SPACE-CHARGE DISTORTION IN THE BROOKHAVEN IONIZATION PROFILE MONITOR*

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Summary

An Ionization Profile Monitor (IPM) has been in use at the Brookhaven Alternating Gradient Synchrotron for several years to measure the horizontal and vertical profiles of the circulating beam (1). The device, which collects ions from the interaction of the beam with residual gas molecules, gives a fast, non-destructive readout, measuring the entire beam profile in a short time interval. It covers a large dynamic range, from less than 10^{10} to over 2×10^{13} protons per pulse, when the signal level is adjusted by controlling the local gas pressure and the integrating time. It can see changes in the beam with a time resolution of about 0.1 ms, except at low intensities where longer integration times are needed to get sufficient signal strength.

However, the forces due to the space-charge of the circulating beam cause the ions to move in a curved path to the collector, distorting the profile and changing the measured beam size. In the worst situation at the AGS - high current beams at high energy, when the size has damped down to less than 2mm rms width - this distortion is substantial and must be understood and corrected, if possible, to properly interpret the measured beam sizes.

This paper develops a model for this distortion, and formulas for correcting it. It is shown that the distortion is more severe than originally recognized, and that accurate quantitative measurements at the highest beam densities in the AGS are not possible. At lower densities, however, the correction is small and the IPM can give a good beam size measurement.

Introduction

The first version of the IPM collected the electrons produced in the beam-gas collisions, and used a magnetic field to limit the sideways motion produced by the space-charge field. This mode was unsatisfactory - the profiles had a large halo - and the IPM was changed to collect positive ions instead of electrons. Because the ions move much more slowly, magnetic focussing is no longer effective and has been eliminated, but since the time for the ion to be collected is several rf periods, the ion sees (approximately) the time averaged space-charge field, which is an order of magnitude less than the instantaneous field.

Figure 1 shows a schematic view of the IPM and the beam, showing the ion path under the combined influence of the space-charge field and the collection field. The distortion of the profile depends on the geometry of the IPM, the mass of the ion, the collection field, the beam intensity, size, and shape, and how the beam is bunched.

An empirical study of the effect is hampered, at the AGS, by the lack of a reliable independent measure of beam size. Instead, the approach here is to attempt to model the distortion, using a Monte-Carlo simulation to include all essential effects. Since the distortion will depend, for a given beam, on the IPM collector voltage, the model can be checked by comparing its behavior against actual data as the collector voltage is varied.

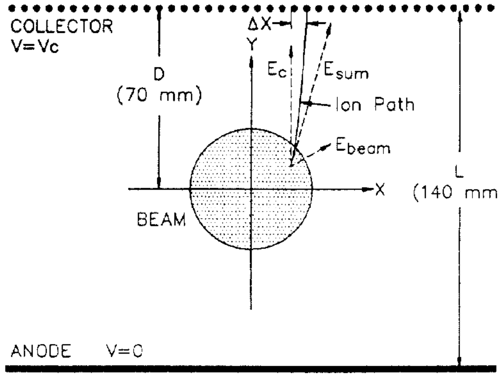

Figure 1. Diagram of the IPM (not to scale), showing the path of an ion under the combined beam space-charge and collector fields.

Figure 2 shows some typical data for the variation of measured size as the collector voltage V_c is varied. The data are plotted vs. $1/V_c$, to allow extrapolation to the limit of infinite voltage, where there will be no distortion. For the larger beam sizes (early in the AGS cycle) the measured size is remarkably linear plotted as a function of $1/V_c$, while for the densest beams there is a flattening of the line as $1/V_c \rightarrow 0$. This linearity suggests a simple correction to extrapolate to infinite voltage, and the nonlinearity for the highest density beams suggests that the space-charge correction for them may be even less than given by the linear extrapolation. Unfortunately, this is incorrect, as the bunched structure of the AGS beam causes the correct extrapolation to infinite voltage to change to $1/V_c^{1/2}$ at voltages above what is attainable in the IPM, and the space-charge distortion is worse than might be expected from the data in Figure 2.

Model For Bunched and Unbunched Beams

The effect of the time structure of the beam can be seen from Figure 3, which shows the time scale for the ion collection, from the production in the beam to collection on the grid, for two ion species and for several collector voltages, ranging from the highest (which is the usual operating condition) to very low voltages used for this test. Also shown on the time scale is a representation of the time structure of the bunched AGS beam, which typically has bunches 40-70 ns full width, spaced 220 ns apart, at high momentum. It is clear that even at the highest collector voltage, the ion does not move out of the beam during the bunch in which it was created. Thus it suffers the full effect from the remainder of the beam in that bunch, and that effect can be calculated as an impulse using the field at the ion's creation point.

The effect of the second and succeeding bunches, however, depends on the voltage. At 45 kV,the highest voltage the IPM can operate at, the ion has moved far enough away by the time the second beam bunch arrives, that the change in direction will be small. At the low collector voltages, however, the ion is still close

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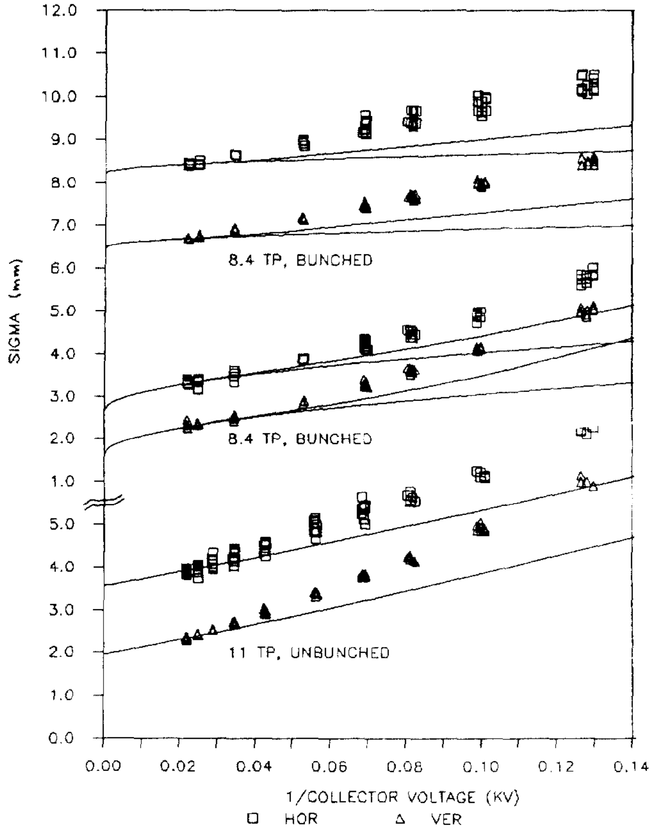

Figure 2. Beam size measured by the IPM, as a function of collector voltage, for several beam sizes and intensities. The large beam is at low energy, early in the AGS cycle. The lines are Monte Carlo predictions and for bunched beams show the effect of the first bunch alone and of all bunches.

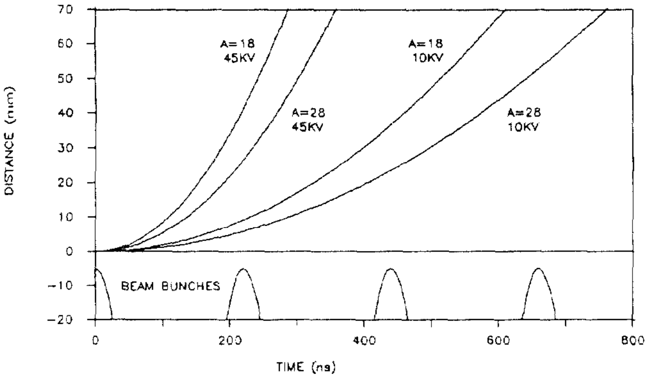

Figure 3. Relationship between AGS bunched beam structure, and the time scale for ion collection, for several ion species and collector voltages.

enough to the beam to receive a significant kick as the later bunches pass. If the beam is unbunched, the space-charge effect will be different, and should be lower, as the ion does not see as large an instantaneous field while still at its origin.

A simple model can show the expected dependence of the distortion on the beam current, ion mass, collector voltage, and the IPM parameters as shown in Figure 1. For an ion of mass M and charge Q, produced at (x,y) = $(x_o,0)$, travelling under the combined effects of the collector and space-charge fields, the position error at the collector is

$$\Delta x = \int_o^{t_c} dt \int_o^{t} dt' \, \frac{Q}{M} \, E_x(x,y) f(t') N \qquad (1)$$

where t_c is the collection time and E_x is the transverse electric field, with the number of particles N and the time dependence f(t) written as separate factors.

Assume that the deviation from x_o is small enough, at least for that part of the path near the beam, that x may be approximated by x_o in the integral. Also, assume that the y component of the space-charge field is negligible compared to the collector field, so the y position is simply $y = 1/2\,(QV/ML)t^2$. Then for an unbunched beam, where there is no time structure (f=1), the x deviation is

$$\begin{aligned} \Delta x &\approx N \int_o^{t_c} dt \int_o^{t} dt' \, \frac{Q}{M} \, E_x\!\left(x_o, \frac{1}{2}\left(\frac{QV}{ML}\right) t'^2\right) \\ &\approx \frac{LN}{V} \int_o^{D} dy y^{-1/2} \int_o^{y} dy' y'^{-1/2} \, E_x(x_o, y') \end{aligned} \qquad (2)$$

where the second line is obtained by a change to the variable $y = 1/2\,(QV/ML)t^2$. The integral depends on the size and shape of the beam, but not on the collector voltage, ion mass, or beam intensity.

For a beam distribution with an approximately uniform central density (a gaussian, for example) E_x is approximately proportional to x for $x < \sigma$. Thus Δx will be of the form $\Delta x = KN(L/V)x$ and will add directly to the width of the measured profile, and not in quadrature as it would if the position and deviation were uncorrelated. Therefore the approximate dependence of the measured size on the true size, for an unbunched beam, is

$$\sigma_m = \sigma \left(1 + K_1 \, \frac{NL}{V} \right) \qquad (3)$$

where K_1 is determined by evaluating the integral in equation 2 and averaging it over the distribution of initial ion positions, and will depend on the beam size and shape.

For a bunched beam, the ion is essentially stationary during the initial bunch, so equation 1 may be evaluated in an impulse approximation,

$$\begin{aligned} \Delta x &\approx N \, \frac{Q}{M} \, E_x(x_o, y_o) \int_o^{t_c} dt \int_o^{t} dt' \, f(t') \\ &= N \, \frac{Q}{M} \, E_x(x_o, y_o) \cdot \left(\frac{2MLD}{QV} \right)^{1/2} \end{aligned} \qquad (4)$$

By the same arguments leading to equation 3, the measured size is

$$\sigma_m = \sigma \left(1 + K_2 N \left(\frac{QLD}{MV} \right)^{1/2} \right) \qquad (5)$$

where only the initial bunch is taken into account. As the collector voltage is lowered, later bunches also contribute to the displacement.

Monte-Carlo Simulation

To get meaningful numerical results requires averaging over the ions' starting positions in the beam - x, y, and time in the bunch - and is readily done with a Monte-Carlo simulation of the ion's path from creation to collection on the grid. The simulation takes into account whether the beam is bunched or unbunched, and the aspect ratio for non-round beams. The beam was considered to have a bivariate normal distribution with no correlation between x and y, and for an elliptical beam, the fields were calculated from a numerical integration of the Green's function over the beam distribution.

The distortion for bunched beams depends, as indicated by equation 5, on the ion mass. At high intensities, where the distortion is significant, the IPM normally operates solely on the residual gas in the AGS, which a spectrometer scan in the IPM region shows to be mostly water (2).

The results of the simulation have been found to fit the following empirical relations, at the normal 45kV value for the collector voltage:

Bunched beam:

$$\sigma_m = \sigma + 0.302 \frac{N^{1.065}}{\sigma^{2.065}} \left(1 + 3.6\, R^{1.54}\right)^{-0.435} \qquad (6)$$

Unbunched beam:

$$\sigma_m = \sigma + 0.076 \frac{N^{1.025}}{\sigma^{1.65}} \left(1 + 1.5\, R^{1.45}\right)^{-0.28} \qquad (7)$$

where

N = beam current in 10^{12} protons

σ = root-mean-square beam size in mm.

R = aspect ratio, (other plane)/(measured plane)

These can be solved iteratively for σ, converging in a few iterations. The form of these equations is suggested by equations 3 and 5, and the constants are from manual fit to the Monte Carlo results. The dependence on aspect ratio is shown in Figure 4, for several beam intensities and sizes.

The validity of the Monte Carlo was tested by trying to match the collector voltage data. Figure 2 shows several sets of data and the Monte Carlo results, where the 'true' beam size to use in the Monte Carlo has been calculated from equations 6 and 7. Although the general features match fairly well, the slopes of the lines at low voltages disagree, indicating that there are other characteristics of either the IPM or the beam that are not accounted for in the Monte Carlo. An example of such an effect is a transverse bunch-to-bunch oscillation (3), which changes the effect of both the first bunch and the later bunches on the ion path.

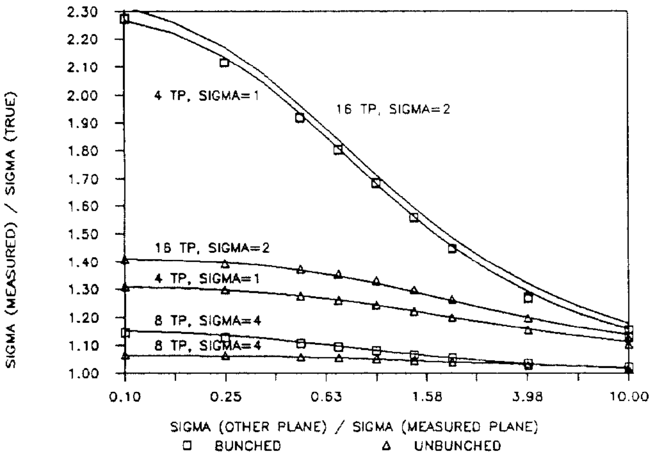

Figure 4. Ratio of measured to true beam size, as a function of beam size, intensity, and aspect ratio. The points are Monte Carlo results, and the lines are from equations 6 and 7.

Conclusions

The relationships in equation 6 are plotted in Figure 5 for a bunched beam with a round cross section. As the beam size decreases below a critical value, the increased space-charge force actually increases the measured width. Clearly, the IPM can give meaningful results for high current beams only if the size is greater than this critical value. The densest beams in Figure 2 are already in this regime, where the IPM is not able to give an accurate size measure, and may in fact show an increase in size when the actual size is decreasing. Above 2.5 - 3 mm, at present intensities, the correction is well behaved and the quantitative results should be good.

However, the lack of good agreement in the Monte Carlo simulation of the voltage curves casts doubt on the accuracy of the correction, and thus the quantitative interpretation of IPM results, in regimes of beam density where the distortion is large. In addition, the dependence of the bunched beam correction on ion mass (eq. 5) is a problem at high intensities, where the IPM operates on the residual gas, whose composition may change.

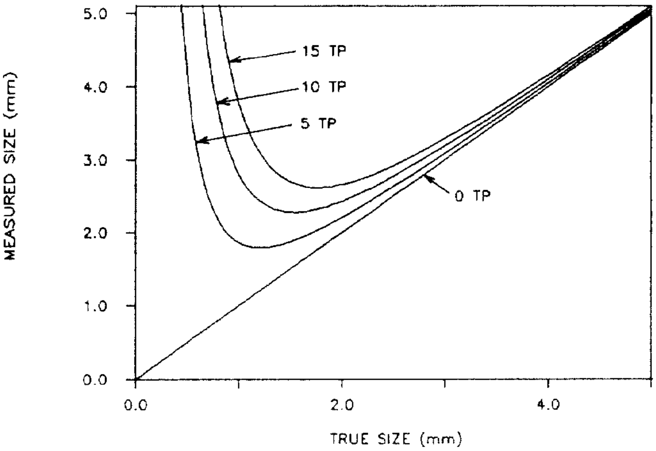

Figure 5. Measured beam size vs true size, for round bunched beams of several intensities. (1 TP = 10^{12} protons).

Acknowledgements

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