Stripping Foil Losses and Space Charge Blowup in the FNAL Booster

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Abstract

An automated profile measuring system using single wire scanners has been implemented in the Fermilab Booster Synchrotron which allows the beam profile to be measured on a turn-by-turn basis. More than 30 profiles after injection can be accumulated before the wire degrades the beam significantly. As the Fermilab Booster utilizes a multiturn injection scheme, foil losses can be studied by comparing 1- and 2-turn injection and varying the number of passes a low-intensity beam makes through the foil. By using the low-intensity results, foil losses can be eliminated from high-intensity, multiturn injection data, thereby allowing a quantitative look at space-charge blowup. The results obtained for foil losses and space-charge blow-up in the Fermilab Booster are presented here.

Introduction

In a circular accelerator, a single wire proves to be an effective diagnostic tool from which profiles of the circulating beam can be extracted on a turn-by-turn basis. The profile is obtained by reading the current on the wire at selected time intervals within the beam cycle and then advancing the wire to different positions and recording the same information on subsequent beam pulses. For thin wires the losses on a turn-by-turn basis are small and readily calculable. For wire thicknesses of a few mils, effective beam profiles can be generated for up to 60 turns before wire distortions significantly alter the beam characteristics. A more serious limitation than wire losses on the data analysis has been found to be the pulse-to-pulse stability of the beam.

A second application of these wires has allowed a view into the internal properties of a beam pulse. If the time interval at which the wire readout occurs is set to a fraction of the total timespan of a beam pulse, individual profiles can be generated which represent a particular time in the beam pulse. In this way intensity and position variations within a beam pulse can be studied.

Experimental Results

Four vertically mounted and four horizontally mounted tungsten wires, all 5 mils thick, are positioned about the Booster Synchrotron. A stepping motor capable of stepping the wire in submillimeter increments is used to control the wire position. Two of these wires were used to make extensive horizontal profile measurements in the Booster. One of them, WINFH, is positioned a centimeter upstream of the H^- stripping foil. It intersects both the injected H^- beam and the closed orbit proton beam. The second one used was just downstream of the last ORBUMP magnet. Four pulsed magnets called ORBUMPs (used to bump the closed orbit) perform injection in the Booster. Because the ORBUMPS move the beam across the injection aperture, the wire just upstream of the stripping foil has the added advantage that it does not intercept the beam continuously until the beam reaches its closed-orbit position (see Figure 1).

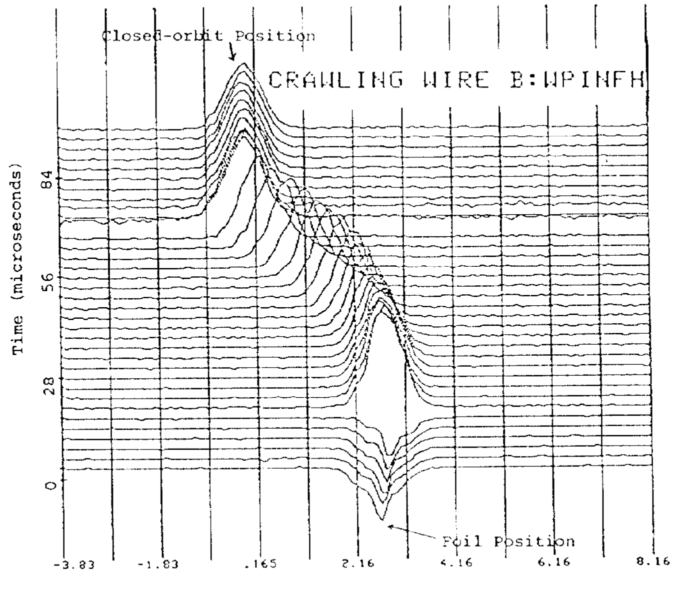

Figure 1. *Turn-by-turn wire profiles generated in the Fermilab Booster Synchrotron at injection. The negative profiles are the incoming H^- beam which eventually strips and moves off the foil into the closed-orbit position.*

For the measurements, the wire was stepped in 1 mm steps across 121 positions for a total of 12 cm across the Booster Synchrotron beam aperture. Since the rotational period of the beam in the Booster is $2.8 \mu sec$ at the injected energy of 200 MeV, this is the frequency at which the wire was read out in order to obtain turn-by-turn injection profiles. The raw wire data is sent through a 1 MHz filter and amplified before being input to a fast digitizing Gould scope. The Gould scope is read out through a GPIB interface and into Fermilab's main accelerator controls system by frontend PDPs. The PDPs then transfer the data into a filesharing utility on a VAX. Because of the limited resources on the PDP frontends, only 36 time ticks of data can be conveniently stored at one wire position, so only 36 profiles are generated per run. For long term data storage

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and ease of analysis the data are compressed into binary ZEBRA [1] data structures.

A series of measurements were taken for low-intensity operation which include 1/2-turn, 1-turn, 2-turn, and 3-turn injection, and high-intensity which included 4-turn, 5-turn, and 6-turn injection using both wires. This corresponded to intensities of 2.5E11 protons for 1/2 turn up to about 2E12 protons for 6 turns in the Booster. To extract foil effects, only one turn's worth of beam is injected into the Booster so that at this intensity space charge is not a problem (5E11 protons extended over the 474-meter circumference of the Booster). In all cases the ORBUMP timing was changed to vary the number of passes the beam made through the foil to isolate foil losses.

In a second application of the wires, internal profiles of a beam pulse were measured in the beamline which transfers extracted beam from the Linac and prepares it for injection into the Booster. The specific vertical wire used, WS2H, was located at the entrance to the injection septum where it intercepts both the H^- beam in the transfer line and the closed-orbit proton beam circulating in the Booster (see Figure 2). Except for timing, the other details of the readout are the same as detailed above. Data were taken on 1/2-turn, 1-turn, and 6-turn injection which correspond to 1.4, 2.8, and 16.8 microsecond long beam pulses, respectively. Data were read out every .07 microseconds to give 20 and 40 internal horizontal profiles on the 1/2-turn and 1-turn data, and every .56 microseconds to give 30 internal horizontal profiles on the 6-turn data.

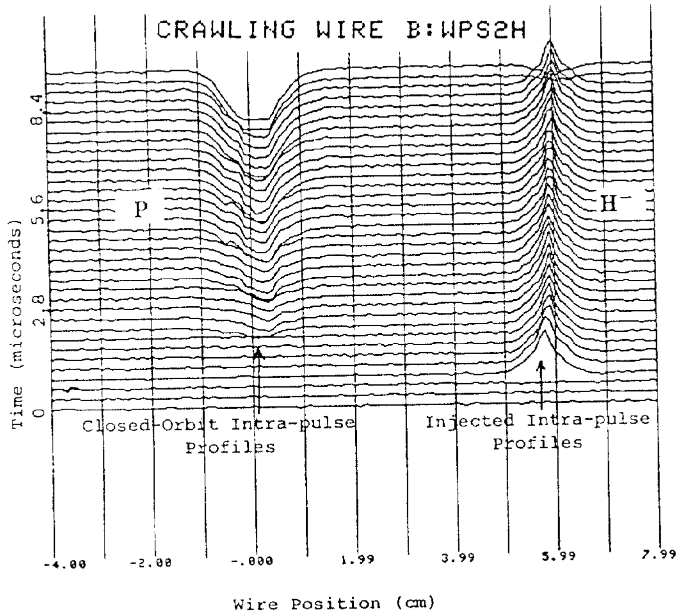

Figure 2.*Intra-pulse wire profiles generated at the injection septum for 6-turn, 16.8 μsec long injection. The profiles were inverted for purposes of data analysis.*

Data Analysis

The stored ZEBRA files were read, analyzed, and histogrammed using a software physics analysis package, PAW [2]. The raw profiles were fit with a Gaussian which proved to be an excellent description of the data giving a χ^2 of less than 1 for the majority of the fits. From each of the Gaussian fits, a central peak position, an overall normalization, a standard deviation, and a constant background were found. The average beam position was found to be consistent to 1-1.5 mm which indicates both stability in overall beam conditions and the effectiveness of this method of measuring beam profiles. Since beam intensity is proportional to the total area under a measured profile, the overall normalization multiplied by the standard deviation was used to describe the relative beam intensity of each profile (ignoring the constant factor of 4π in the integral of the area). The beam intensity when derived in this fashion typically exhibits fluctuations of around 10% between runs. This variation appears to be due to both the accuracy of the fit and real fluctuations in injected intensity.

Foil Loss Results

Foil losses were determined using the WINFH wire because the first profiles captured of the beam as it moves off the foil do not entail losses from wire scattering (see Figure 1). To measure foil losses, the time of the ORBUMP cutoff was extended by 33 μsecwhich had the effect of causing the beam to make an additional 12 passes through the foil (2.8 μsec per turn at 200 MeV). In practice, foil losses proved difficult to determine because they are about .5% per pass through the Booster's 200 $\mu gm/cm^2$ stripping foil for 200-MeV H^- beam. Foil scattering was finally measured using 1-turn injection at a time when the pulse-to-pulse intensity stability was 3%. Data were taken with the ORBUMP timing alternated between the runs to compensate for any long term drifts. Foil losses were found to account for a 6% degradation in beam intensity with a standard deviation of 2% for the 12 additional passes made through the foil. This implies .5% scattering loss per turn through the foil with a σ of .17%.

Injection Loss Results

A more interesting result to come out of the foil loss and space charge studies was a measure of the losses suffered at injection presumably due to a mismatch between the transfer line and the Booster. These injection losses were over by the third turn injected beam took around the Booster (Figure 4). Unfortunately over ten turn's worth of data were unanalyzable due to the field changing in the ORBUMP magnets as they shut off. The wires were so close to these magnets a current was induced by the decaying magnetic field wiping out an intensity determination for this interval. Hence the blank spot in the figure. Future data will be taken with wires well away from any stray fields.

Injection losses measured off the wires were around 10% per turn in the first 2 turns (after correcting for wire losses). The effect of wire scattering on the beam was estimated using an exponential with a varying exponent. Well away from injection the beam losses are strictly due to wire scattering, and the exponential factor used to describe the drop in intensity as a function of turn number is readily pulled out of the data. The variation of the second term in the exponent with respect to turn number corresponded to an approximate linear widening of the beam profile due to wire scattering (the equation used to calculate the profile width was extracted from profile data extending over 35 turns). Wire losses are inversely dependent on profile width so that the factor which describes broadening appears as a denominator in the exponent.

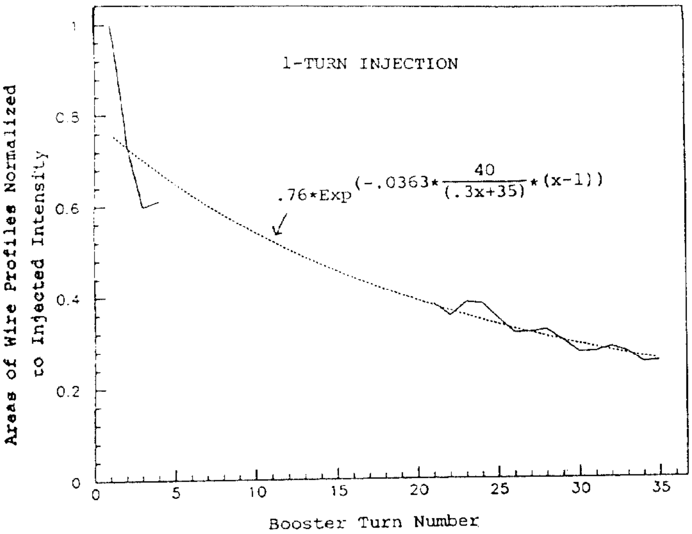

Figure 3. *Intensity as a function of turn number in the Booster. The exponential wire losses plotted (- - -) are described by the equation shown. The variable x in the equation is the turn number.*

Space-Charge Results

A possible hint of a space charge blowup was evidenced in the 5-turn data where after 9 turns, or 4 turns after injection is complete, another dip in beam intensity is observed (Figure 4). This dip is not observed in the 1-,2-,and 3-turn data. A toroid located in the injection region also shows a decrease in beam intensity about 4 turns after injection for 6-turn injection. However, given the problems with the wires near the ORBUMPs, we plan on taking these same data using a different wire.

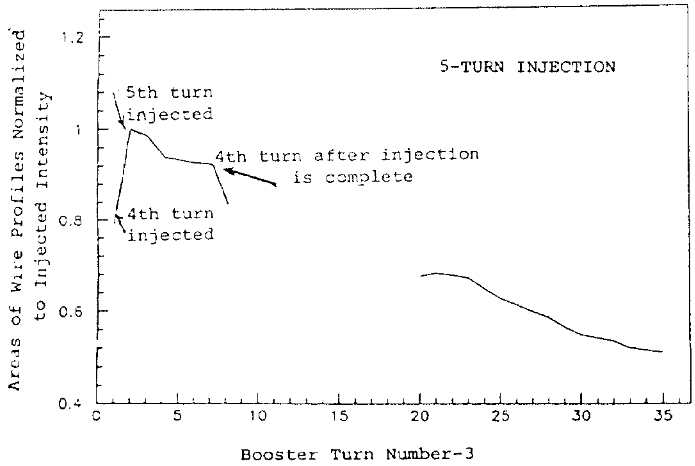

Figure 4. *Beam intensity as a function of Booster turn number.*

Intra-pulse Studies

The original plan when intra-pulse studies were initiated was primarily to study the effects of the transfer-line debuncher on beam pulses. In Figure 2, raw 6-turn profile data is displayed for the septum wire, WS2H. One can observe both the inverted positive H^- profile to the right and the well-separated negative closed-orbit profile on the left (also inverted) on this wire. Based on the Gaussian fits to these data, the entire position history of the beam pulse as a function of time can be displayed (Figure 5). Half of the central peak movement of the 6-turn pulse occurs in the first 2.8 *μsec* or the first turn around the Booster with a slower drift following. More dramatic position changes can be accomplished by changing the debuncher settings as also shown in Figure 5, yet the internal position structure remains the same. Presumably the jumps in overall peak position are due to energy changes in the beam as a result of the debuncher. One- and also half-turn data also show 2 mm internal position changes from beginning to end.

From the position movements, an approximate spread in energy can be calculated if the entire shift is attributed to changes in the beam energy. Using TRANSPORT, a 300-keV difference in energy produced a .2 mm spread at the injection septum for this line. This is in good agreement with a BPM measurement [3] which gives a $\delta p/p$ of 250 keV.

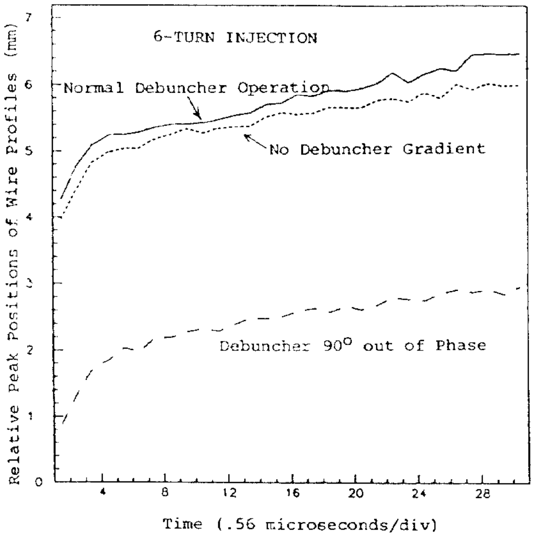

Figure 5. *Central peak postion plotted versus time within a 16.8 μsec or 6-turn injected H^- beam pulse for different debuncher settings.*

References

[1] R. Brun, O. Couet, C. Vandoni, P. Zanarini, *"Physics Analysis Workstation," CERN Computer Center Program Library, Long Writeup, Q121, Oct. 1989.*

[2] R. Brun, J. Zoll, *"ZEBRA-Data Structure Management System," CERN Computer Center Program Library, Q100, 1989.*

[3] E. McCrory, *private communication, Jan. 1990.*