

An ACNET Application Program to Measure the Energy  
Spread of the Beam in the Booster at Injection

Jovan J. Nelson, Brown University

Supervisors: C. M. Bhat, B.S. Hendricks, and M.J. Yang,  
Accelerator Division, Fermilab

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Fermilab

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## Overview

The Booster [1] is one of the five synchrotrons in the Fermilab accelerator complex. It is a proton synchrotron that accelerates protons from 400 MeV to 8 GeV. It is 150 meters in diameter and made of 96 combined function magnets that are arranged in 24 repeating cells. It is capable of providing beam to downstream machines at 15 Hz. The Booster was built to be the intermediary between the LINAC (Linear Accelerator) and the Recycler Ring/Main Injector Ring. Therefore, it is the second stage of proton acceleration and crucial to Fermilab's current and future HEP Experiments. These experiments demand high quality and high intensity beams. Booster plays a major role for all of the downstream facilities. In this regard, monitoring the energy spread of the beam coming from the upstream LINAC to Booster and how the properties of the beam are maintained during the acceleration cycle is quite critical. This paper focuses on our recent work on development of an online ACNET application program to measure the energy spread of the beam in the Booster at injection.

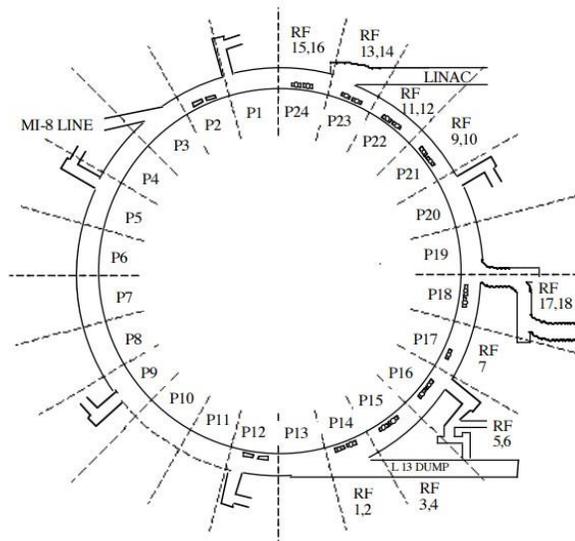


Figure 1: Schematic of the Booster Ring with various sectors.

### Brief description of Injection

Booster receives 400 MeV  $H^-$  ions from the LINAC with 200 MHz bunch structure. Typically each LINAC beam will be of length varying from a fraction of microsecond to 40 microsecond. On its way downstream, the beam travels through a quadrupole (Q6) that gives the

beam an additional upward bend into the Lambertson (B:LAM) which bends the beam 10.96 degrees West. The beam then experiences bends in the LINAC enclosure into the Booster enclosure. This requires the beam to travel vertical thus increasing vertical dispersion of the beam. The LINAC beam is transported through the “400 MeV transport line” for about 70 meters before it is injected in to the Booster. As the bunched beam travels through the transport line, the beam shears. At about three-fourths of the way from LINAC to the Booster, beam goes through an 800 MHz debuncher RF system which helps reduce the beam energy spread at injection into the Booster.

As the  $H^-$  ions are injected into the Booster, they are bent radially outwards and pass through carbon foil that strips the electrons. It takes a proton, at injection, about 2.2 microseconds to go around the Booster once. The Booster can create up to 18 Booster turns (BT) (about 39.6 microseconds of the LINAC’s 40 microsecond pulse.). As turns are added there is no interference because  $H^-$  and protons are of different “type” therefore the incoming beam can merge with the beam already circulating around. Usually for operations, less than 14 turns are used. Once the filling is completed the beam is no longer bent into the foil and is moved inwards radially.

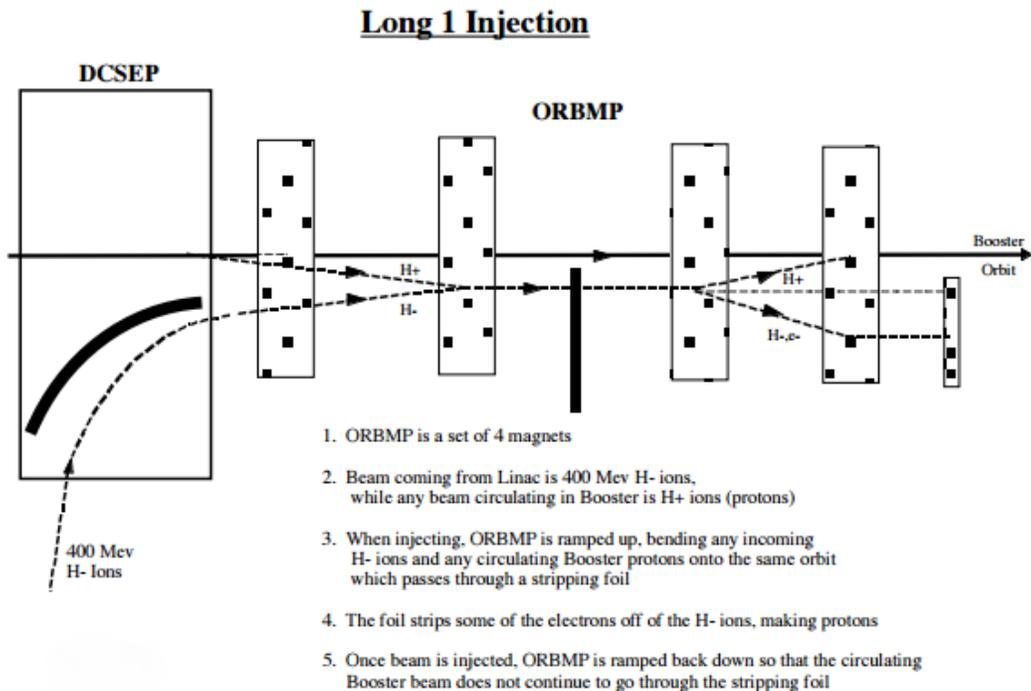
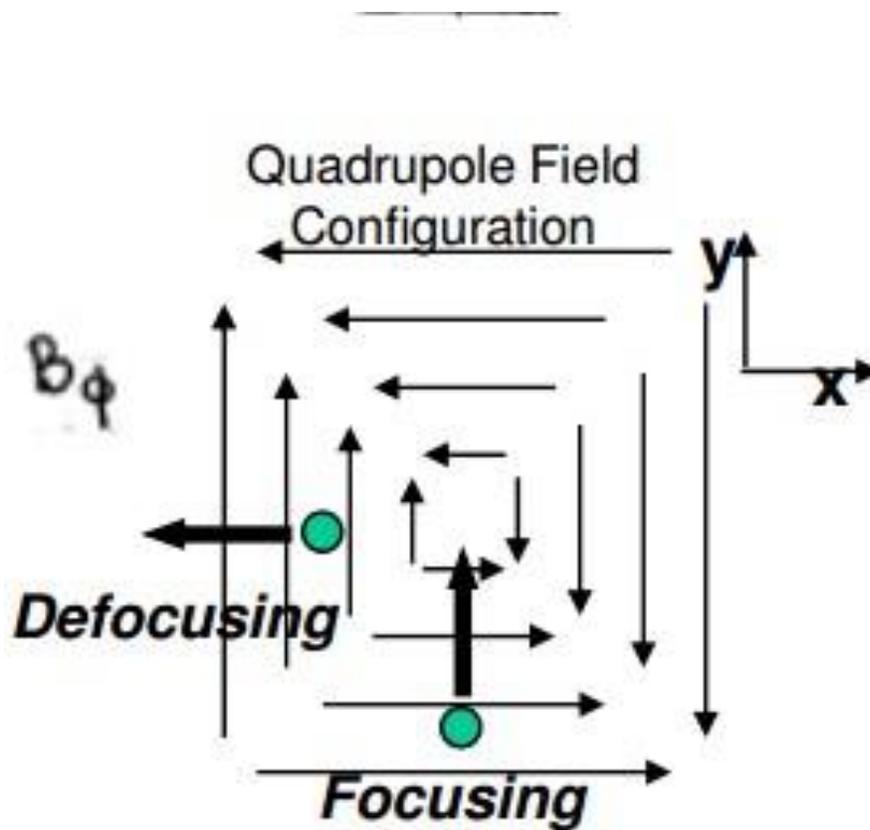


Figure 2: Schematic description of beam injection into the Booster.

### *Brief description of the Booster*

The Booster combined function magnets are responsible for bending the injected beam around the arc of the Booster ring. Combined function magnets, means the poles of each magnets are slanted. As a results of this, these magnets have dipole, quadrupole and other higher order magnetic field components built in. Dipole components bends the beam and the quadrupole components focus the beam horizontally and vertically. There are number of additional multi-function magnets in the Booster ring which act as corrector magnets whose magnetic field configuration is very difficult to represent. However, magnetic field of a standalone quadrupole magnet is shown in Figure 3, just for information. In any case, the combined function magnets along with the multi-function magnets are arranged into repeating units called a lattice.



*Figure 3: Particles are considered focusing as they move towards the center of the beam line while defocusing as the move away.*

The focusing and defocusing occur simultaneously when particles pass through these magnets, particles will focus horizontally and defocus vertically or vice versa. This setup helps the beam stay in a stable closed orbit around the ring.

The beam is accelerated as it passes through 19 ferrite-tuned resonators called cavities. These are powered by RF amplifiers driven by low level RF. There are two groups of Booster RF stations, A and B. These refer to their vector phase relationship which is 180 degrees out of phase. There are three phases to the acceleration cycle, 1) injection, debunching, and capture 2) acceleration, and 3) extraction into the Recycler Ring or Main Injector. Because the Booster is a synchrotron, the frequency of the RF and the strength of the magnets must increase while being in sync with the acceleration of the particles (from 400 MeV to 8 GeV). The frequency increases from 37.86 MHz to 52.81 MHz. The harmonic number of the Booster is 84 (which is equal to the ratio of RF frequency to that of the revolution frequency of the beam). This creates 84 buckets or bunches of particles that can be captured and accelerated.

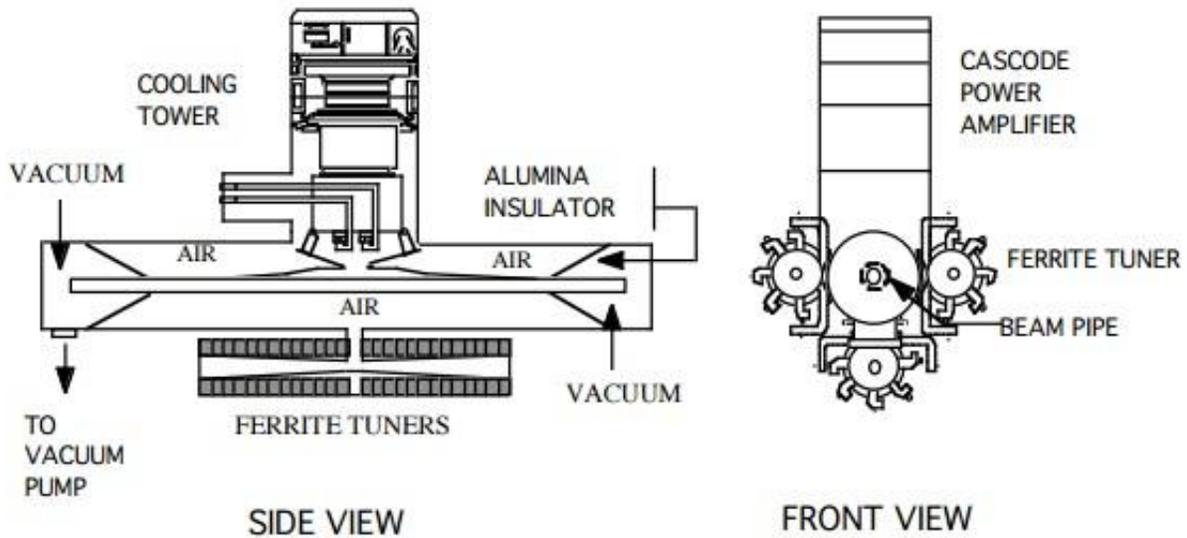


Figure 4: A Schematic of ferrite-tuned resonator cavity.

No accelerator can properly function without proper diagnostic (“eyes”) and control devices. There are multiple beam diagnostic devices such as wall current monitors, beam

position monitor, beam loss monitors etc., added in the drift spaces of the Booster lattice. Each of these devices play important role in controlling the beam in the Booster and understanding the dynamics of the beam at various stages of the beam cycle from injection to the extraction. The signals from the wall current monitors (WCM) are used to measure the image charges of the beam which are converted in to beam longitudinal profile. We use these signals to measure the beam energy spread in the Booster. Recently a systematic measurement on the multi-turn beam energy spread in the Booster [2] has been made using offline data analysis of WCM data. Here, a console application program, which runs on the Fermilab ACNET environment, is written to instigate online measurement of the Booster beam energy spread using the WCM. In the next section we explain the methodology and detailed structure of the newly developed application program.

## The Application Program

### *The Physics behind the Program:*

Generally, beam in an accelerator like the Booster has a finite energy spread. This is a measure of the extent of the beam energy envelop with respect to a central beam energy, also called synchronous energy (for example, 400 MeV, etc.). As the beam circulates in a synchrotron, the higher and lower momentum particles drift differently relative to the

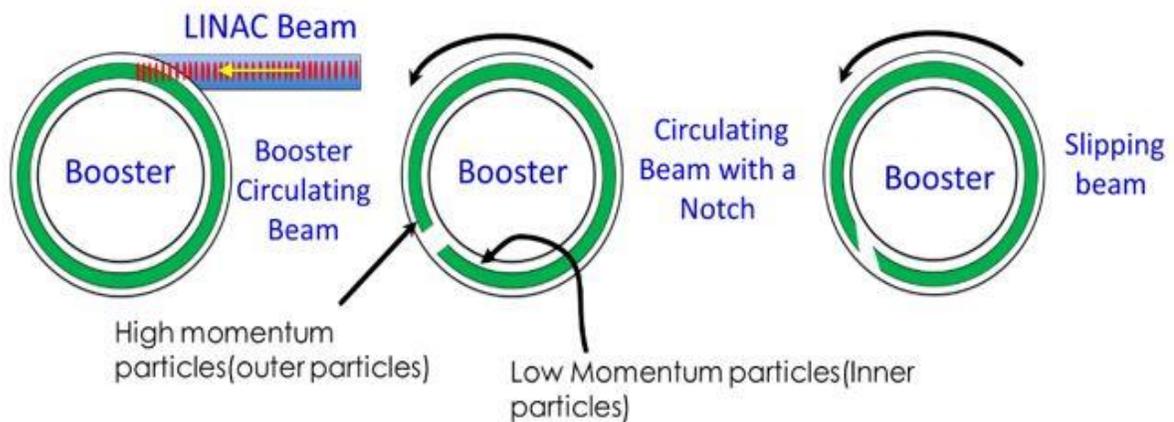


Figure 5: The beam pulses enter form the LINAC and create a continuous beam in the Booster (left). Notch at its creation (middle). High and low momentum particles are also shown. Beam

*after some time begins to slip and particles line up 'touch'(right).*

synchronous particle. For example, at 400 MeV the particle with slightly more momentum will bend less in a pure dipole field relative to the synchronous particles at 400 MeV. Similarly, a low momentum particle will bend more and travel more inside. A schematic view of beam particle distribution injected from the Fermilab LINAC in to the Booster is shown in Fig. 5. If one creates a short gap (notch) in a fully debunched beam using a fast beam kicker, the slipping of high and low momentum particles can be seen very clearly as shown in the last picture above. The WCM records the line-charge distribution of the beam particles as it circulates in the ring. The first trace of the WCM after formation of the notch will be essentially a continuous beam with a gap, and the subsequent traces represent evolution of notch filling as the beam particles continue to slip.

By analyzing the notch shape in a continuous beam and its evolution we can extract two values, the notch width ( $W_{notch}$ ) and the time at which the high momentum particles of the tail of the beam cross or ‘touch’ ( $T_{graze}$ ) the low momentum particles at the head of the beam. Using the equation [2]:

$$\Delta E = \frac{\beta^2 E_s W_{notch}}{|\eta| T_{graze}}$$

where  $\beta$  is the relativistic speed,  $E_s$  is the synchronous energy, and  $\eta$  is the slip factor, we can calculate the energy spread ( $\Delta E$ ).

#### *Program Overview:*

This application program was created in Fermilab’s ACNET Environment which is a system that has access to the hardware and devices that are essential to the beam operations and diagnostics. This program controls various types of hardware that are necessary to measure the energy spread of the beam. The program works as follows:

- 1) Check if the executing the program is safe (all necessary instruments are available to measure the Booster energy spread) and warns if another the user is using the same devices. If so one cannot proceed.
- 2) Sets necessary parameters on the wall current monitor (WCM) scope like, a) channel upper and lower amplitude levels (default values are 1 V and -.04 V, respectively, b)

number of data points (default is 50000 for “Record length”), c) space between the data points (“interval” 0.4 nsec), d) TCLK event of interest.

3) Execute an ACL script upon permission from the Main Control Room (MCR) crew chief which enables a) a 1-shot timeline with beam on \$17 (a TCLK beam event), b) moves all timers related to RF paraphrase settings to a later time, c) moves notch timer to soon after the injection, d) moves radial feedback loops to later time so that one can collect nice WCM data on the injected beam for first 200 micro seconds.

4) Collects WCM data from the scope.

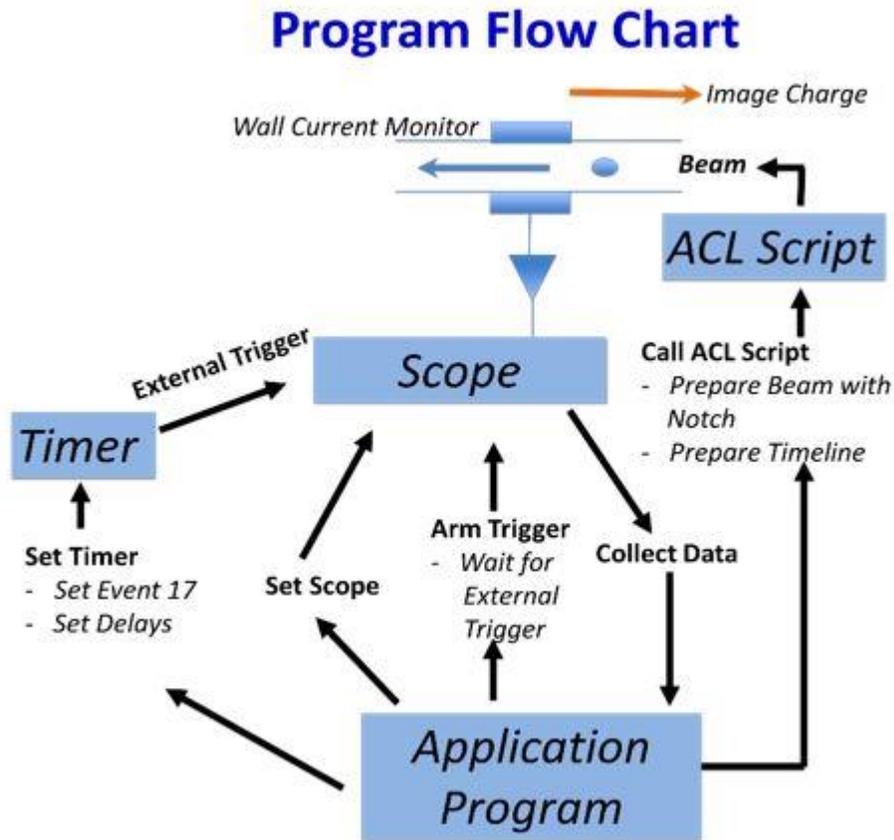


Figure 6: The Application program interacts with the Timer, which is responsible for sending an external trigger to the scope, the scope which reads from the Wall Current Monitor, and it calls an ACL Script that prepares the beam with a notch and sets a new timeline for the beam.

- 5) Analyze the data to extract the beam energy spread.
- 6) Give a graphical output on a separate window for the user's perusal.

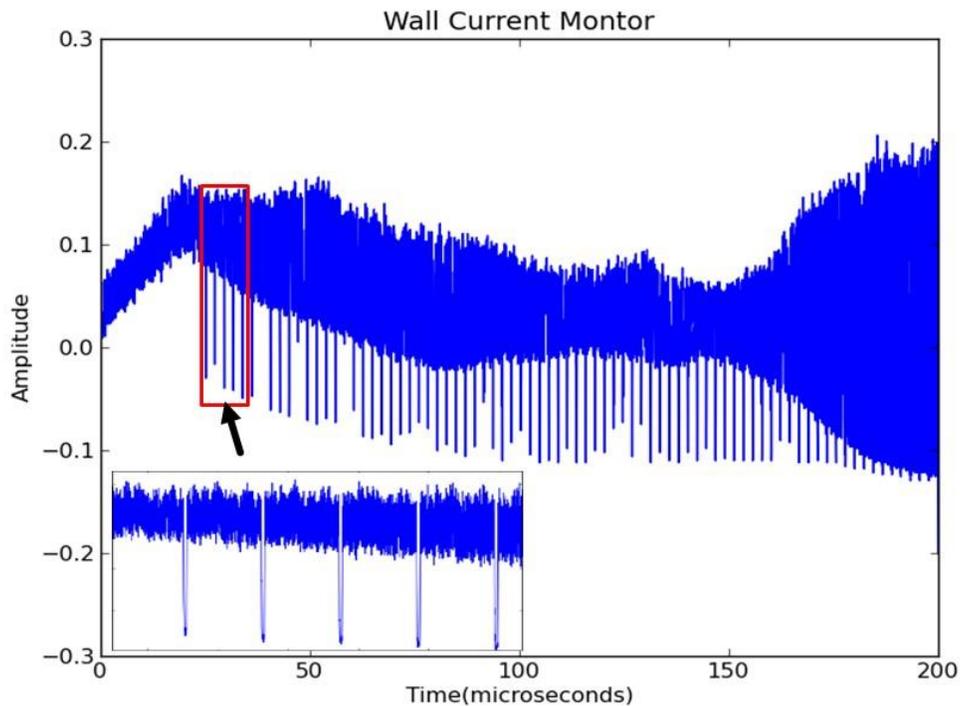
A schematic view of the block diagram representing the structure of the application program is shown in Fig. 6.

Some highlights of this programs functionality is, it is the first application program at Fermilab that can measure beam energy spread of a multi-turn beam in the Booster at injection. In the past, the beam energy spread was measured only on a partial beam and only during a dedicated beam study. This program gives an ability to measure beam energy spread with minimum interruption on the operation. Further, the instant measure of beam energy spread at injection helps us to improve the overall Booster performance.

### Analyzing the Data

#### *Following the notch*

The data received by the WCM looks like that shown in Fig. 7. This data is continuously



*Figure 7: WCM data for the first 200 microsecond after injection. The icicles are the results of notch appearing at the WCM on every revolution. Zooming in it is possible to see a few of these notches, each is about 2.2 microseconds from each other (as shown in inset).*

taken for nearly 100 revolution of the beam. The many notches that are present in this graph are actually the same notch but at a different revolution around the Booster. WCM is an AC coupled system. Because of a small amount of DC coupled part in it, the beam amplitude increases while it is being injected and then slowly starts to decline as it begins to settle. Also after about 150 microseconds the RF in the Booster starts to ramp up.

Over time this notch starts to evolve as seen by the WCM. As the particles drift in the notch the notch begins to ‘fill up’.

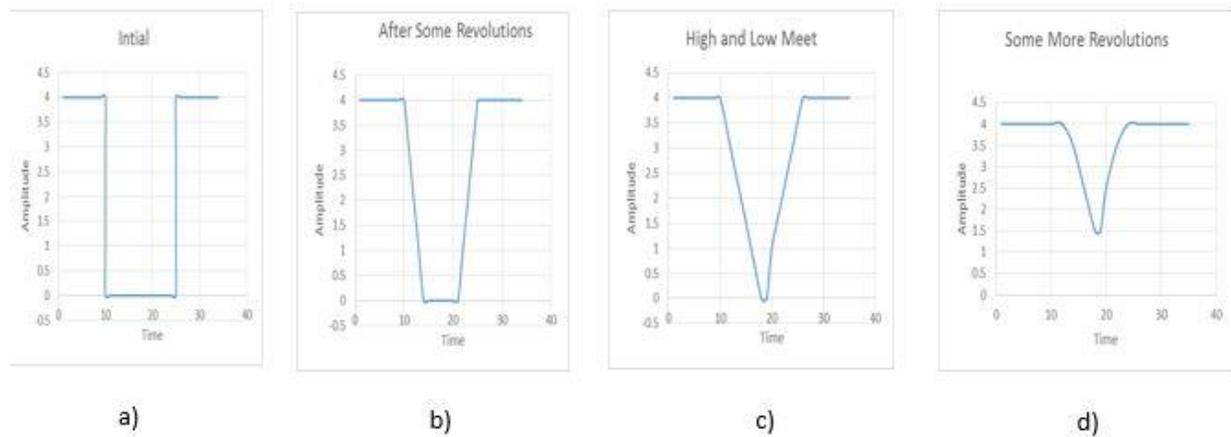


Figure 8: This is a schematic to explain the notch filling in an ideal system. a) is where square like the notch is created, b) the notch becomes less square and begins to ‘fill up’, c) is where the high and low momentum particles meet or ‘touch’, d) is where the minimum begins to increase right after they ‘touch’.

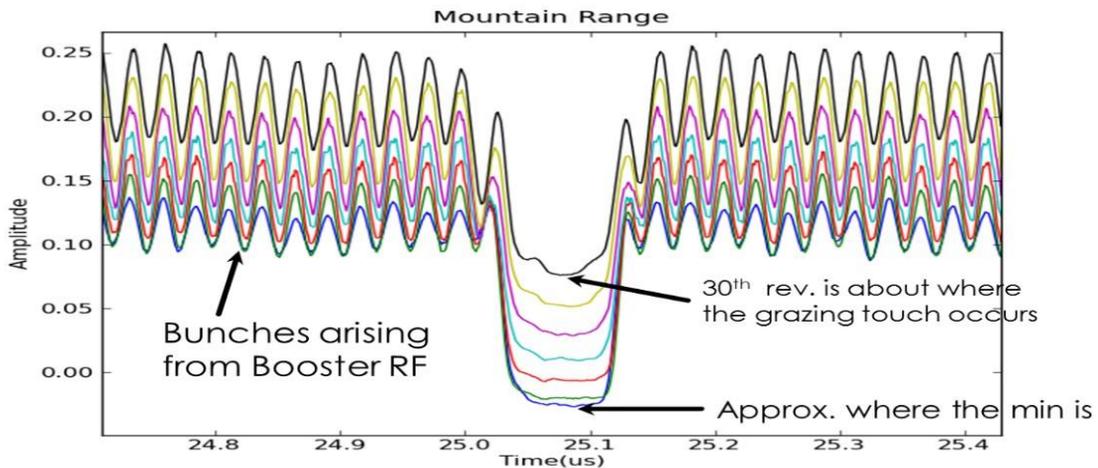


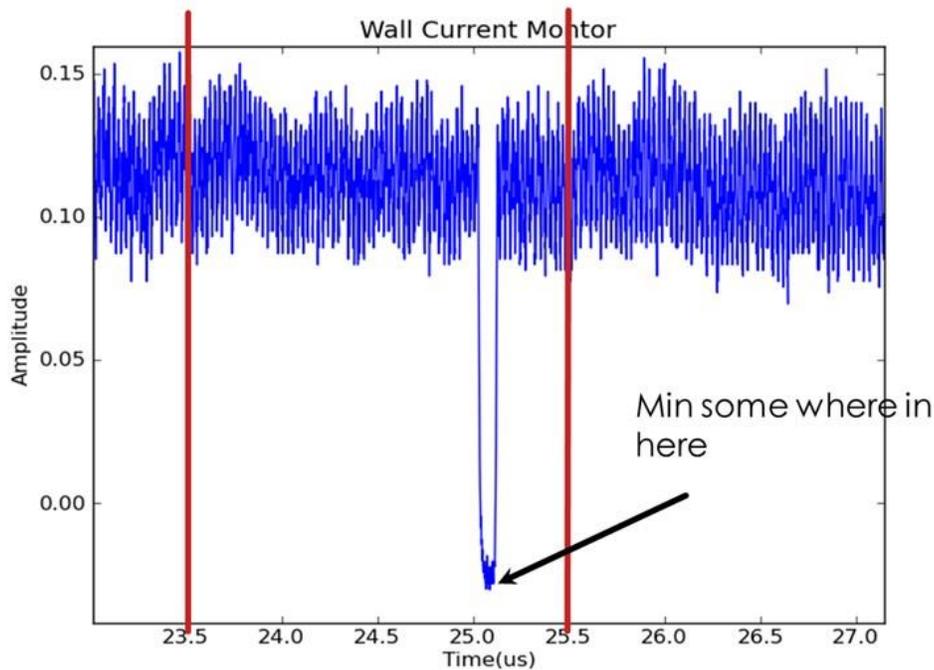
Figure 9: This is actual data from the WCM and is smoothen to show how the notch transforms

over time. The blue notch is the first notch while the subsequent notches are every 5 revolutions until the 30th revolution. The presence of RF makes developing bunches and decision difficult.

In Figure 8 we show a schematic (ideal case) of notch fill up. Until the grazing touch (for example see, picture c) in Figure 8), the notch depth or integrated area between two successive notches in the WCM data remains constant. When the high momentum and low momentum particles “touch” the minimum value of the notch begins to increase. Therefore, by following the minimum of the notch as the notch transforms, we are able to find the grazing touch.

### *Finding the First notch*

First the program takes the entire WCM profile and then uses a guess period of 2.2114 microseconds to make “rough cuts”. The program then searches for the minimum in each piece and saves those amplitude values and their corresponding time values.



*Figure 10: Rough cuts made by the program to find the minimum in segments of the data.*

Since we are interested in measuring the notch width accurately, first notch should be identified in the WCM data and studied in detail. To do this the program compares all minima and looks for where a sudden step occurs. The time associated with first large excursion point represents occurrence of the first notch in the WCM data. The program infers that the subsequent minimum from the first notch are the notch at subsequent revolutions. Figure 11 shows results of such a search for the first notch in the WCM data shown in Figure 7.

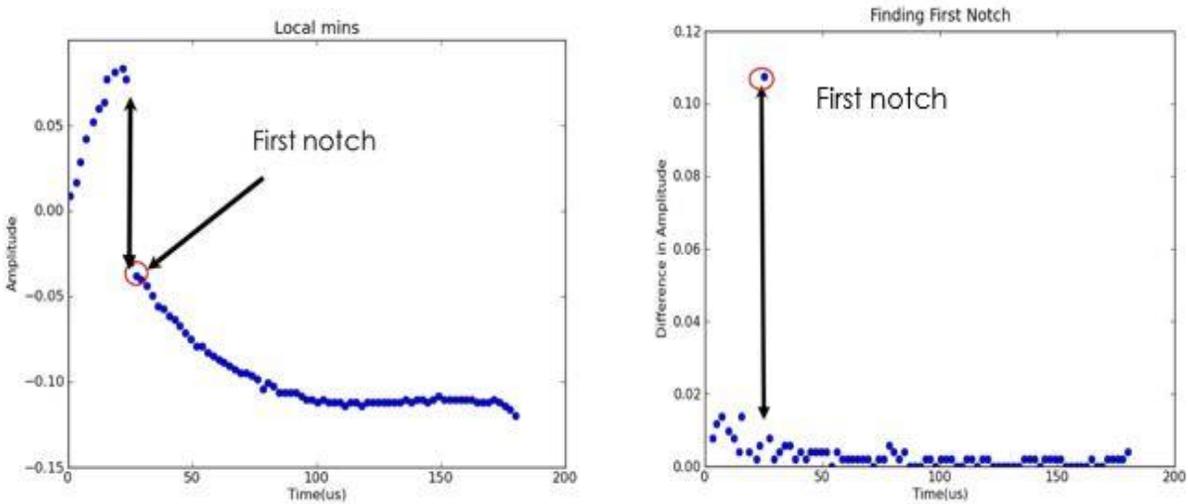


Figure 11: Left figure is a plot of all the minimum for every 2.2115 microseconds. The first notch appears after a large gap. In the right figure is the absolute difference of the next point and its 'left neighbor'. This is how the program identifies the first notch.

Afterwards, the revolution period is calculated using the first few notches. Figure 12 (left) shows revolution period versus number of revolutions. Using this calculated revolution period we can obtain better cuts of the data (see Figure 12 (right)).

Next, by finding the area under the curve between two consecutive notches as shown in Figure 13 (left), we can plot the relative intensity versus revolutions (see Figure 13(right)). The minimum area base is made by taking the minimum amplitudes and taking an average. Data shows that, after the grazing touch the area sharply falls.

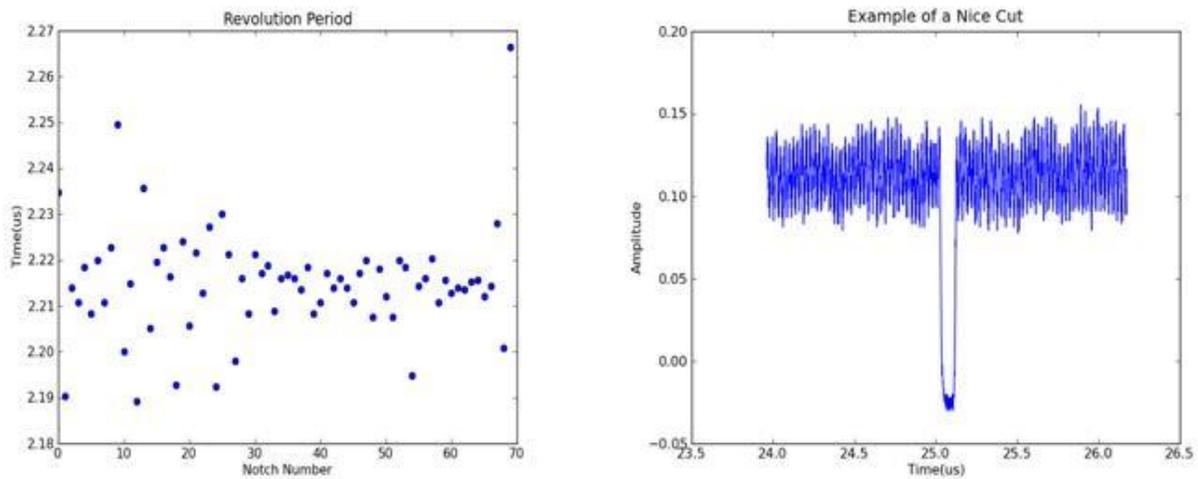


Figure 12: The plot on the left shows the revolution period of the notch as a function of turn number. They are a bit more scattered at the beginning because of noise. The plot on the right is an example of a nice cut made when a few of the revolution periods are averaged.

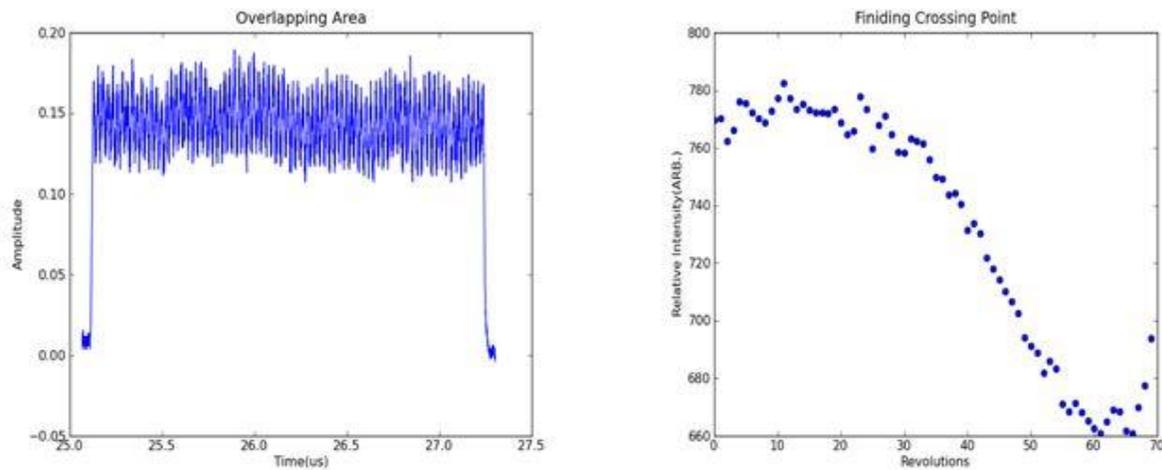


Figure 13: The plot on the left is slice between the first notch and the second notch. The area is taken under the curve as function of turn number is shown on the right. This plot shows how the notch transforms over time.

By eye one can easily determine where the curve in figure drops off. This inflection point is crucial because this is where the grazing touch occurs. After the grazing touch occurs the minimum amplitude increases (as shown schematically in Figure 8), therefore the area under the

curve will decrease.

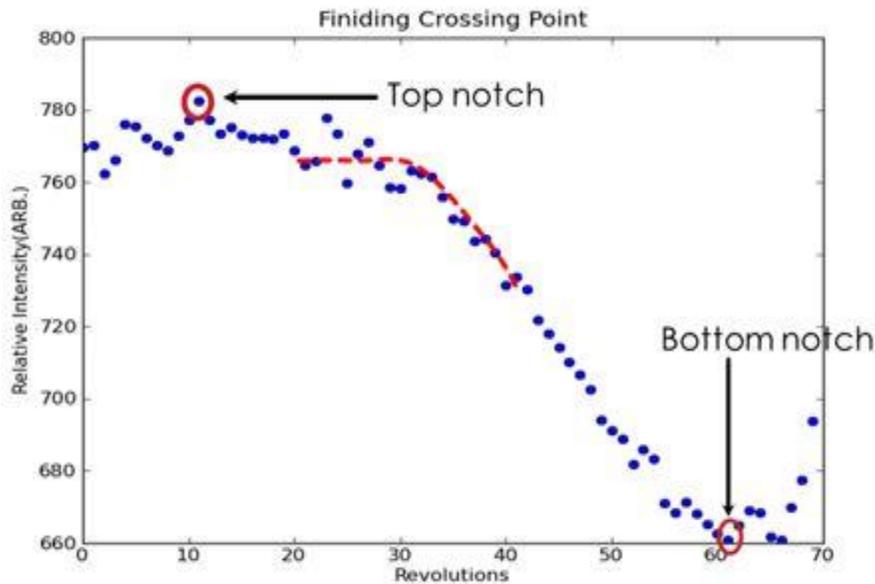


Figure 14: The red line is the region in which the program will most likely choose a grazing touch.

The program makes a decision based on an algorithm. It first calculates the approximate area of the Tgraze (which is the top notch-(top notch-bottom notch)\*.15) and then starting from the bottom notch comparing each point to this approximate area of the Tgraze. When it reaches a value greater than or equal to this approximated value the program produces this value as the revolution number with a confidence level of about 1-2%.

#### *Finding the notch width*

The notch width is found by taking an average of the baseline of the beam and then finding the width 95% of this average on the trace of the 1<sup>st</sup> notch. Two points are found, one the left most part of the notch and one the right most part of the notch. Their times are subtracted and the width is calculated as shown in Figure 15.

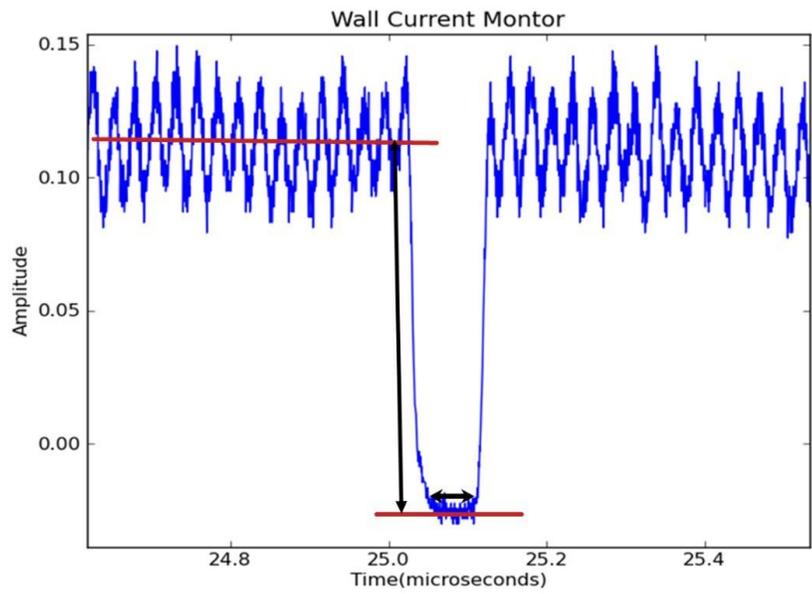


Figure 15: Width of the first notch

## Final Results

Z3 \*Pgm\_Tools\*

<p style="text-align: center; margin: 0;">Scope&amp;Devices Config</p> <p>Devices</p> <p>Tclk: 19                    *Send Setup</p> <p>Bucket Delay: 30        *Arm Digitizer and Set Timeline</p> <p>Trigger: 3000</p> <p>Ch 1</p> <p>State: ON</p> <p>Range: 1</p> <p>Offset: -.4</p> <p>Record Length: 500000</p> <p>Traces: 1</p> <p>Interval: .4</p>	<p style="text-align: center; margin: 0;">Plot Adjustment</p> <p>Wall Current</p> <p>xmin 0    xmax 200</p> <p>ymin -.4   ymax 1</p> <p>Notch</p> <p>xmin 0    xmax 0</p> <p>ymin 0    ymax 0</p> <p>Relative Intensity</p> <p>xmin 0    xmax 70</p> <p>ymin 0    ymax 1.05</p> <p>*Plot</p>	
<p style="margin: 0;">Save and Recall Files</p> <p>Use Scope/File Data: Scope Data/File Data</p> <p>File Location: [ /export/home1/jneilson/FBMS/PythonBooster/FB-2 ]</p> <p>Filename: [ FB-20150606-12BT-dE-1 ]</p> <p>*Save File</p>		
<p style="text-align: center; margin: 0;">Messages</p> <p>Trigsource= EXTERNAL Trigcoupling = DC Trigslope= RISING</p> <p>Trigtype= EDGE Trigmode = NORMAL level= 1.500000</p> <p>Scope link = connected</p> <p>Scope is locked by this console</p>		

Figure 16: The user page of the Program.

Figure 16 shows front page of user interface upon opening. This comes with three windows. In the “Scope & Devices Config.” window various settings on the scope can be set. The “Arm Digitizer and Set Timeline” button arms the scope to wait for the external trigger and calls the ACL script. When this button is pushed a warning box appears that prompts the user to check with the MCR before proceeding. The program has the ability to plot data either straight from the scope or from saved files. There is also the option to adjust the plot sizes of the analysis window.

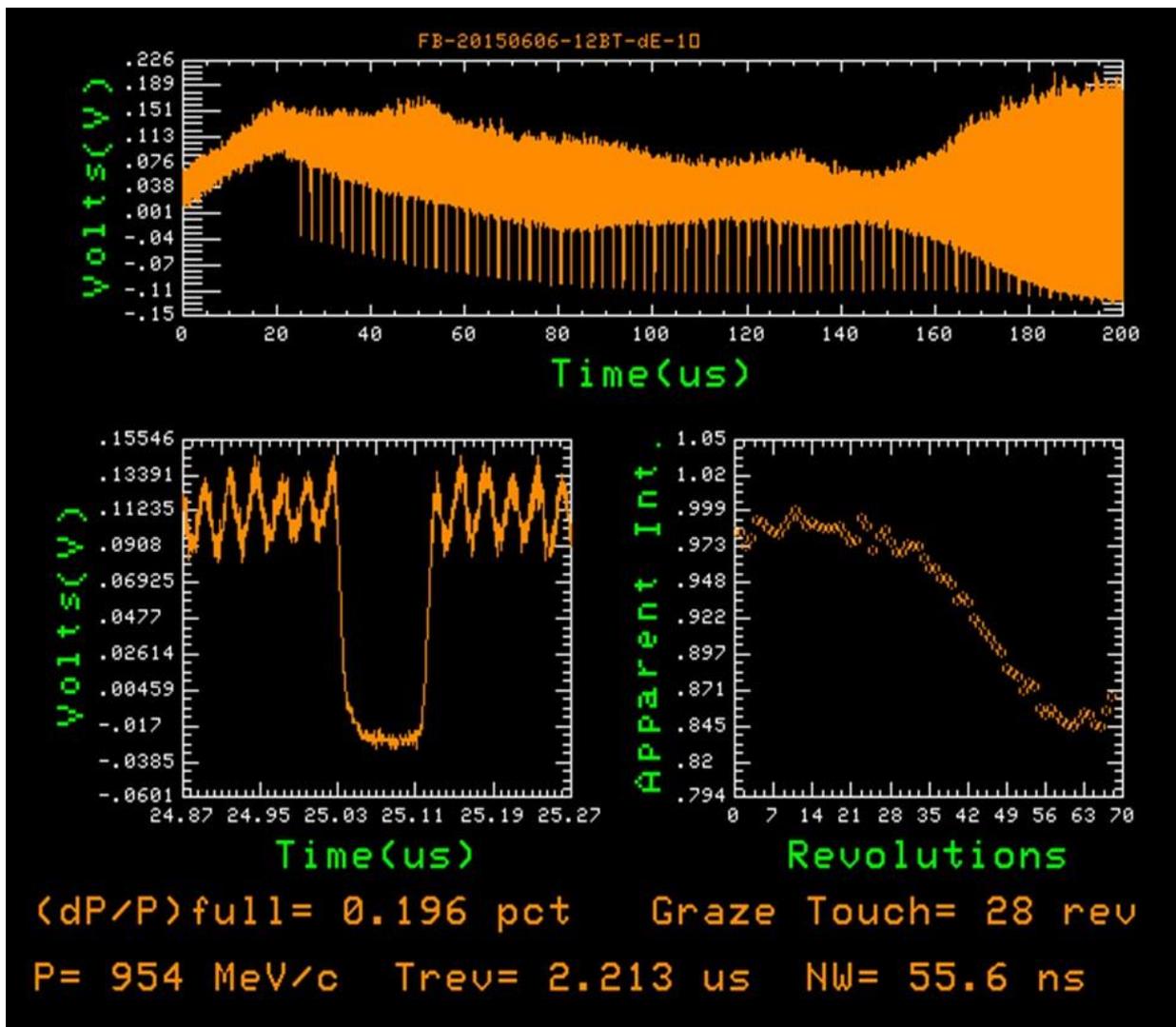


Figure 17: The Analysis graphs. The top graph is the raw data, bottom left is the first notch, and bottom right is the apparent intensity graph normalized. At the bottom, the useful values for

understanding the energy spread are displayed.

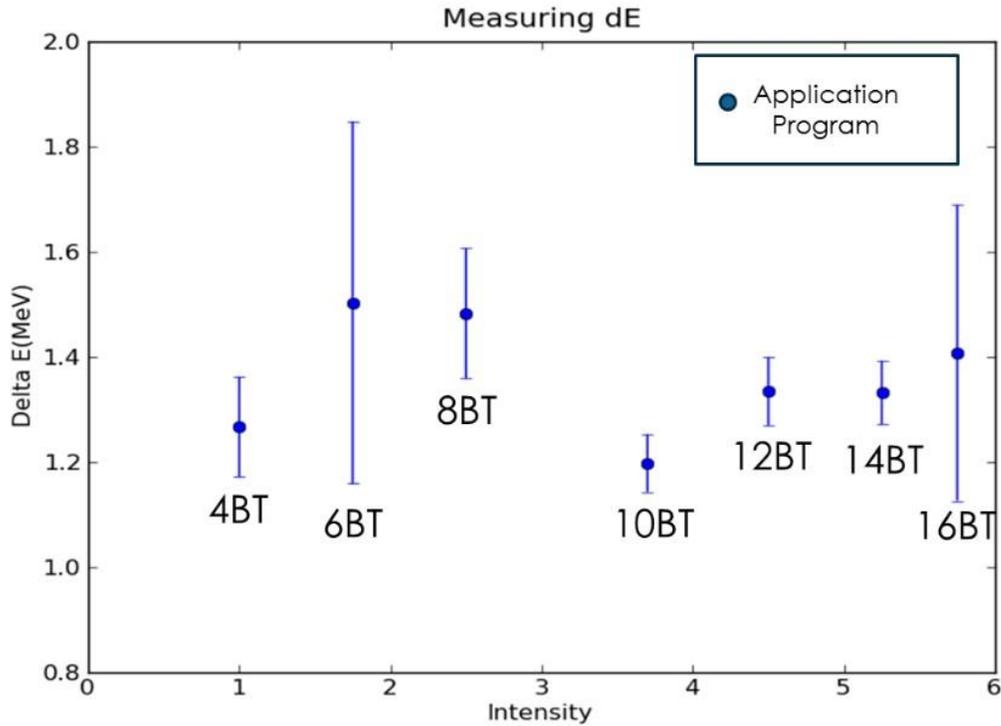


Figure 18: Very few data sets were taken during the time this application program was being completed therefore the error bars are huge. With more data the energy spread can be better justified.

In the analysis window, Figure 17, the raw data (top), notch in the beam, and an apparent beam intensity used to determine the grazing touch are shown. At the bottom the values of the measured full momentum spread, measured number of revolutions needed for grazing touch, momentum of the synchronous particles, the measured revolution period, and the measured notch width are displayed. These values can be cross checked with the raw data.

In Figure 18, the values of the energy spread are plotted for different Booster turns. Based on this data we do not see a strong correlation between beam intensity (each BT corresponds to about  $0.37 \times 10^{12}$  protons per Booster cycle).

## **Final Remarks**

Understanding the energy spread of beam upon injection into the Booster can be extremely useful in improving the beam performance in the Booster. This allows for quick diagnostics of multiple Booster turns thus giving a fuller picture of the beam. It also can then be used as comparison of how the energy spread from injection changes at other points in the acceleration cycle. Therefore having an application program that can help identify trends in the energy spread of the beam is useful for the operators that maintain the beam for experiments associated at Fermilab.

## **References**

- [1] *FNAL Booster Rookie Book*. Dec. 1998. Print Jan. 3, 2004.
- [2] C. M. Bhat, et al., IPAC2I015 (2015), THPF113.