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Observation of Bethe-Bloch Ionization Using the Booster Ion Profile Monitor

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Abstract: The Booster Ion Profile Monitor (BIPM) was recently (April 1998) used in a test to study the feasibility of collecting the electrons instead of the more traditional ions. These electrons and ions are created by the ionization of the residual gas in the beam pipe by the proton beam. As a consistency check, the proton beam current is compared to the integrated area of the measured profile through the acceleration cycle. It was found necessary to include the effect of the proton beam energy upon ionization by means of the Bethe-Bloch equation in order to have satisfactory agreement.

Introduction:

The Booster Ion Profile Monitor (BIPM) is one of a family of profile monitors [1,2] which are found throughout the Fermilab Accelerator Complex. The BIPM [3] was the first "operational" IPM of the family. An IPM utilizes the ions or electrons from ionization of the residual gas by the particle beam. The density of ionization is proportional to the beam intensity distribution. An external transverse electric field drifts the ions or electrons towards a microchannel plate. The incoming charges are amplified in the microchannel plate and deposited on collectors (approximately thirty-two 1.5 mm width x 10 cm length strips in the Booster) which run parallel to the beam direction. The distribution of signal among the strips is representative of the transverse profile of the beam. These signals are further amplified and then digitized by the IPM electronics. The electronics can capture profiles on a turn by turn basis, which in the Booster amounts to 20000 turns of data.

Among the advantages of an IPM are that it is non-invasive and can capture turn-by-turn transverse beam profiles. One of the disadvantages is that the radial electric field from the charge distribution of the beam itself is comparable to that of the external field. This causes a spreading of the ion or electron cloud, and necessitates a "correction" to the measured profile distribution. This correction depends upon the beam density. A modest external magnetic field (400-3000 Gauss dependent upon beam density) can confine the electrons (but not the ions) and eliminate the need for a theoretical correction. An experiment to test this proposal was attempted in the Booster. The Booster was chosen because it was the only operational circular machine at the time (we are preparing for the startup of the new Main Injector and Run 2). Unfortunately, the correction is smallest in Booster because the beam is transversely quite large. At the intensities (up to 2.5e12 protons) we were able to achieve in the study, the total correction effect was at most 10%. As will be seen, this is at or below the level of the hardware uncertainties of the current IPM system. The correction can range up to 300% in the case of the Tevatron IPM.

Experiment:

The Horizontal BIPM (H-BIPM) was fitted with an electromagnet whose field strength could be varied from 0 to 700 gauss. Two other electromagnets were utilized so that the total effect of the magnets would be a local 3 bump to the Booster beam orbit, thereby minimizing the impact on Booster operations. The external electric field could be reversed in order to collect ions or electrons on any particular Booster cycle.

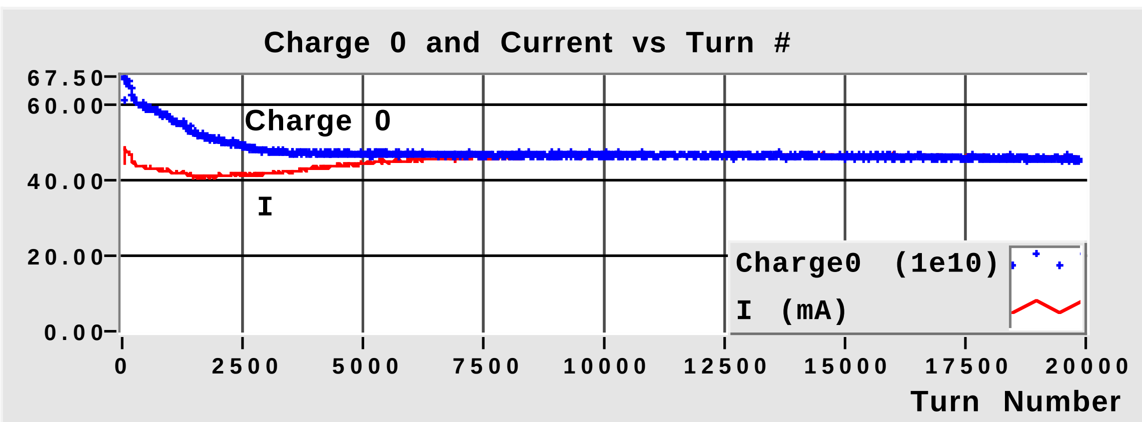

Figure 1. The Booster charge ("Charge 0") and current (I) through one acceleration cycle (approximately 20000 turns).

The particular data described in this paper were actually acquired in the ion collection mode and with negligible magnetic field. As a control, we desired that the H-BIPM exhibit self-consistency. Whenever we record the turn-by-turn profile, we also simultaneously record the turn-by-turn measurement of "Charge 0". Charge 0 in the Booster represents the total charge in the circumference of the machine. To be consistent, the IPM should track this total charge through the acceleration cycle. The ionization of the residual gas is proportional to the beam current (velocity *Charge 0). The velocity of the Booster proton beam varies from about 0.713 c at injection (T = 400 MeV) to 0.9945 c at extraction (T = 8 GeV). Figure 1 shows plots of Charge 0 and the current. As seen by the IPM, the intensity of the ionization is the area of the beam profile. We extract the area from a 5 parameter gaussian fit,

$$y(x) = Ae^{-\frac{1}{2}\left(\frac{(x-\mu)}{\sigma}\right)^2} + B + Mx,$$

where A = amplitude, μ = centroid, σ = sigma, and M and B parameterize a sloping background. The area of the gaussian is $\sqrt{2\pi}\sigma A$. The gaussian parameters, as well as βγ ($\beta = v/c,$ and $\gamma = \left(1-\beta^2\right)^{-1/2},$ the Lorentz quantities of the proton beam) are plotted in figure 2. The activity between turns 9000-12000 is due to the Booster going through transition. The results shown in this figure were derived from 1000 fits (equally spaced 20 turns apart) throughout the cycle. Each fit was made to the average of 20 turns of data to improve statistics. The results found by dividing the area by the beam current (with arbitrary normalization) are shown plotted in figure 3a against βγ. From the injection point, βγ ~ 1 (turn 30) to βγ = 2.7 (turn 5000), the Area/I drops by about 60%. This is followed by a slow rise to extraction, βγ =9.5 (turn 20000). In addition some instrumental effects were still observed, primarily coming from large transverse beam motion.

While calculating the ion production vs. gas density, it was realized that the Booster is running from below the minimum ionization energy (at injection) to above it at extraction. The slowly rising Area/I could be explained by the relativistic rise of -dE/dx and not a mundane instrumental effect. A subroutine was written to include the variation in ionization, using the Bethe-Bloch equation,

$$-dE/dx = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right)\right]^4,$$

with Z = Atomic Number , A = Atomic Mass, δ = density effect, I = the mean ionization energy of the target medium, and z, β, γ, referring to the Atomic Number and Lorentz quantities of the ionizing particle. K= 0.307075 MeV g^{-1} cm^2. The maximum possible kinetic energy which can be given to the electron is $T_{\max} = \dfrac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + \left(m_e / M\right)^2}$, with

m_e and M being the electron mass and the ionizing particle mass (the proton in the Booster case) respectively.

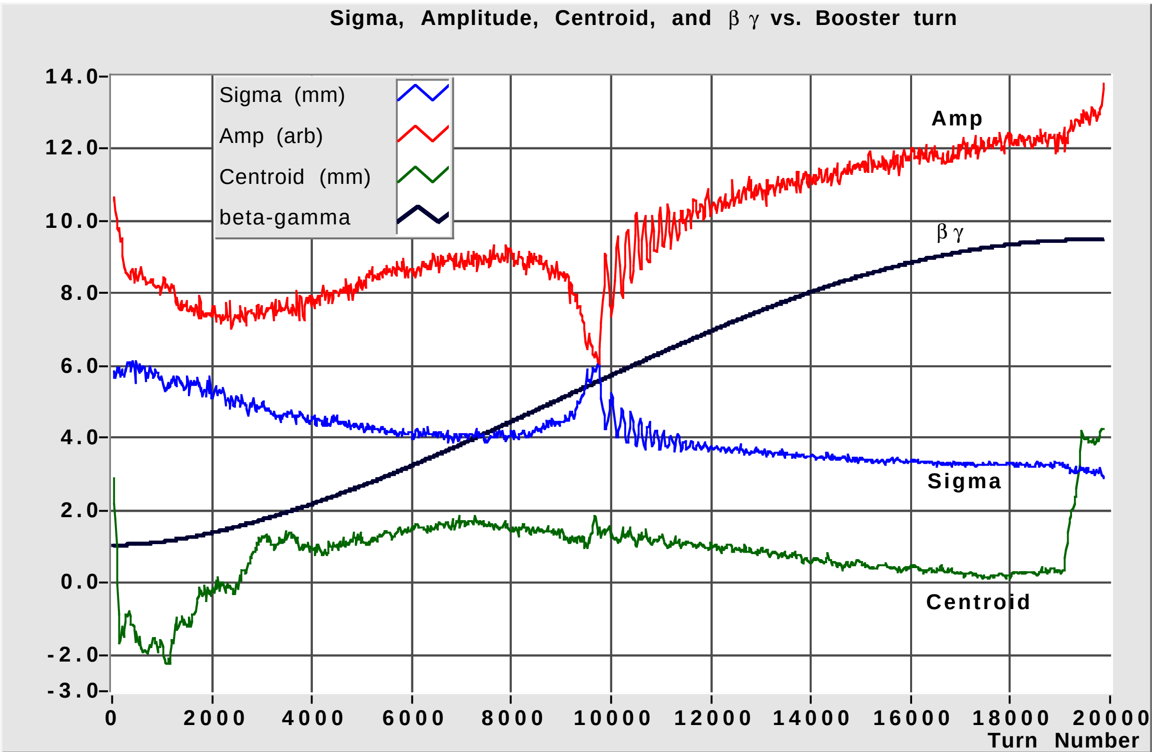

Figure 2. Plot of Sigma, Amplitude, Centroid from the fitting of 1000 turns spaced 20 turns apart through the Booster cycle, as well as βγ vs. Booster Turn Number. Each Fit was to the sum of 20 individual turns. The activity between turns 9000 and 12000 (5 < βγ < 7) is due to the Booster going through transition.

The parameters (Z, A, I) chosen (2, 2, 38 eV) were those for Hydrogen gas (H_2) which represents 42% of the residual gas in the Booster. The density effect (δ) was ignored since it is chiefly applicable to liquids and solids, not gases. In any case since we do not know the absolute gain of the IPM, we are insensitive to the exact parameters (Z, A, I) of the medium. The results are shown in figure 3b. The agreement with the Bethe-Bloch equation is quite good. One can still see “glitches” which are correlated with the Booster Beam slewing across a wide region. However these remnant effects are at the 5% level, providing hope that they can be corrected once we have installed an overall gain measurement system (using a UV light shining on the microchannel plate).

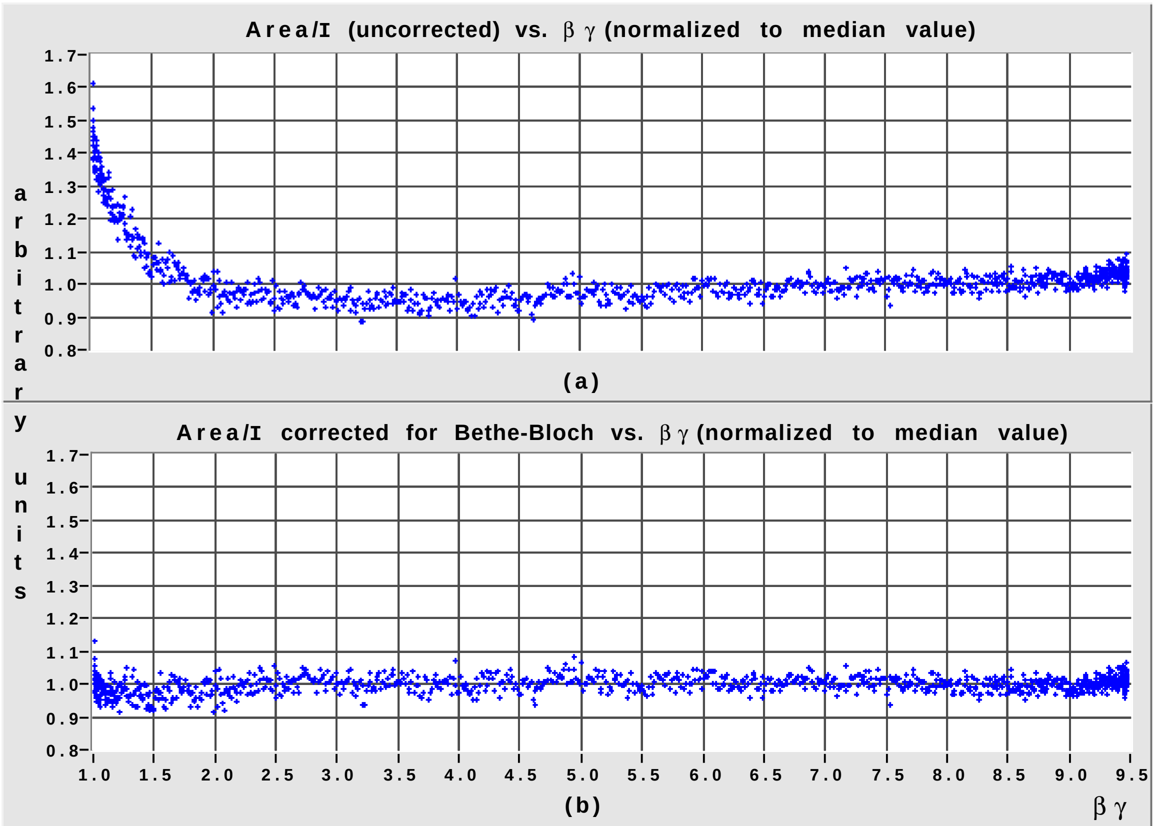

Figure 3

(a) The Area/I calculated from the Amplitude and Sigma (from 2a) and the Booster Current (Fig. 1). Note the suppressed zero.
(b) The Area/(I(-dE/dx)) as calculated from the Bethe-Bloch equation shown on the same scale as figure 3a. The deviation from 1.0 at $\beta\gamma < 1.75$ and $\beta\gamma > 9.2$ are thought to be associated with the large position change of the beam and the gain variation of the microchannel plate as a function of position - see figure 2. This systematic effect is at the 5% level.

However the H-BIPM seems to be working near the limit of its linear region. In another data set where the microchannel plate gain was only 10% higher, the system clearly showed saturation effects. The Area/(I*(-dE/dx)) test is a useful method to demonstrate linearity, but it is clear that a more robust IPM will require an increase in its dynamic range, either by raising the saturation level of the microchannel plate (a "hot" microchannel plate with increased bias current) and/or increasing the sensitivity of the preamplifier electronics.

Finally, the H-BIPM did give reasonable profiles when run in the electron collection mode, however we cannot at this time(because of saturation effects in that data at the 10% level or more) conclusively prove that the electron mode is really better than the ion. The final results of that test will be reported in another paper.

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[1] Zagel,J.R., Chen, D., Crisp, J.L. "Fermilab Booster Ion Profile Monitor System Using LabVIEW",1994 Beam Instrumentation Workshop, AIP Conference Proceedings 333, pp 384-390.

[2] Zagel, J.R., Crisp, J.L., Hahn, A.A., Hurh, P.G., "Fermilab Main Ring Ion Profile Monitor System", Contribution to PAC97 Proceedings, Vancouver.B.C (1997).

[3] Graves, W.S., "Measurement of Transverse Emittance in the Fermilab Booster", PhD Thesis, University of Wisconsin-Madison, (1994)

[4] Review of Particle Physics, Phys.Rev D(54), (1996) p132