beam size of only about 0.5 mm rms at flat-top, a strip spacing of ¼ mm is required to accurately reconstruct the beam size. Smaller strip spacing would be advantageous, but already ¼ mm is difficult to produce.

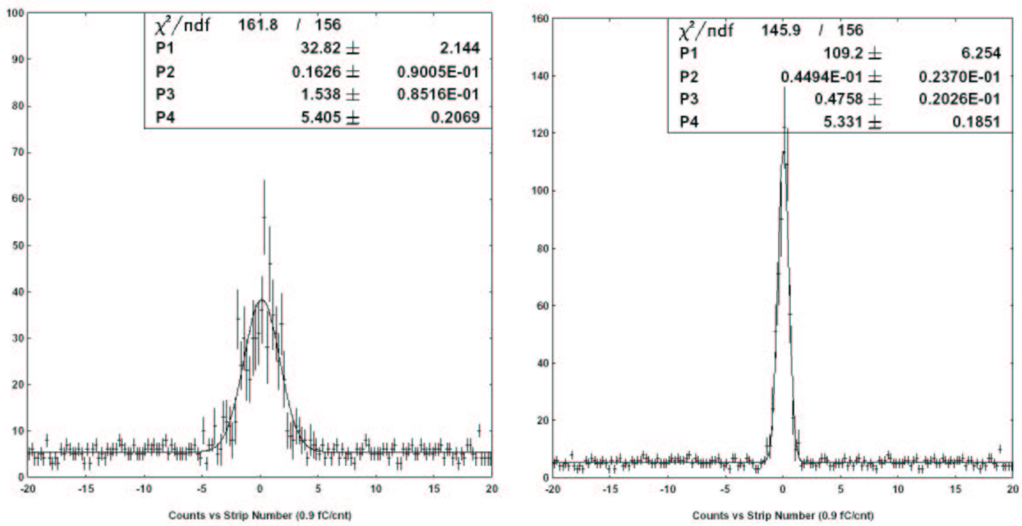

FIG. Simulated beam profiles at injection and flat-top. A primary signal of 300 electrons, an MCP gain of 10000, and a noise of 6000 electrons/bunch was assumed.

The active area must be wide enough to accommodate both beams, the helix separation, plus some margin to accurately detect the beam size. Also, there must be some room for closed orbit variations. Nevertheless, the entire aperture needs not to be instrumented.

The number of anode strips is a trade-off between detector coverage (width) and keeping the channel count reasonable. The value chosen is 128 channels. With a strip width of ¼ mm, this would give an active detector width of 32 mm (corresponding to about 20 sigmas). However, by instrumenting only every second strip in the outer 16 channels on each side, this width can be increased to 40 mm.

Due to the large aspect ratio of the strips, it is very important that they are accurately aligned with the beam. This will be ensured using mechanical movers in each end of the detector assembly. These will enable both alignment and centering of the anode board with respect to the beam.

Mechanical detector design

The internal components of the IPM detector will be largely based on the so-called MARK II IPM in the MI, with some modifications. Notably, there will be a solid ion collection plate with an electron suppression grid. The MARKII IPM originally had only a screen, which did not effectively capture the ions nor suppress the electrons. It is also being retrofitted with the solid collection plate, instead of the mesh that was used in the MI. Also, the connections to the anode board have been reworked to save space for a calibration electron source (electron generator or hot wire). The open aperture is 3”, as in the cold Tev magnets..

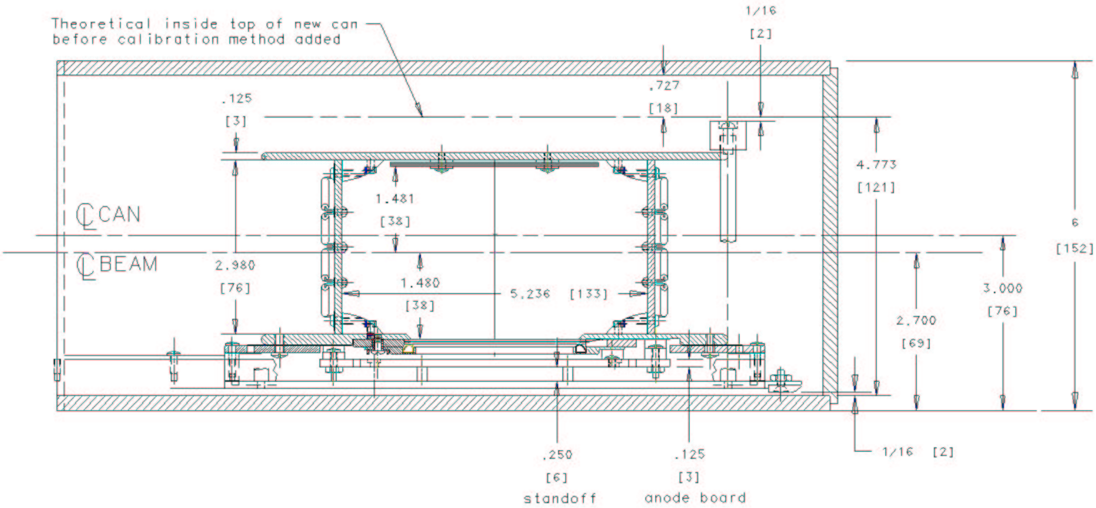

FIG. Interior detector design (adapted from MI MARK II IPM). The free space on the top is reserved for a calibration electron source.

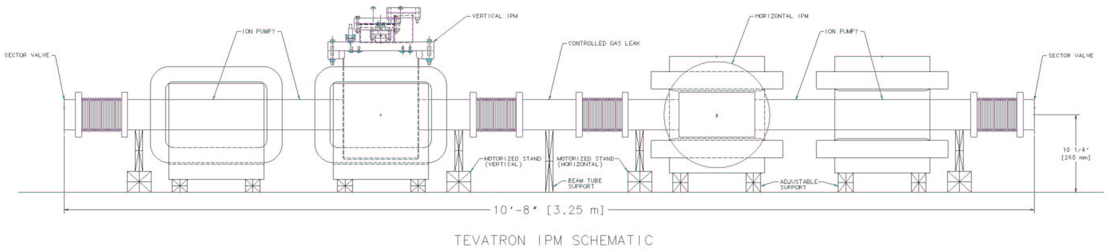

FIG. Layout of the two IPM units. The required space is 3.25 m, which is readily available in E0.

□ eadout electronics

Front end cabling

There is clearly a need to bring many signals thru from the vacuum to the outside. The highest density feed-through connector available is a 50-pin flat connector. The cabling from the anode board to the feed-through will be implemented using flex circuit. It is very important to keep the interior as well as exterior cabling a matched transmission line, to avoid resonance and signal reflections. The input impedance of the QIE amplifier can be set to either 50 ohms or 93 ohms to match the impedance of coaxial or twisted pair cables. Special care must be taken at the vacuum interface not to cause reflections.
The QIE is a ‘difference’ amplifier. Two input signals, the signal itself and the reference are integrated and subtracted before they are digitized by the internal ADC. Due to the input signals are unidirectional (only current flowing into the input), a return signal wire is necessary per each input. Since each signal has its own signal return associated with it, four conductors per channel are necessary. The QIE and the input cable form a differential topology to improve the common mode (CM) noise rejection of the system.

The signal cable and the reference cable have to be pulled alongside to optimize the CM noise suppression. Based on previous studies for the forward hadron calorimeter (VF HCAL) at CMS, the best results can be obtained if the signal and reference pair run together inside a common shield. It is foreseen to use in our application two twisted pairs with a common shield per channel or multi-conductor twisted pairs with common shield. Current studies are conducted to analyze the performance of these two options. The final decision will be based on these studies and the complexity of the final implementation.
To reduce the number of feed-through, the reference cables will not be pulled thru into the vacuum side, but terminated on the outside with a capacitor to simulate the anode strip capacitance and balance the differential circuit. Similarly, it is foreseen that the signal return wires will be connected on the outside and only a few connector pins will be used to connect them to the signal return plane of the flex circuit. This should not have any major effect, since the anode board has a common signal return path.

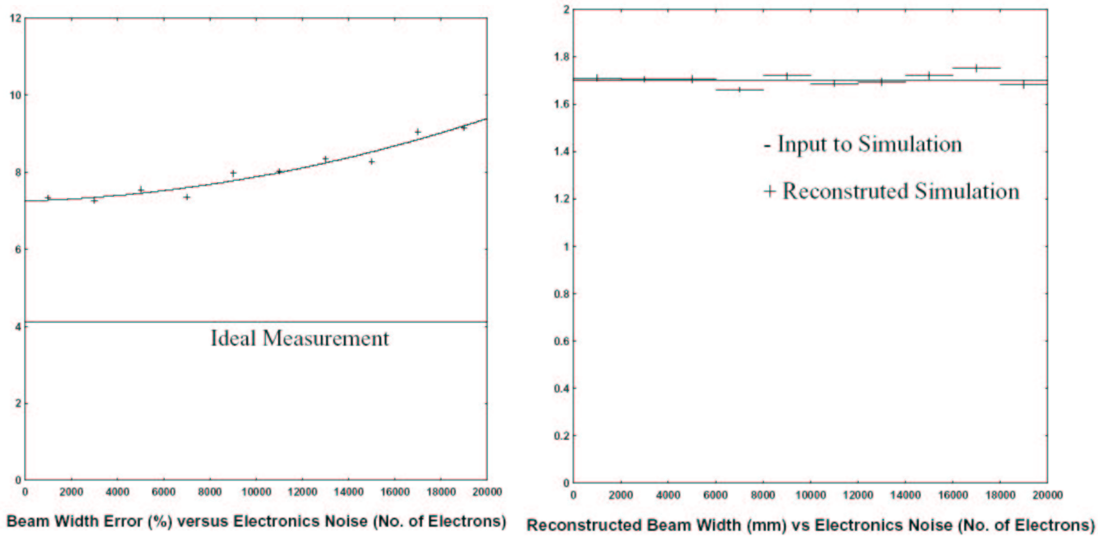

FIG. Simulated detected beam size versus noise. A primary signal of 300 electrons, and an MCP gain of 10000 was assumed. In order to avoid systematic effects, a maximum likelihood fit had to be used instead of a standard chi-square fit.

Digitization

Two quantities determine the signal quality: the total output charge (S/N), and the number of primary electrons (statistics). As discussed earlier, the total signal output is limited by saturation effects in the MCP to about 200 fC (~1 10^6 electrons) per anode strip and bunch passing. For pbars, this signal is currently about 10% of that (this ratio is supposed to increase eventually).

Simulations show that an additional noise of about 10000e is acceptable. This additional noise is the combined contribution of the thermal noise of the QIE input stage, the electromagnetic or environment noise picked by the input cables, noise couple into the micro strips by the beam, etc. Since the anode signals are so low, low noise electronics is

needed and located as close as possible to the anode circuit board. It introduces the restriction that the front-end electronics has to be radiation tolerant.
The QIE charge integrator chip combines very low noise with a very large dynamic range due to internal auto-ranging. In the most sensitive range, one count corresponds to 2.6 fC. This means that the binning noise is about 4300 electrons, and therefore the QIE is sensitive to single ionization electrons (with an MCP gain higher than this value). It is also radiation tolerant (tested to at least 20krad, which would make it last at least 8 years under current running conditions). In addition , it is a dead-timeless integrator, meaning that is continuously samples the charge collected between clock edges. The chip exists in several versions. The one that is most interesting is the QIE8-CMS, built for the CMS experiment at CERN. It includes the sampled charge integrator and the ADC into the same chip. Since the production yield for this chip was higher than expected, there are chips available.

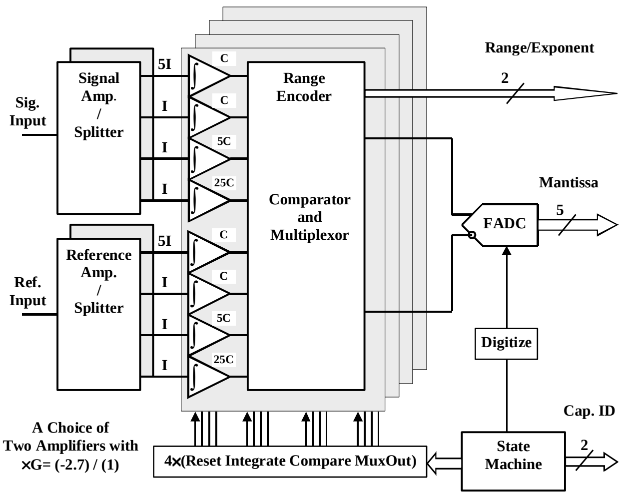

FIG. QIE (Charge Integration Encoding) chip multiplexes the input signal to one of four identical integrator/ADC stages. Each stage has an internal auto-ranging. The output is a 2 bit exponent and an 5 bit mantissa, plus a Cap ID# that indicates which of the four stages where used.

Alternatives to QIE were also considered. In particular the SVX chips, used in the vertex detectors of the experiments. These chips have a very attractive feature of high channel density (128 channels per chip). Several versions of SVX exist. However, some of these versions only accept positive signal (after all, they are made for silicon detectors). Also, even if the noise figure is better than the QIE, the range is also limited to 60fC, about a factor three less than the MCP can produce. Moreover, the SVX chips are highly specialized chips and would require a lot of controls overhead, whereas the QIEs are relatively simple.

Several board designs employing the QIE already exist. The one that has been selected as a basis for development is the CKM test beam board. This board contains two QIE input channels and a serial output on optical fiber. To test the board, a test stand has been set up at the Feynman Computing Center. Studies have been conducted using this test stand and part of them has been the noise characterization of the QIE in order to measure the overall noise performance of the complete system. To define the thermal back-ground noise of the QIE, the equivalent noise charge (ENC) at the input of the charge amplifier has been measured for different input capacitances. Results of these measurements are shown in fig. XX. The ENC is evaluated for different input impedances of the QIE (50 ohms and 93 ohms) and different sampling times (25nsec and 66nsec). In addition, noise measurements for different input cable connections have been evaluated. Table XX gives the ENC for different connections of two shielded twisted pair cables at the input of the QIE. The cable length was 12 ft (4 mts). Additional measurements will be performed to define the final cable selection, the noise immunity of the front-end, the signal integrity and signal reflections, etc.

TABLE Anticipated QIE noise

QIE input impedance	Input cable connection (Cable: twisted pair with individual shield, Zo = 95ohms)	ENC [electrons]
50 ohms	Two cables with shield and return disconnected at the detector end	11319
50 ohms	Two cables with shield connected and return disconnected at the detector end	10276
50 ohms	Two cables with shield and return connected at the detector end	11005
93 ohms	Two cables with shield connected and return disconnected at the detector end	6858

Some modifications are needed to this card in order to use it for the IPM. Notably, the number of channels should be increased to at least 8. Moreover, the board components must be selected to be at least as radiation tolerant as the QIE chip. This means, for example, using antifuse programmable logic. Depending on how many channels can be packed into a single board, about 16 QIE cards are needed to per IPM. The number of channels per board, in turn depend on the availability of radiation tolerant serializers.

The QIE have several internal modes, including inverting mode (positive charge), non-inverting mode (negative charge) and calibration mode (low noise, fixed range). It is foreseen to allow selection between some of these modes thru a “QIE mode” input (2 bits) to the cards. In addition a special debugging mode, sending counter data, will be implemented on the card to be used to debug the data uplink, if needed. Moreover, a “QIE reset” input will allow to reset the QIE chips. This is necessary to synchronize the Cap IDs, but may also be needed to clear any latch-ups.

In addition to sampling the analog data, the cards should also include some timing information in the serial data stream. It is foreseen to include the proton and antiproton markers and an injection event tag (in all, three bits). This header information will be used upstairs to calculate the position and enumeration of proton and pbar bunches, as well as the timing of injection events. In addition, the QIE mode (2 bits) and Cap ID# (2 bits) should be included in the data stream. In all, this adds seven bits per clock cycle.

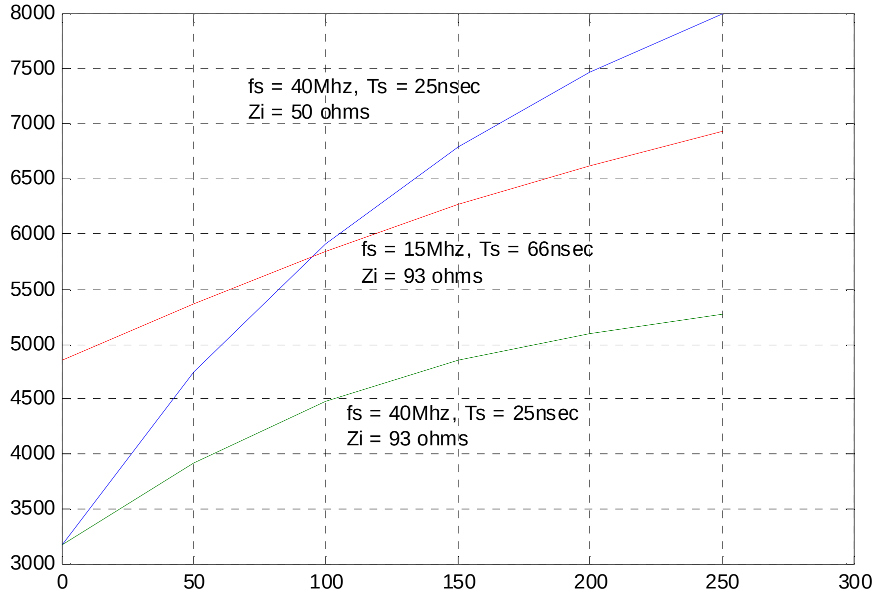

FIG. Measurement of inherent noise level for the QIE chip, versus input capacitance. The blue trace is measured, and the green and red are inferred from there.

Timing

The QIE chip was not designed to sample at the Tevatron RF frequency (53 MHz), not is this required. A suitable sampling frequency would be 2/7 RF (15 MHz), since this means an even number of samples per turn (the prime factors of the Tevatron harmonic number 1113 are 3, 7, and 53). A 65 ns sampling period should also be short enough to separate protons and pbars in time at the location of interest. Operating at a multiple of 1/7 RF also guarantees a fixed phase between clock ticks and bunches.

The timing system should be phased so that protons and pbars are fall in separate integration interval, and are not close to the interval boundaries. This is rather easy to achieve for a sampling frequency of 2/7 RF, and a location at E0. A sampling frequency of 1/7 RF could also be used. However, using shorter intervals reduces noise, and also enables a zero sample between protons and pbars (to make verify that there is no cross-talk).

The timing signals that should be provided to the QIE board are:

- Clock. Used to drive the QIEs (and perhaps the serializers).
- Proton marker. High on first proton bunch. Used to reset header counter that labels the samples (and hence to find the protons).

- Pbar marker. High on first pbar bunch. Sent back at bit in header. Used to determine cog state (and hence to find the pbars).
- Injection marker. High on first turn following (any) injection. Sent back as bit in header. Used to label first turn.

The markers should be synchronized to the clock, so that they are high for the clock cycle in which the bunch arrives, which requires a variable clock delay. Moreover, there should be a variable delay to adjust the distance between the clock edge and the proton bunches, and this delay should be unambiguous (i.e. no phase ambiguity of the divided RF clock).

The timing signals will be generated upstairs and sent down to the tunnel (most likely on a serial link) and fanned out to the cards. In addition to the timing signal, the same system must also provide some slow control signals, namely a QIE reset signal and the QIE mode setting.

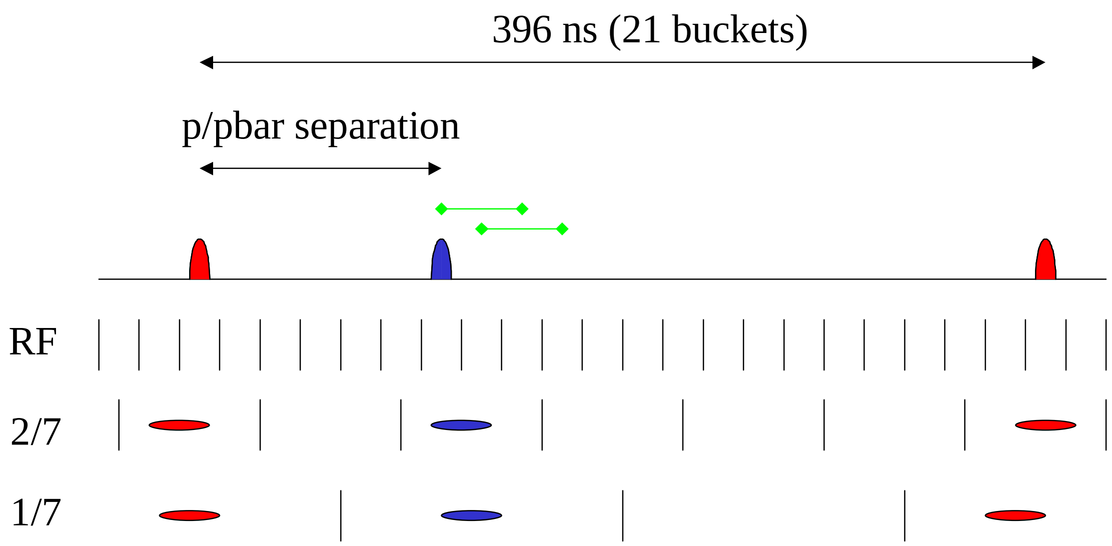

FIG. Sampling using the QIE charge integrator at 2/7 and 1/7 of the RF frequency. The green bars show how much the proton arrival time changes between injection and collision cogging, for two different locations of the IPM within the available space.

Readout

The serial data from the QIE cards must be gathered, stored and then analyzed remotely. The data rate when sampling at 15 MHz is about 2 GB/s. Handling this requires a specialized receiver card. Fortunately, such a card is being developed for the BTev experiment. This card is foreseen to have twelve serial inputs (optical fiber) and a buffer memory of 2 GB. The serial data is buffered in the card and can then be read out through a standard PCI interface by a commercial PC, in which the card resides. Modifying the

BTev design for use in the IPM essentially involves reprogramming the on-board FPGA, and potentially increasing the number of fiber inputs from 12 to 16.

The buffer card will receive the QIE card data from 12 (16?) serial inputs. It uses the header info (in particlar the Cap ID# bits) to synchronize these streams. For each clock cycle, defined as 12 (16?) data packets with the same header, it saves a profile to the onboard buffer memory. Together with the profile, it saves the header itself (for debugging purposes) and three counter values. These counters, which will be used by the analysis software to identify bunches and turns, are:

- Proton sample count (modulo-318, increments each sample, reset by the proton marker bit in the header)
- Pbar sample count (modulo-318, increments each sample, reset by the pbar marker bit in the header)
- Turn counter (modulo-N, increments on proton counter, reset by injection marker bit in the header)

Here, N should be larger than the number of turns that fit in the buffer memory (about 7000 with 2GB). If for some reason the headers get out of sync, this means that data has been lost on the link. The card should then try to regain sync and report an error.

Since only 10-20% of the samples contain interesting data, the card should also be able to decide which samples to save by applying a mask to the proton and pbar sample counters. There are 48 different masks of interest, namely

- Save all samples
- Save all 72 bunches
- Save all proton bunches
- Save select proton bunch(36 different masks, used at injection)
- Save select pbar batch, e.g. four select pbar bunches (9 different masks, used at injection)

These masks should be programmable over the PCI bus. The data acquisition may also be done in two ways:

- Hard trigger. The board waits for an injection marker and then saves a preset number of turns. This will be used at injection, when it is important to catch the first turn.
- Soft trigger. The board immediately starts saving a preset number of turns. This will be used on circulating beam.

The type of trigger as well as the number of turns to acquire should be programmable over the PCI bus. When the card is done acquiring data, is should issue a “data ready“ message and wait for download.

The transfer rate on the PCI bus is about a factor ten slower than the transfer rate on the data uplink, but since usually >80% of the data is thrown away on the board, the transfer to local PC RAM should be about as quick as the data acquisition itself.

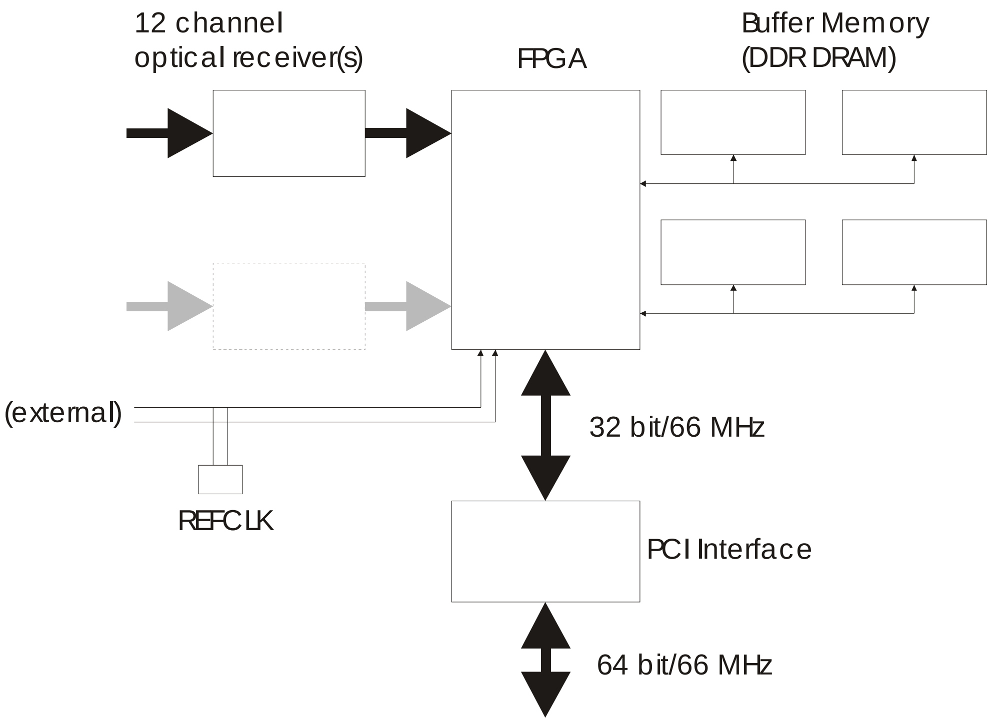

FIG. Schematic of the BTev buffer board. Modification for use with the IPM include FPG reprogramming and an optional extension of the number of optical input channels.

Soft□ are needs

Low-level software

The QIE cards do not need any software to function. The buffer card will need a driver for transferring the data to the computer RAM or disk, which the Computing Division would provide along with the card.

High-level software

A LabView program is available for the existing IPMs, and the idea is to modify this for use with the Tev IPMs. Mainly, the program will have to be modified to read out and decode the data from the buffer card. However, there are also some conceptual differences in the data analysis, compared to previous IPMs. In the Booster and Main Injector, there is no bunch-by-bunch resolution and the ramp is short enough that the entire machine cycle can be recorded and analyzed after ejection. In the Tevatron, there will be two different modes of operation. The data acquistion is similar for both modes, but the analyses differ significantly. At injection, the injected bunch (or bunches, in the case of pbars) is analyzed turn-by-turn for N turns. This requires N fits (e.g. Gaussian), and will take a significant amount of time. For circulating beam, N turns are acquired, but the raw data profiles are added before the fit (to improve the signal to noise ratio), meaning that only 72 fits are required to analyze both protons and pbars. Hence, the update will be much faster in this case. For detailed studies and debugging purposes, the turn-by-turn analysis may be called upon for circulating beam as well.

Further tests needed

Short term

The RF tests on the Booster IPM can have shown that avoiding resonances is a key issue. It is expected that this should not be a problem in the Tev IPM, since flex cable will be used to provide a matched (and shielded) transmission line all the was from the anode strip. It will not be possible to fully test this until the Tev IPM vacuum can an interior is actually built. However, further tests on the Booster IPM should be made to try to understand and eliminate all possible sources of resonances.
I
At the time of writing, the test stand for studying MCP behaviour is being assembled, after several months of delays. Results from the test stand will tell us more about e.g. MCP saturation, and will also be used in deciding on whether to use an electron generator of hot wire as internal electron source in the IPM.

In addition , the interfaces between the different DAQ subsystems (e.g. serial ldata uplink, buffer card readout) need to be fully defined, so that development work can continue in efficiently in parallel.

Long term

Once the system is built, it would have to be tested before installation. A DAQ system test would have to be performed to see that the different components work together as expected. A separate test of the RF properties of the finished detector unit would also have to be done. Finally the DAQ should be connected and tested with the detector.

Calibration and commissioning

Timing commisioning

Once the system is installed in the machine, the timing system needs to be phased correctly. This involves adjusting the phase of the QIE clock as well as the delay of the proton and pbar markers, and must be done empirically with beam, varying the timing delays to find the optimum timing. The clock phasing is best performed with circulating beam in the machine. The relative phase of bunches with respect to the clock edge can be found by locating the clock phase until the bunch charge is evenly distributed between two samples. Adjusting the delay of the revolution markers can be done parasitically during shot setup, by taking data with a single proton bunch as well as a single pbar batch.

Debugging and calibration

The QIE cards will give an absolute measure of the charge extracted per strip and bunch. From this, the average signal current draw can be calibrated, and hence field distortion saturation in the MCP can be detected by comparing this value to the maximum allowed (given by the MCP bias current).

To detect permanent damage to the MCP, two methods will be used. The IPMs will be fitted with stepping motors to align the anode strips with the beam. These stepping motors can also be used to move the entire MCP with respect the beam, for a beam-based detection of MCP gain variations. To complement this method, an electron source will be incorporated in high voltage plate of the detector. This will consist of either an electron generator (Burle) or a hot wire. Which one will be determined from experience in the MCP test stand. This will make it possible to track changes in the MCP gain without relying on the beam..

The focusing effect of the magnetic field can be verified by changing the field strength and recording the effect on the detected beam size. There is unfortunately no good way of checking the field quality on-line, but this should not change significantly.

Any parasitic electro-magnetic coupling between the beam and the anode strips can be detected by turning off the clearing field and/or MCP voltage. Since care is taken to remove any such coupling, and this measurement will be made in the lab prior to installation, any such coupling detected with the beam will signal that something is broken.

In the end, however, the only way to absolutely calibrate the IPM is to compare it to another measurement. For this reason, it is proposed to install a cheap and simple (but destructive) profile monitor, such as an OTR screen, next to the IPMs. There is interest from the instrumentation group to develop a generic OTR detector that, once developed, could potentially be used in many locations. In the Tevatron, this detector could probably only be used for a couple of turns, before the beam must be ejected to avoid quenching the magnets. The exact number of turns that can be tolerated still needs to be investigated. In principle, however, a single turn would be sufficient for IPM calibration purposes.

Maintenance

Since the MCP suffer from aging, it will have to be replaced at regular intervals to avoid distorted measurement results. How often depends on the usage (the gain reduction in an MCP is linear in the total extracted charge), but may be on the order of a year. Calibration measurements will tell when a change is required.
The other obvious maintenance issue is radiation. The electronics in the tunnel is supposed to last at least eight years at current running conditions. However, it is likely that some cards or channels may die prematurely. Loosing a single isolated channel is not a disaster, but if many channels are lost, this may affect the measurement. As with any system, spare cards will be produced to exchange broken cards. However, given the limited access, it would be preferable to predict which cards are about to die. One way may be to measure the current draw of the cards, since an increased current draw typically signals radiation damage.

Time and cost estimate

Budget

The initial estimate for the cost of two IPM units (horizontal and vertical) was based on the cost of the MI IPMS and the Tech Division's estimate for the magnet cost.
This very crude number has been refined, based on new quotes and more detailed knowledge of the hardware to be used. Although there are still uncertainties, the current best estimate is as follows

Subsystem	initial estimate	item cost	#	total M&S	manpower
Magnets	180000				
magnets		12400	4	49600	none
power supplies		3300	2	6600	?
power cable		1500	2	3000	
power controls		3200	2	6400	
water plumbing		1000	1	*1000*	?
DAQ	100000				
QIE power supplies		1000	2	2000	
QIE 8/10ch cards		60	350	21000	Eng (PPD): 6 months
Combiner cards		5000	2	10000	Eng (CD): 6 months
Timing fanout		2000	2	*4000*	?
QIE rack		1000	2	*2000*	
rack PC		1000	2	2000	
PCI timing card		500	2	*1000*	
optical fiber		500	2	*1000*	
contol cables		500	1	*500*	
frontend cabling		3500	2	*7000*	
Technical	150000				
vacuum can, spool pieces machining		10000	2	*20000*	Eng (BD): 6 months
detector head machining		16000	2	*32000*	Draft (BD):4 months
magnet stands, movers		7000	2	*14000*	Tech B(D): 2 months
misc components		14000	2	*28000*	
sector valves		3000	2	*6000*	
vacuum pumps		3000	2	*6000*	
N2 controlled leak		5000	1	*5000*	
E-field power supplies		3000	2	*6000*	
MCP power supplies		1000	2	*2000*	
control cables		1500	2	*3000*	
MCP		5000	2	*10000*	
misc components					
misc tests				5000	

total no contingency	254100
40% contingency	101640
total budget	355740

The main cost driver, in terms of M&S, is the mechanical parts. This is also the post that is most uncertain. It has been estimated simply by recalculating the cost of producing similar parts for the MI IPM to todays dollars, taking into account the increase in prices from the lab machine shops. It is possible that this post may be reduced e.g. by going to an outside vendor (although this would not represent a real saving for the lab).

Manpower

The persons who are principally involved in the project, and whose time would be required, are:

Mechanical design	L.Valerio, BD
Drawings	Drafter (100% for 4 months)
Detector assembly	Technician (100% for 2 months)
QIE board design	K. Bowie, PPD (100% for 6 months)
CD liaison	M. Bowden, CD
Buffer/Combiner board design	R. Kwarciany, CD (100% for 6 months)
Timing fanout	T. Fitzpatrick, PPD (?)
Front end cabling etc	C. Rivetta, BD
Software	D. Slimmer, CD (100% for N months)
MCP test stand	A. Bross, PPD
Simulations and PPD liaison	H. Nguyen, PPD
Project oversight etc	A. Jansson, BD
Instrumentation liaison etc	J. Zagel, BD

In addition a number of others have participated in meetings and helped with measurements. …

Time estimate and milestones

The delivery time for the magnets is about 4-5 months, and the estimated time to develop the QIE cards and readout buffer cards about 6 months. The lead time on the mechanical components (vacuum can and interior detector components) should be a few months depending on the work load in the shop, and whether parts will be ordered from outside vendors. Before parts can be ordered, however, production grade drawings must be produced which may be another 3-4 months, so the total time estimate for the mechanical components is also about 6 months.

A reasonable schedule would hence be to do a system test of the DAQ in about 6 months. This would involve setting up a complete data acquisition chain consisting of timing generation, fanout, one QIE card and a readout buffer card, and would also enable testing of software. This would mainly require commitment of manpower to design the cards etc.

In parallel, at least one detector unit (vacuum can plus interior) would be built for testing, and if necessary further improving, longitudinal impedance and RF screening (including cabling inside the vacuum). This would require some M&S (about $30000-40000 for a single unit) in addition to the design manpower. Thoroughly testing the detector structure before installation is however essential to ensure proper operation of the IPM.
Following successful tests of both the DAQ and detector units, the two systems (Detector and DAQ) would be connected for a final system test. In parallel with this, the remaining components (e.g. additional cards) would be built.

Summary and conclusions

Ionization profile monitors would be useful in the Tevatron to study emittance evolution both at injection and later in the cycle. In this report, a design has been proposed that would be capable of a single bunch resolution of about 10% for both protons and pbars. It is estimated that the current vacuum pressure ($3\ 10^{-8}$ torr) would be sufficient for this. However, since there is some uncertainty in the exact ionization rate and detection efficiency, a controlled local pressure bump around the IPMs may be needed, especially if the vacuum would improve from its current levels. The estimated cost for two such devices (horizontal and vertical) is about $250k, plus a $100k contingency.

Acknowledgements

In addition to the people listed as authors, many others have contributed, including Dave Harding, Vladimir Kashikin, Vince Pavlicek, Brian Fellenz, Lawrence Short Bull (summer student). The list goes on…

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