Response of the FBI and SBD in Store 1834

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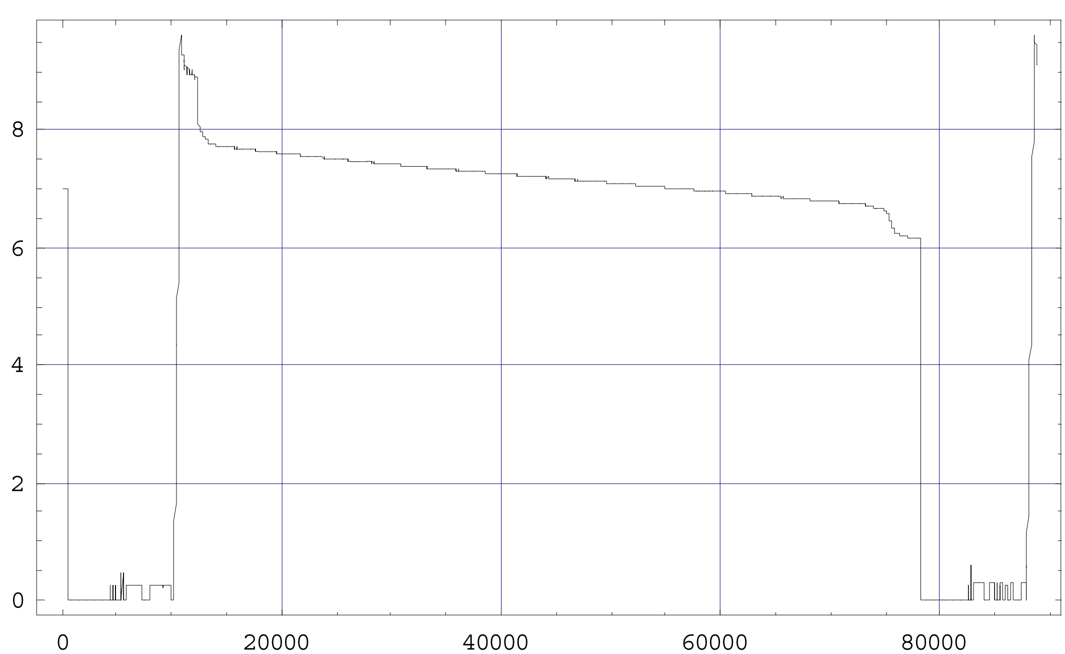
Abstract: Store 1834 had the pbars cleaned out the end. This makes possible a calibration of the FBI. The base line correction is studied, and a different algorithm is suggested. The cable dispersion in the SBD is calculated and a method of minimizing the impact of this correction is studied.

Introduction

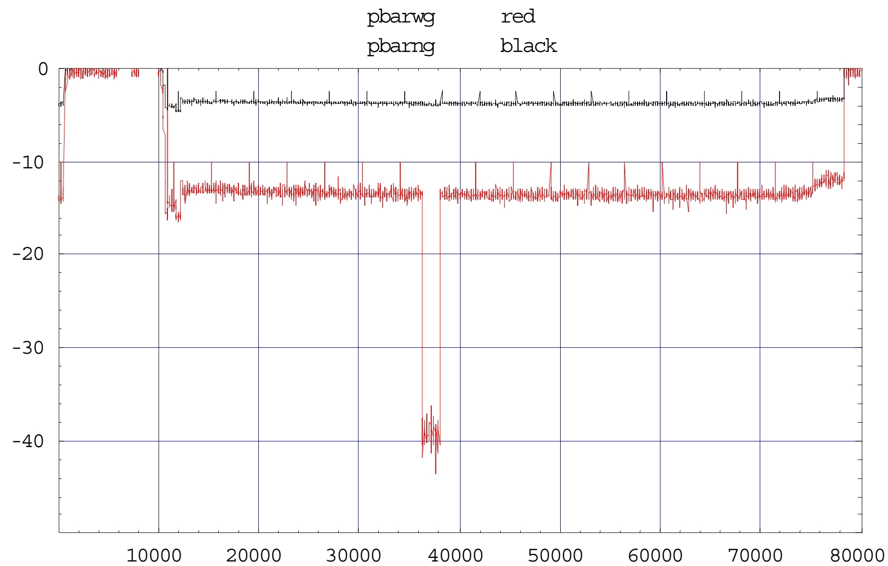
We study Store 1834 as a tool for learning how the FBI and SBD are processing the data from the RWM. The period we take covers time before the store which is used to obtain the no beam response of the integrators. Then we study what happens after the beams are injected. During this period, the pbarwg sample time was increased from a nominal value of 3 buckets to 9 buckets. Finally, the pbars were scraped away at the end which gives us more data. Finally, I have one SBD display taken near the middle of the store that will be used to explore the role of the SBD.

T:IBEAM for this data set is shown below. The time starts at 07:30 am on 10-08-02 and is measured in seconds. The end of the last store and the beginning of the next can be seen. The pbars were scraped out at the end of the run leaving only protons.



Baseline corrections with and without beam

The data for the pbar wide gate and narrow gate is shown below. The period when the wg was set to 9 buckets is clearly seen.



The averages and variances were computed for the following time intervals which are short enough so that long term effects do not affect the variances

a. No Beam   1000 to 4000
b. Beam   20000 to 22000
c. pbar wg=9   36500 to 37500

The data are at 15 sec intervals. The following numbers were obtained, the scale is units of 10 e 9 and they all apply to be set of base line variables like FBIPWG>37, etc:

proton wg mean,rms	-1.82954	0.262469
proton ng mean,rms	0.30355	0.382614
pbar wg mean,rms	-0.369059	0.137084
pbar ng mean,rms	0.264156	0.0165771
proton wg mean, rms	-21.0891	52.8898
Proton ng mean,rms	-6.44751	0.31686
pbar wg mean,rms	-13.5326	0.163318
pbar wg=9	-39.1769	0.691591
pbar ng mean,rms	-3.73221	0.0106869

The first 4 rows are values with no beam and give the dc offset of the 4 integrators. If this is truly constant, it shouldn't affect the answer as it will cancel out in the

measurement. Note that the noise is rather small. To set the scale, we see that there are about 7000 e9 protons in the machine or about 194 e 9 per bunch so the noise on the png base line is about 0.38/166 Sqrt[2]= 0.32%. The last 5 rows are with beam and include the special point where wg = 9. The samples for WG = 3 are taken just before the WG = 9 sample.
The data allow a consistency check. If the two pbarwg points are fit with a straight line and the assumption that the integration times are accurately in the ration of 3:1, the intersection is found to be -0.280 compared to the measured offset of -0.369.
No other checks are possible since there are 4 different integrators.
The total correction to the wide gate beam measurement is 36 times the numbers in the table, and is -0.759 e 12 for the pwg. This is a sizeable correction (about 11%) since the total number of protons in the machine is about 7 e 12. However, the correction is even more important for the pbars, where the number for the pbarwg is -36 x 13.53= 487 e 9 and the total number of pbars in the machine is of the order 700 e 9!

Beam study for Store 1834

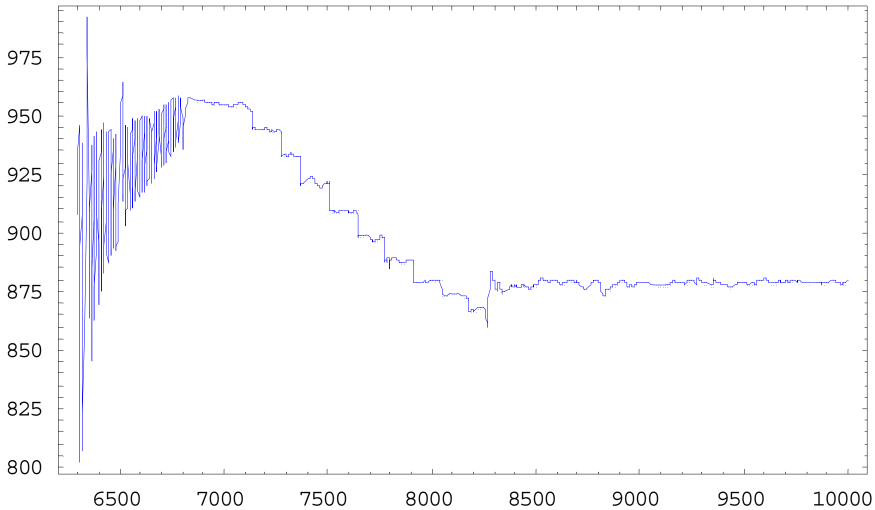
A. Near injection.

Next we will look at the 5 variables that measure beam: IBEAM which is a current transformer, the four variables FBI(A/P)(WG/NG) which come from four different integrators. These integrators use the baseline correction studied above. There are two regions that are interesting:

a. 150 GeV just after the protons have been injected.
b. 980 GeV near the end of the store when the pbars are cleaned out.

The first region is shown below as a ratio C:FBIPWG / IBEAM. If there were no DC beam and no satellites, this ratio would equal 1000. (The factor of 1000 comes from the ratio of units for IBEAM and FBIPWG).

Ratio of P wide gate / Ibeam .
If correctly calibrated the ratio would be 1000.
The loading of pbars is clearly seen .
The bottom scale is seconds



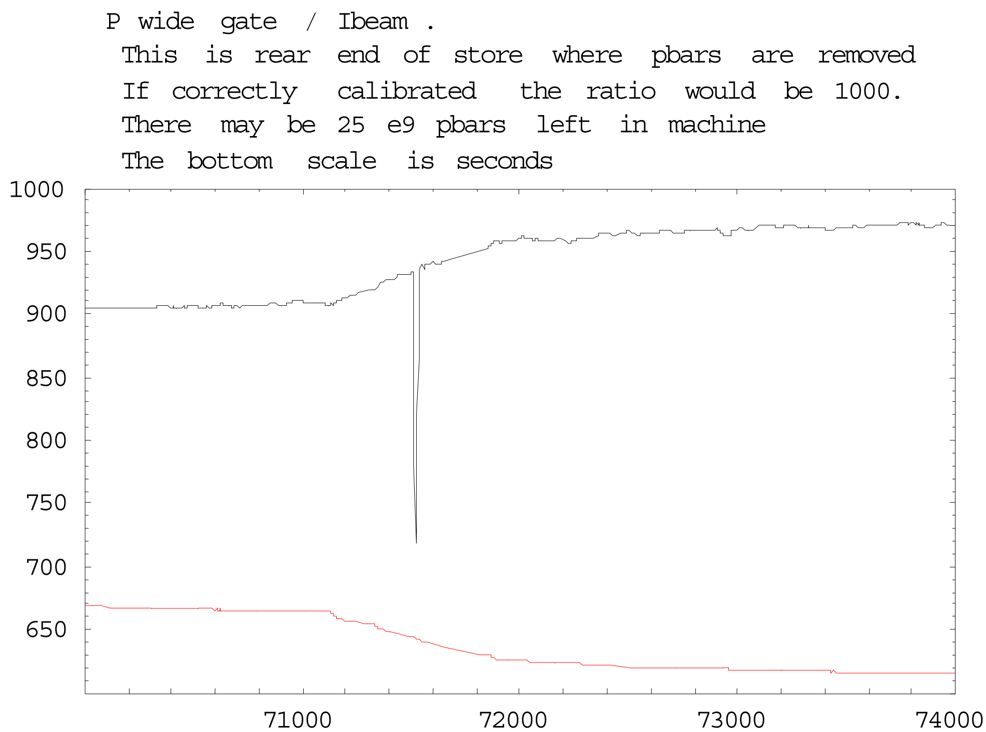
The ratio reaches 957 and may not be equal to 1000 because of:

A. Miscalibration of the integrator
B. Incorrect base line subtraction
C. DC beam in the Tevatron injected from the MI or generated internally
D. Satellites outside of the two adjacent buckets.

The small step of about 10 units occurs at acceleration and results from cleaning out any DC beam from the two injection processes. Adding this to the value at t = 7000 suggests that the FBIPWG calibration is perhaps 3% low in its calibration.

<u>Results near the end of the store</u>

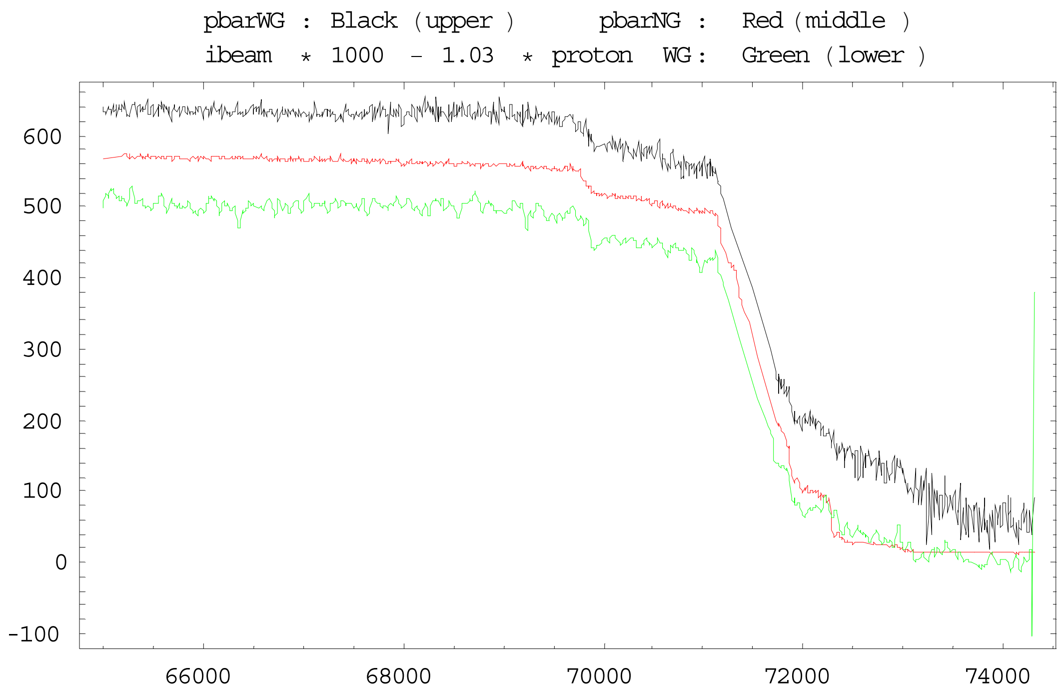
Near the end of the store, the pbars were removed and this provides a second place to examine the calibration of the proton system.



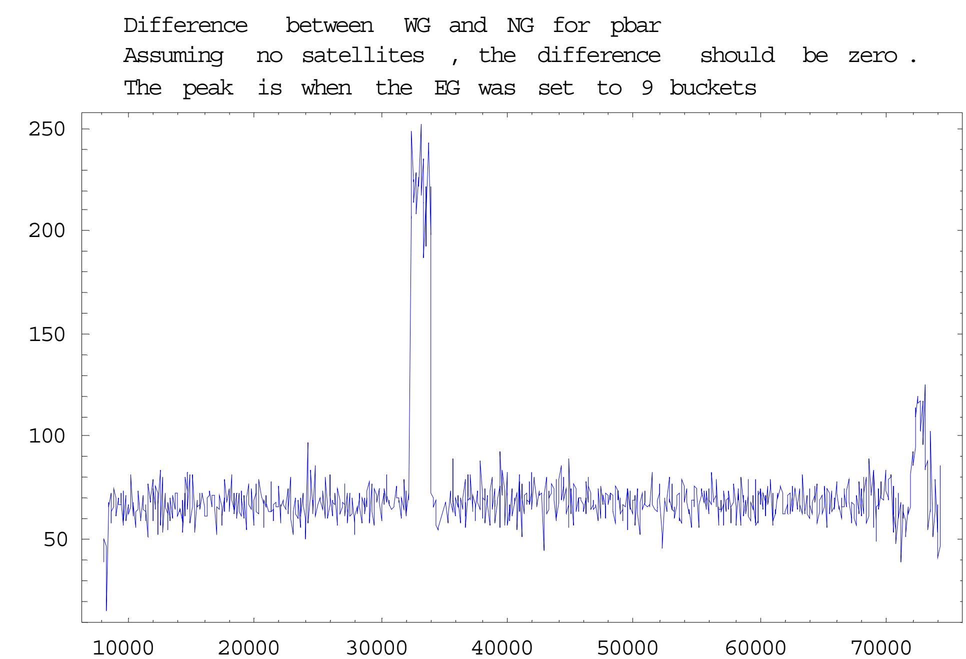
The above figure shows the ratio of the PWG / IBEAM, The lower red curve is given by 1000 x IBEAM and clearly shows the pbars being removed. The plateau to the right is at 970, so this would suggest that the calibration of PWG to 0.97 low or that there are about 3% satellites present outside PWG or that there is some DC beam being measured by IBEAM.. The DC beam at the end of the cycle can be calculated from the abort gap counter B0MSC3 whose rate at the end of the store was about 20 counts/sec. This gets multiplied by 1.43 e 5 to give a proton loss / sec = 2.86 e 6. The time to spiral in to the edge of the TEL scraper has been measured to be 1200 seconds. Thus the DC beam is equal to 3.4 e 9, which is only about 6 e -4 of the protons. In general the DC beam is too small to be detected.
The conclusion from both the early and late measurements is that PWG is about 3% low in its calibration.

Pbar channels

Now we can try to calibrate the pbar channels. In principle the total number of pbars in the machine should be equal to the difference between IBEAM and FBIPWG. There is clearly a problem here as we have just seen that there may be a correction to PWG of as much as 3% and the total contribution of the pbars is only 5-10%. However, we push on!



The plot above shows pbarNG, pbarWG and the difference just mentioned. The correction of PWG by 3% makes a big difference and if it had not been used, the ibeam curve would be between the red and black curves. At this point, there is not much more that we can do. However, we can look at the consistency of the pbar system. If there were no satellites, the pbarWG and pbarNG would be the same. We will look at the satellites later, but for now we will treat them as negligible. The question arises as to why the two curves differ by so much. The plot below shows the difference for the whole store.



Note the peak at 33000 when the WG was set to 9 units. This is a direct indication of either a very large satellite population or a trouble with the algorithm. If there are no satellites, the answer should be independent of the gate width, and in fact the whole curve above should average around zero. This plot directly shows that there is trouble with the base line subtraction procedure.

There is a second point that should be observed from the above curve which is that there is no time variation during the whole store even though the net charge is decaying away. This apparently comes from an amplifier in the pbar integrator saturating on the proton pulses. Since the protons determine the base line, if these pulses are limited, the base line correction will be flat.

A serious trouble arises from trying to measure the baseline, which is about -13.53 (see above table) to a high accuracy. Since this number is multiplied by 36, 1 unit error corresponds to 36 e 9 pbars. Several notes have described the position in time at which this base line correction should be measured. The next section deals with this problem.

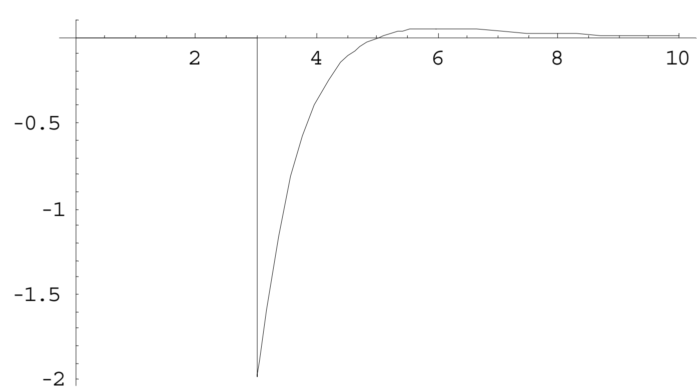
Base line response

The resistive wall pickup is simply a one turn transformer where the beam is the primary turn. The secondary is loaded with a 1.288 ohm resistor and results in a time constant of about 50 micro sec. There is a second RC coupling in the integrator with a similar time constant. The details are not very important and for the following, we will take them to be equal to two turns in the machine.

Assuming that the beam pulse is a delta function of current, the response up to the actual integrator is given by the Laplace Transform of:

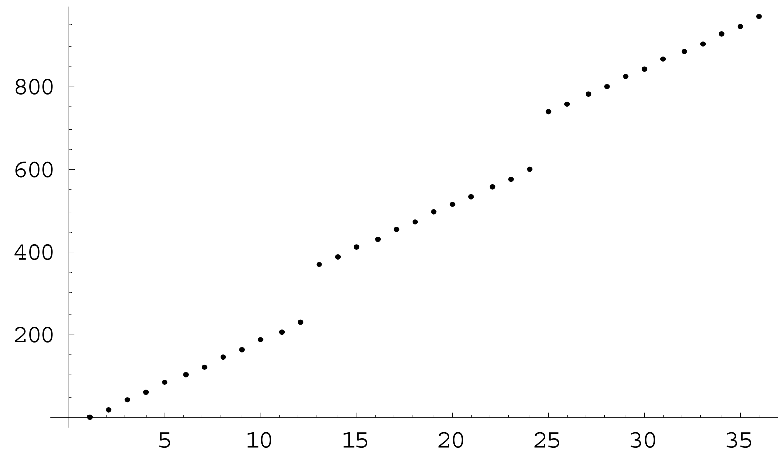
$$V[p] = \frac{p^2}{(p+\tau)^2}$$

The response is: $V[t] = \delta[t] + \frac{e^{\frac{t}{\tau}}}{\tau^2} - 2t\frac{e^{\frac{t}{\tau}}}{\tau}$ This response, time shifted by 3 tau is shown below:

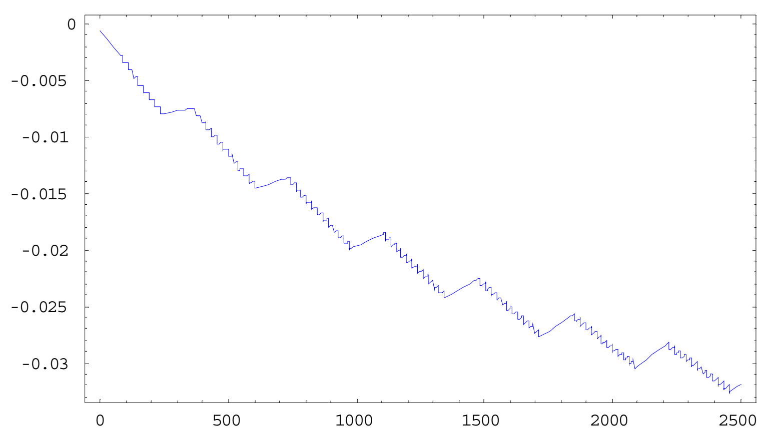


The input is a unit delta function, and since there are two time constants, the undershoot is two units with an initial slope of one halt the time constant.

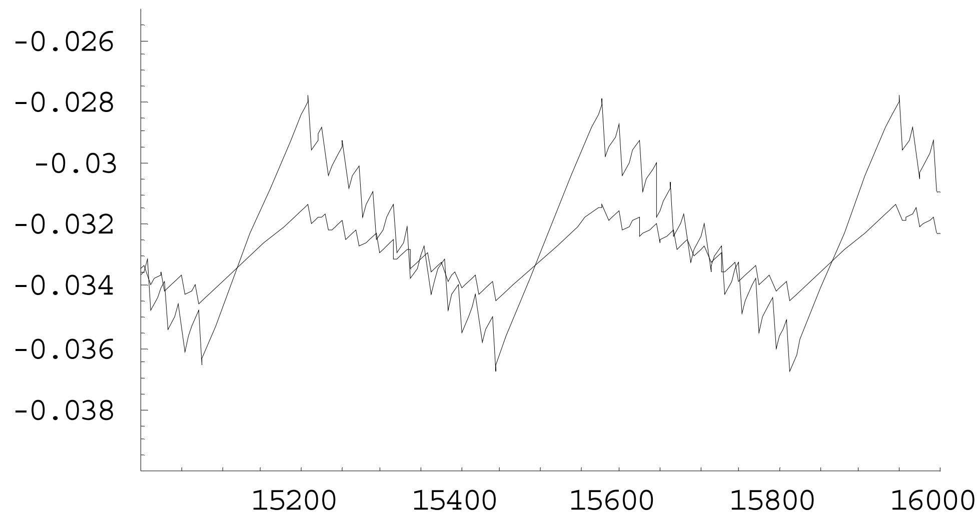
We next build a comb of delta functions that mimic the beam:



The bunch number is along the x axis and the bucket number is vertical. Next we compound twenty of these combs into a large array of delta functions and apply it as input to produce the response. The answer is shown below for the first two turns after turning on the train. It takes about 10turns. to come into equilibrium. The horizontal scale is rf bucket number and the delta functions are not shown of coarse!



An expanded view near the end is shown below for two different values of the coupling time constants: (The averages do not quite equal because not enough turns were calculated for the circuit to reach equilibrium)



The 12 bunches insert charge which then decays away during the abort gaps. The average value is obtained by noting that we inject 36 units of charge. The average over the whole turn must be zero. So the average base line shift must be given by 36/1113 =0.32345. We also note that some of the 36 buckets will be integrated with a more positive base line than average and some with less and so if the proton bunches are more or less equal, the base line contribution just equals the average base line.

THEOREM:

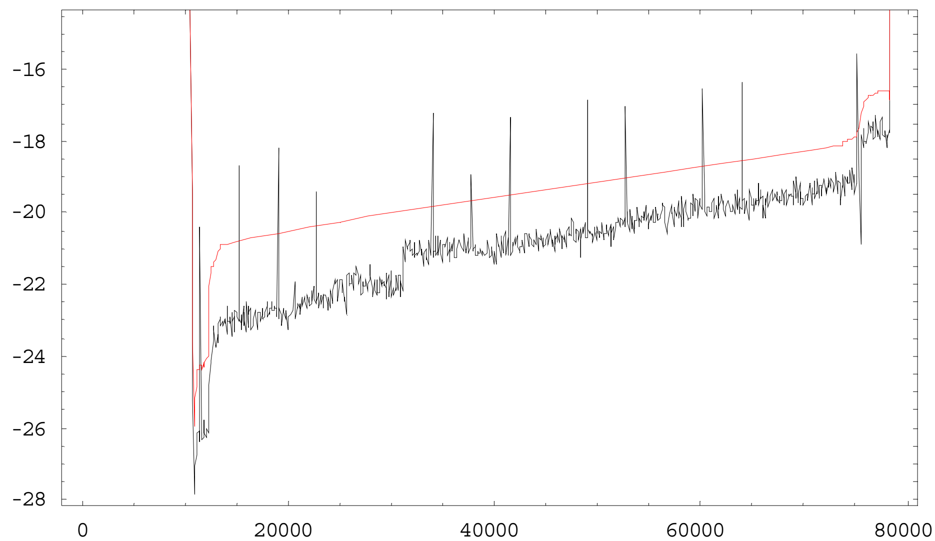
The average base line correction is just given by T:IBEAM and is:

$$baseLineCorrection = \frac{36 \times IBEAM}{1113}$$

This equation is exact for three equal batches and under various other charge distributions. For instance, it is still exact if complete batches of 12 proton buckets are missing or small. Small errors occur when the batches are all different. It assumes that the time constants are long compared to the bunch spacing (the abort gaps set the most stringent criterion). Its main advantage is that it is much more accurate (given by T:IBEAM) than trying to measure a small correction at some prescribed bucket and then multiplying by 36. One can see from the above graph that the local base line can fluctuate by 10% or more depending on where it is sampled. The only correct place is in the center of the abort gap, and that is only true for the case when the three bunches of 12 protons is the same size.

Application of the above to FBIPWG

The graph below shows the difference between the above algorithm and the PWG>37 as actually measured in 1834. The black data is the measured value, the red is derived from the value of T:IBEAM using the equation above.



Using the slightly smaller value given by the red curve above increases the discrepancy of PWG gain by about ½%

The SBD

Let's look at the SBD for this run. We can obtain two numbers from the SBD:

a. The size of the satellites
b. The ratio of the number of protons to the number of pbars.

The SBD can be absolutely calibrated by using ibeam:

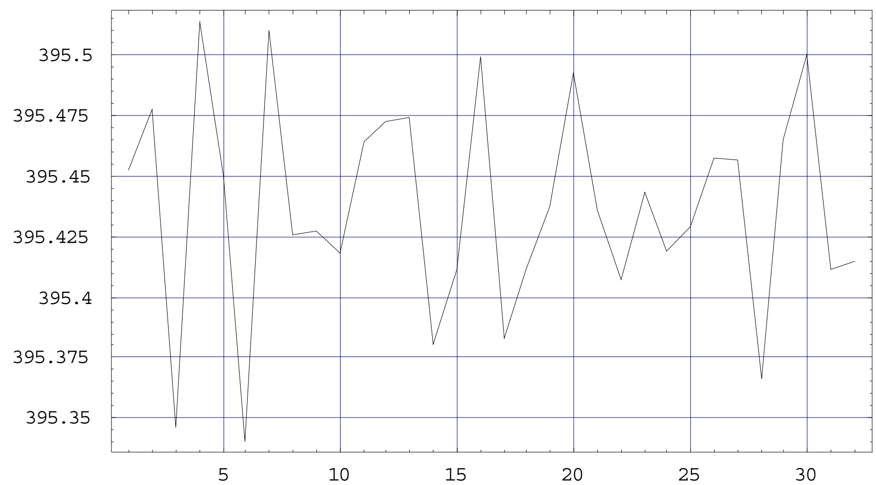
Eq.1 $$ibeam = protons(1 + \frac{pbars}{protons})$$

. Since the pbars are only about 10% of the protons, the calibration only depends on the accuracy that proton pulses can be integrated in the SBD. This calibration can be checked since in principle the SBD is an absolute device. This is a little difficult in practice because of the attenuation in the cable and the accuracy of the various splitters.

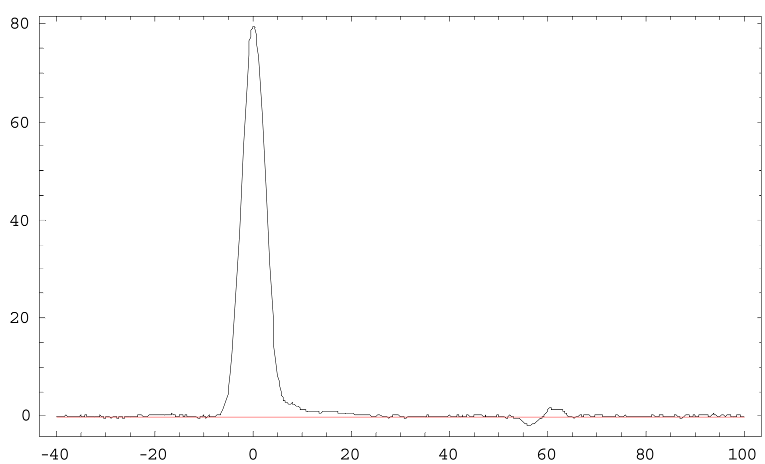
For this note, I used an SBD sweep that was taken around t=33000 in the above run. . For both the proton and pbar traces, a local fit of each bunch was made using an equation of the form:

$$signal = c_1 + c_2 t + c_3 e^{-c_4(t-t_o)^2}$$

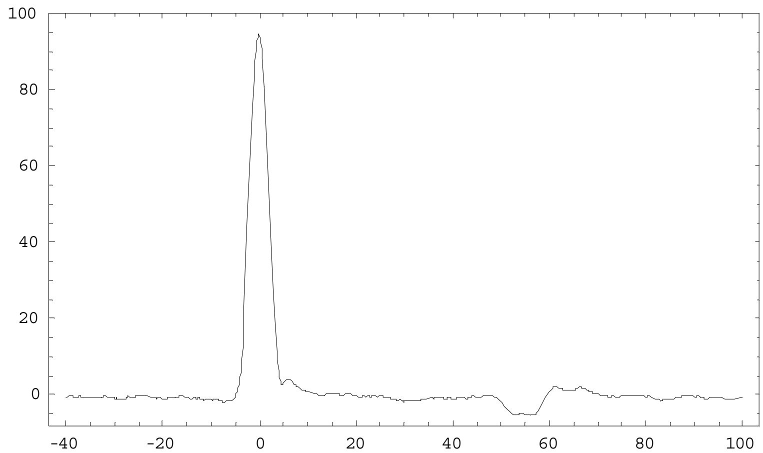
For the protons, t_o was determined to a small fraction of a nsec. This is exhibited by subtracting adjacent buckets and plotting the difference as shown below:



The vertical scale is in ns difference between bunches with the abort gap eliminated. The pbars are not quite so good, but still the maximum deviation is less than 0.1 ns. Next a continuous interpolation function was generated from the digital data, and using the value of t_o the curves were all superposed and added together and divided by 36 to give the following for protons: Figure 1

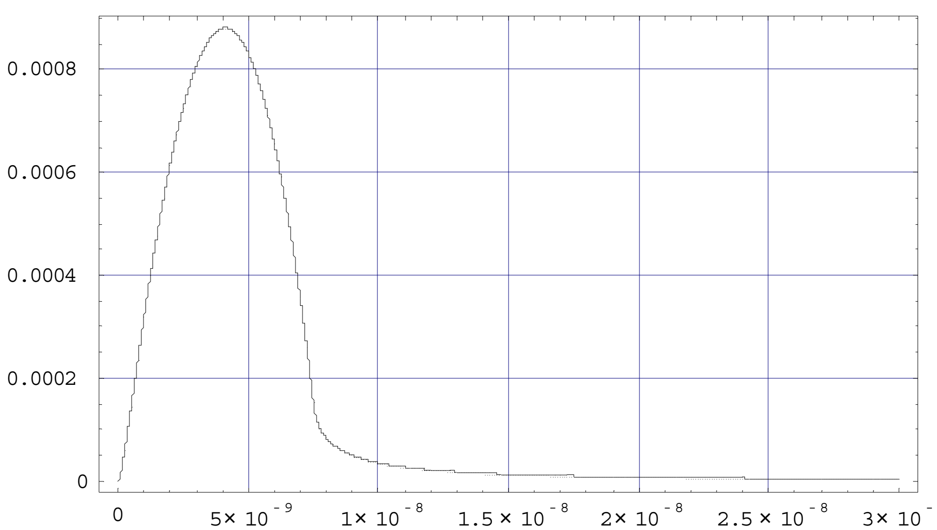


and pbars: Figure 2



The scale at the bottom is ns relative to the central pulse. A small satellite is seen in front of the protons and it integrates to 0.5% of the protons. The small tail on the pulses is due to some local reflections at the scope due to a tee used to connect to both inputs of the sampling scope (needs cleaning up!) and due to dispersion in the cable.

The question comes up what the dispersion in the cable does. The curve below shows what happens to a parabolic pulse 8 ns wide at the base when it travels up the heliax. The scale at the bottom is from 0 to 30 ns as measured from the front of the pulse.

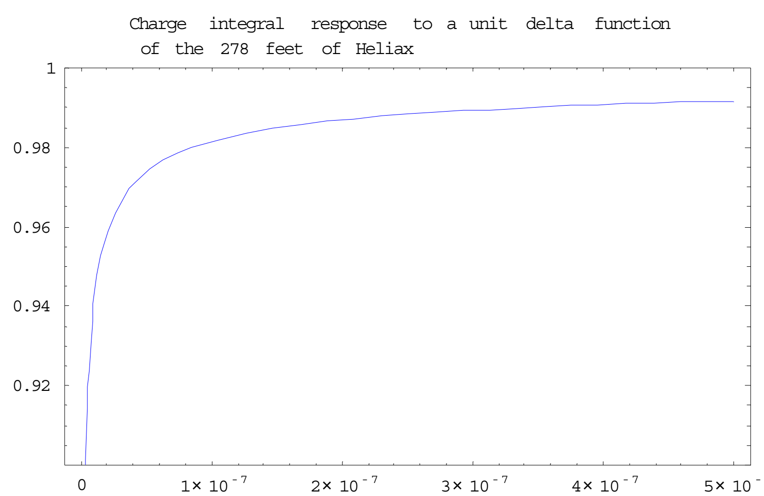


The long dispersive tail is clearly seen. There is an interesting observation here, in that the tail after about 20 ns is pretty independent of the shape of the pulse. In fact the integral of the charge in the tail of a delta function and a parabolic pulse of the same net charge are nearly the same. The table below shows the missing charge for a unit delta function of charge and a parabolic wave of total base width 8 nsec and unit charge when integrated from t equal zero to the value given in the left hand column. Note that t starts at the leading edge of the parabolic pulse, so the bucket edge is at 4 + 9.4 = 13.4 ns and the end of the next bucket is at 32.2 ns. The difference in the missing charge is only about .24%.

nsec	delta	Parabola
2	0.889348	0.13121
4	0.601996	0.0930442
6	0.285565	0.0760619
8	0.104938	0.0659214
10	0.0790267	0.058995
12	0.0672888	0.0538792
14	0.0597456	0.0499017
16	0.0543512	0.0466946
18	0.050223	0.0440376
20	0.0469336	0.0417894
22	0.0442119	0.039855
24	0.0419253	0.0381675
26	0.0399639	0.0366786
28	0.0382609	0.0353521
30	0.0367534	0.0341604
32	0.035419	0.0330822
34	0.0342184	0.0321006
36	0.0331306	0.0312019
38	0.0321459	0.0303751
40	0.0312404	0.0296111

The important point to be gleaned from this is that the ratio can be calculated for just one bucket and since the tail is proportional to the charge, it will cancel out in the ratio above. Thus by using this approach, the dispersive tail correction is avoided almost entirely.

. The curve below shows the tail for a delta function at t=0. The time is 500 ns total.



or in tabular form:

```
nsec     integrated charge
20       0.958398
60       0.975974
100      0.981388
140      0.98427
180      0.986127
220      0.987451
260      0.988457
300      0.989254
340      0.989906
380      0.990452
420      0.990918
```

SBD and FBI calibration

Integrating over the proton and pbar sum pulses that were described above and shown in Fig 1 and Fig2, we find following results (the units are not important, but there is a factor of 10 in scope gain between the protons and pbars):

Upper limit	9 ns	18 ns	27 ns	36 ns	45 ns	54 ns
Proton Area	467	474	474	470	467	465
Pbar area	454	462	464	458	457	443
Pbar/p	.0972	.0974	.0979	.0974	.0979	.0953

The integral went from -9 ns to the upper limit shown in the first line. The pulses are centered at zero. The pbar channel is not as clean of noise and reflections as is the proton.

We have applied the reasoning above to use only ratios and to truncate the integration at 18 ns which yields a ratio of pbar / p =0.0974. The measurement was made at 17:56 in the afternoon and the table below gives the various ACNET values as read at that time. The values listed for the WG and NG under the SBD column are derived using Eq. 1 above. The proton signal given by this equation correspond to the total number of protons in the machine, it is listed under WG. Careful analysis of the SBD indicates about 1% satellites, and so 1% is subtracted for the NG value. The pbars do not have visible satellites so the same value is used both places. The last column is the FBI value over the SBD reading.

CHANNEL	Reading	From SBD and ibeam	FBI / SBD
Ibeam	7.331 e12	7331 e9	
P NG	6378 e9	6613 e9	0.964
P WG	6519 e9	6680 e9	0.976
Pbar NG	675 e9	651 e9	1.037
Pbar WG	743 e9	651 e9	1.141

The correction to PWG is very close to the 3% found above by direct measurement. The PBARNG is high as is the PBARWG due to troubles in subtracting the base line.

Suggestions:

1. Eliminate the FBI in the long run. In the short run, give up on using it to detect DC beam (it can't) or satellites. The satellites are small enough now so that they aren't a problem, and in any case should be measured by the SBD. One should try the algorithm suggested above for managing the base line correction. If this device is really necessary, it should be re-configured so that only one integrator is used and the gains and timing are changed electronically. The problem of keeping 4 separate integrators tracking accurately enough to be useful is really difficult.
2. Commission the SBD. The cabling should be cleaned up and the reflections removed. The indications are that there are nasty reflections caused by the dual scope inputs and also there is a reflection from a mismatch at the 3-way splitter. One or more of the cables is not accurately 50 ohms by fraction of an ohm and there is some indication of a small reflection from the splitter.
3. The SBD should use only one channel of the scope and read out in 0.25 ns intervals. This will eliminate reflections that are bothering now and will increase the accuracy and help with the noise problem for the pbars. Noise can be reduced farther by combining results from multiple sweeps. Or alternatively, the scope gives a marker pulse that could be used to add up multiple sweeps and then processed as a single sweep.
4. The SBD should be used to give ratios of pbar / proton and then the program should calibrate automatically to IBEAM. A three bucket integration is probably all that is necessary. In this approach, the dispersive tail is not important. Satellite information could come out separately.

Finally, the intention of this note is not to give new calibration constants, but to illustrate some of the problems and possible solutions.