Calibration of the SBD using T:IBEAM as a reference

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This note describes the procedure used to calibrate the SBD using T:IBEAM as a reference. We give the calibration for Stores 2495, 2502, 2503, 2505 and 2507. The fluctuations between stores are a few tenths of a percent. There is also a measure of the DC beam accumulated at injection which seems to be 1-3 percent of the T:IBEAM. The calibration can be checked on line by comparing T:SBDTWG (the SBD sum of p and pbar) with T:IBEAM. Some information on the statistical noise is given. The statistical fluctuation of SBDPIS / AIS is measured to be about 0.3% and data is also given for SBDPWS / AWS.

Theory

The DCCT is the most accurate device we have for measuring the current in the Tevatron. However it does not measure separately the protons and pbars. However, the SBD is set up to do this job. In principle, it is an absolute device but in practice, it has errors due to the cable dispersion that must be corrected. We will develop a scheme for calibrating the SBD and this calibration can be compared to the calculated response.

The total current in the machine can be written as:

$$I = I_p + I_{\bar{p}} = I_p \left(1 + \frac{I_{\bar{p}}}{I_p}\right) = (K_{cal}\,\mathrm{SBDwg}) * \left(1 + \frac{I_{\bar{p}}}{I_p}\right) \tag{1}$$

In the end expression, the first term is meant to mean the output from the SBD wide gate. This gate encloses the bunch, and one RF bucket on either side. In general any satellites are confined to the adjacent buckets, but occasionally with bad coalescing, there is a slight indication of 5 buckets being active. K_{cal} is the calibration constant for the SBD. There is a separate one for the pbars since they are measured with a scope gain that is a factor of 10 higher. In what follows, we will assume that this is exactly 10. If this is off by a few percent, it will directly affect the pbar calibration by the same amount, but will have negligible effect on the proton calibration.

$$r = \frac{I_{\bar{p}}}{I_p}\text{, then} \qquad K_{\mathrm{cal}} = \frac{I}{(1+r) * \mathrm{SBDwg}} \tag{2}$$

We now observe that r can be measured using the SBD. We use the wide gate in order to contain the satellites. In eq.2 we assume we know I from T:IBEAM which measures the sum of the proton and pbar currents. However there is a catch in that it also measures any DC current circulating in the machine but the equations (1) and (2) only apply to bunched beam which the SBD measures.

DC beam

DC current can be generated at injection if some of the injected protons miss the bucket. If they are outside the bucket, they will drift around the machine indefinitely as there is no energy loss mechanism to sweep them out. At 980 GeV/c there is synchrotron radiation that abstracts 9.5 eV/turn, but at 150 GeV/c the synchrotron radiation is essentially zero. However, when acceleration takes place particles not in the bucket will be swept out very rapidly. Their change in radius is given by:

$$\Delta \mathrm{R} = \mathrm{D}\ \frac{\delta \mathrm{p}}{p} \tag{3}$$

Since the dispersion D is several meters, the first one percent change in the field will sweep out any DC beam. Thus if we calibrate the SBD just after acceleration finishes, the effect of DC beam is minimized. We will show later that DC beam at injection is generally less than 2%. At 980 GeV/c things are more complicated. Particles do diffuse out of the bucket and circulate around the ring. This effect increases with time and near the end of store proton losses from the bucket of 2-4 E6 protons per second are measured. Depending on how the scrapers and TEL are set these protons will circulate in the machine for 2000 seconds or more creating a stored current of several E9. Thus one can expect discrepancies between T:IBEAM and the SBD at this level.

Satellites

Coalescing can cause some of the particles to appear in adjacent bunches and this is measured by comparing T:SBDPIS (a single bucket gate) with T:SBDWID (three buckets) for the protons and T:SBDAIS with T:SBDBWI for the antiprotons. One can see from the above formulas that since the pbar current is only about 1/10 of the proton current errors in the latter will not induce big errors in the K_{cal}. However, this is not true for the protons and the calibration depends directly on T:SBDWID. One could ask why not make the wide gate cover more than three buckets? The answer is that one has to be careful about the base line correction noise.

Baseline correction

One unfortunate characteristic of the SBD is that it is basically a transformer coupling to the beam with a relaxation time constant of about 50 μsec. Thus to get the area of each p and pbar bunch, a base line must be subtracted. (In addition, the base line has been offset by about 86 counts in order to make use of the full range of the scope digitizer.) Bob Flora has instituted a rather nice method for doing this. A histogram of the full turn output sampled in 1/2 ns intervals (42000 samples) is constructed. Since most of the samples are of the baseline only, the peak of this distribution gives a good value for the correction. A histogram for the protons in store 2424 is shown in Figure 1.

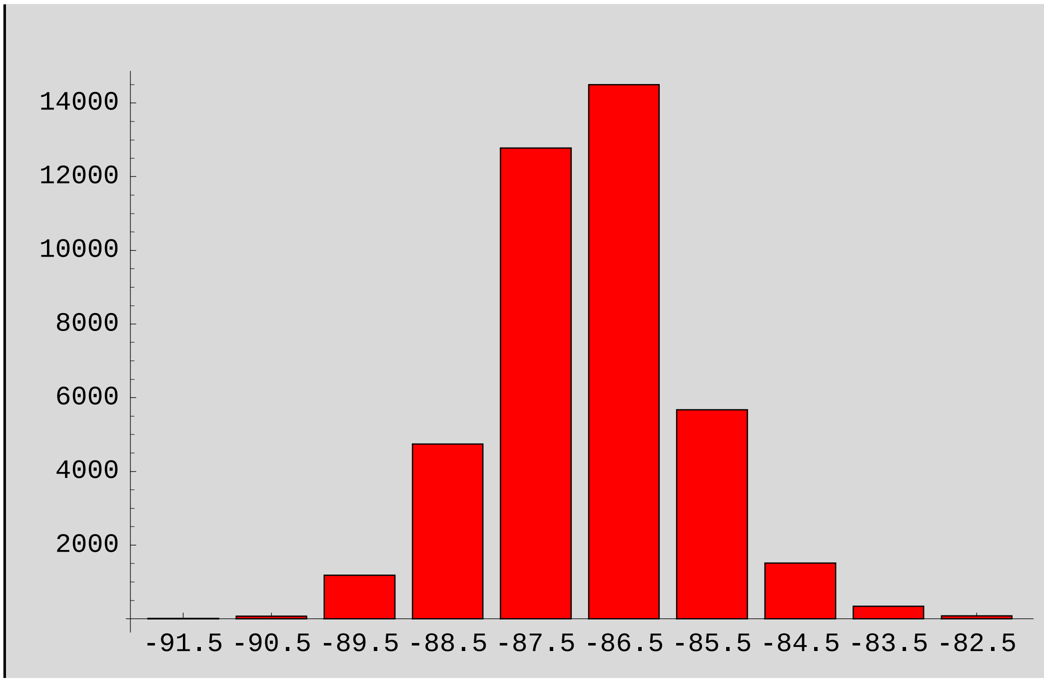

Figure 1. baseline histogram for the protons in Store 2424. The calculated base line is 86.39.

The pbar histogram is not as nice. The gain is 10 times greater and the proton pulses saturate the scope amplifier causing a small shift in the base. There are a number of sources of small pulses which blend with the base and cause a systematic tail to the distribution on the upward side. This can be seen in the following figure.

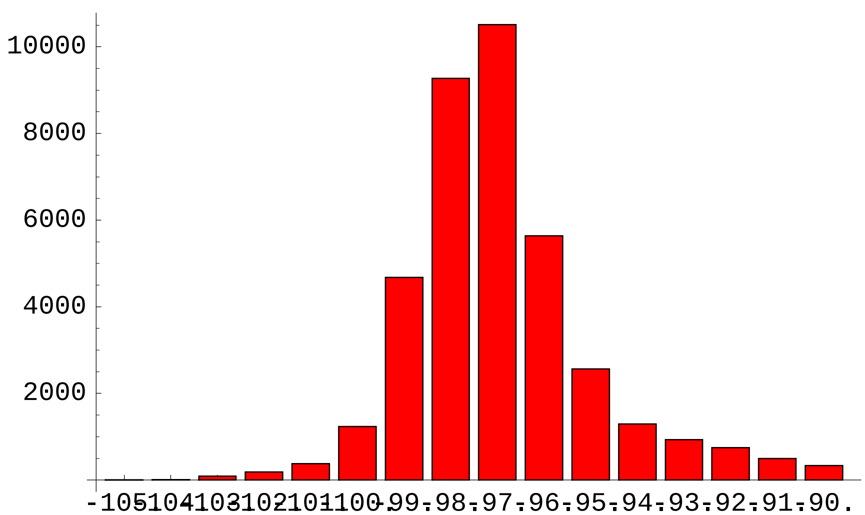

Figure 1

Fig 2. Histogram of the pbar channel showing the tail on the high side. Store 2424.

The sbd program selects the three highest channels, fits a parabola and chooses the peak as the baseline correction. The square root of the variance of the proton baseline is 1.03 counts = 0.187 e 9 protons and that for the bar baseline is 1.0 counts =0.0182 e 9 bars. These numbers were measured with no particles in the machine and represent the noise in the digitizer. These numbers will be used to estimate the SBD accuracy.

Dispersion in cable

Dispersion in the cable causes a tail on the proton pulses which reduces the height in the correct bucket and spills out about 5% of the total charge over a time period of almost a micro second. Equation (4) gives the integrated charge as time from a delta function input. The cable from the Deviatory up to the scope is 278 ft of 7/8" heliax with a net attenuation at 1000 MHz of 3.67db, 4 ft 1/2" line with 0.09db, and 22 ns of 1/4" that adds another 1.43db for a total of 5.19db .

```
Cable[t_] := 1 - Erf[bl / Sqrt[2 * t]]
bl = 1.45 10^-6 * dbl
dbl = the total attenuation in the cable at 1 GHz.
```
(4)

The following graph shows a plot for the Tevatron SBD

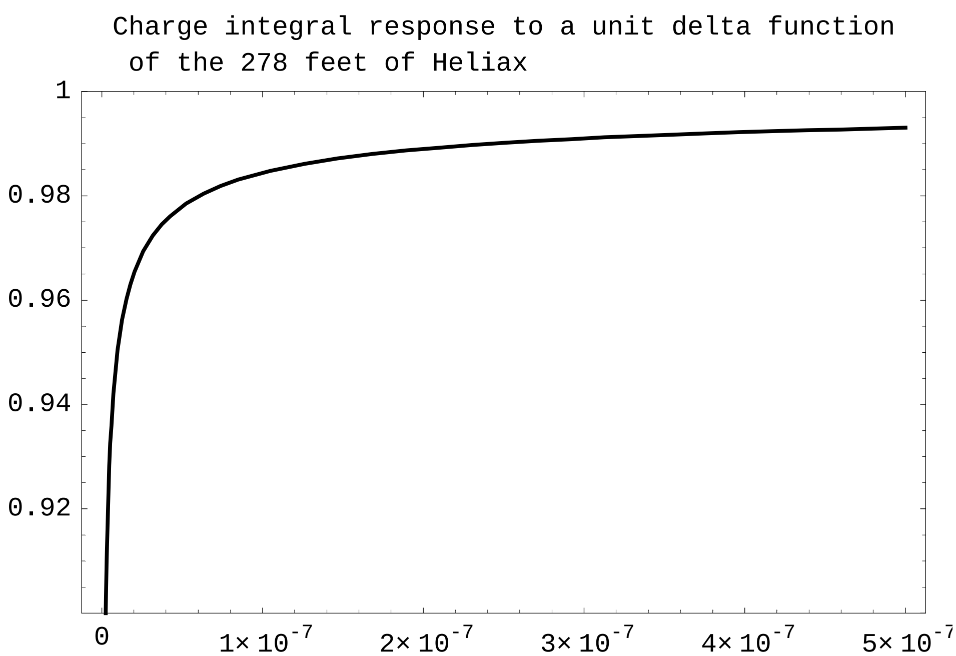

Figure 4. The integrated charge from a delta function at t=0.

There are two bad effects. The first is that charge leaks out of the bin which affects the calibration and the second is that some charge appears in the following bins which interferes with measuring the satellites. Fortunately, one can deconvolve the effect of the cable.

FIR Filter

We generate the FIR filter as follows. Eg. (4) gives the integrated delta function response. Next generate the convolution function that takes a signal to the dispersed form. Since the data is in 0.5 ns bins, we generate a convolution function in 0.5 ns bins.

```
res = Table[{(2 * n - 1) / 2 * deltaT, Cable[n * deltaT] -
    Cable[(n - 1 + .00001) * deltaT]}, {n, 1, N0}]
```
(5)

A plot of this series is in the next figure.

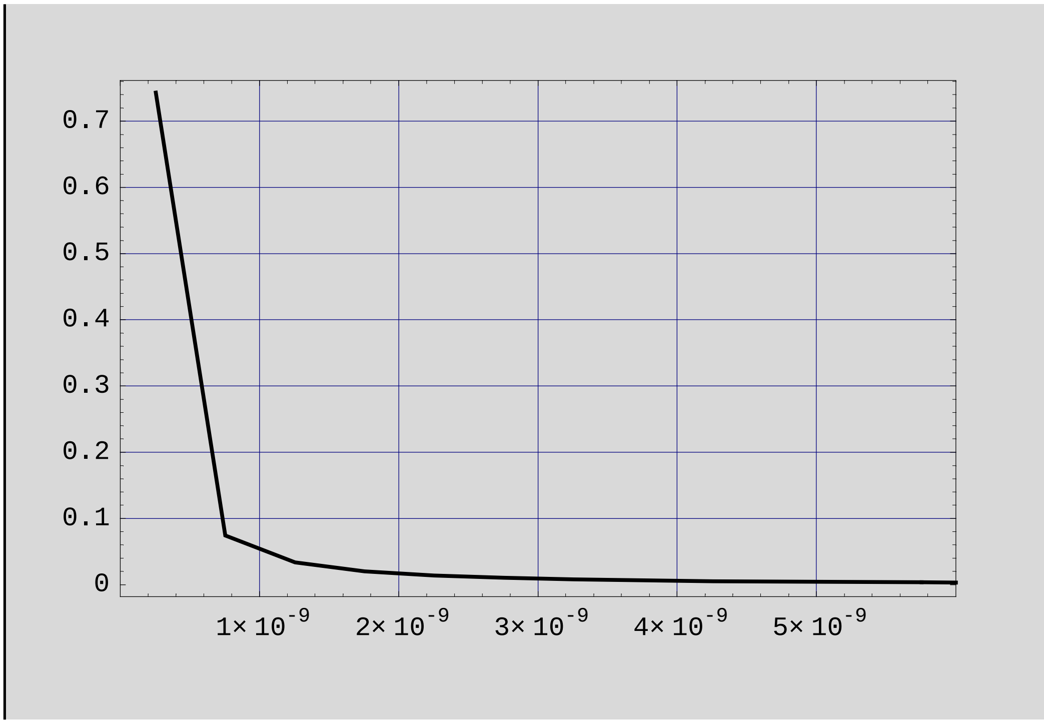

Fig 5. Response function in 0.5 ns bins.

This is a series of pairs of numbers. The first is the time and the second is the response. The convolution of this function with a waveshape generates the dispersed wave shape. However, the problem we have is the reverse: we have the dispersed form and want the undistorted form. The convolution can be written in matrix form. Let v[t] be the input and vout[t] be the dispersed form, both vectors at 0.5 ns intervals. The convolution can be written:

$$\text{vout} = M.v \qquad v = M^{-1}.\text{vout} \tag{6}$$

Where the matrix M is just the shifted response function, res above. The first few lines look like:

$$\begin{pmatrix} 0.782361 & 0 & 0 & 0 & 0 \\ 0.0627697 & 0.782361 & 0 & 0 & 0 \\ 0.0281513 & 0.0627697 & 0.782361 & 0 & 0 \\ 0.0168606 & 0.0281513 & 0.0627697 & 0.782361 & 0 \\ 0.0115353 & 0.0168606 & 0.0281513 & 0.0627697 & 0.782361 \end{pmatrix}$$

This is a triangular matrix and inverts very easily. The inverted matrix then allows us to calculate the vector v from vout. M^{-1} looks like:

$$\begin{pmatrix} 1.27818 & 0. & 0. & 0. & 0. \\ -0.10255 & 1.27818 & 0. & 0. & 0. \\ -0.0377645 & -0.10255 & 1.27818 & 0. & 0. \\ -0.0208261 & -0.0377645 & -0.10255 & 1.27818 & 0. \\ -0.013606 & -0.0208261 & -0.0377645 & -0.10255 & 1.27818 \end{pmatrix}$$

Both of these matrices have been given for only 5 terms for convenience of display. However, the SBD program uses a filter that covers 77 bins or 38.5 ns. The FIR filter is just the last line of this matrix.

An example of how well the effects of the cable can be removed by this technique is shown in the following figures.

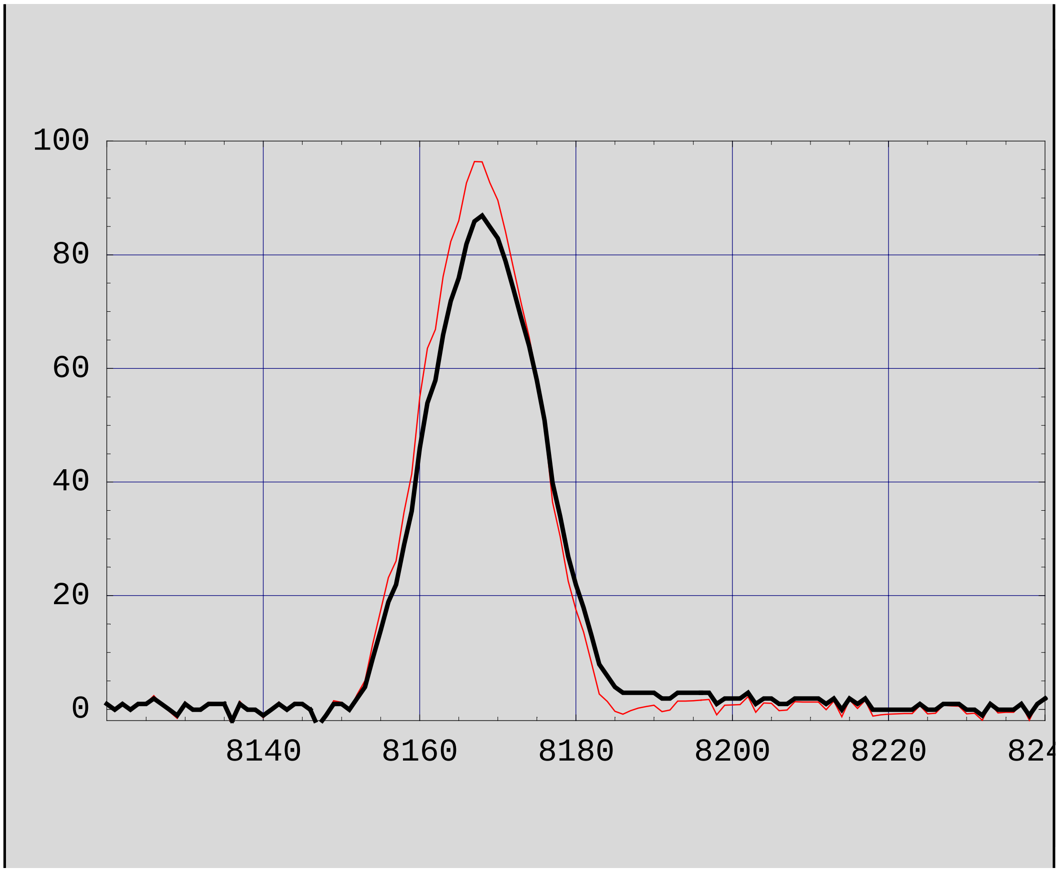

Figure 6. The black curve is raw data from the SBD for a proton pulse at 150 GeV/c. the red curve shows the corrected curve. The FIR filter corrects for the tail that the cable causes. The time scale is in units of 0.5 ns.

The area within the rf bucket (18.8 ns) is increased because some of the charge that is in the tail is pulled back into the pulse. The decrease in the tail has increased the sensitivity to trailing satellite pulses (narrow gate vs wide gate response) and has made the calculation of the rms mean more accurate as this calculation is very sensitive to pulse tails.

Timing

The timing of the individual proton and pbar pulses is determined by fitting the following curve to the individual pulses:

$$V[x] = C0 + C1\ x + C2\ e^{C3\,(x-x0)^2} \tag{7}$$

The width of the gaussian is put out as SBDPSS, but an investigation of this fit shows that it is not very good. However, it is a very good way to find the position. The following figure shows the difference in nano seconds between the positions found for the protons at 150 GeV/c and the same bunches at 980 GeV/c. The horizontal scale is bunch number. The systematic difference is just the 0.4 ns predicted from the difference in velocity at the two energies.

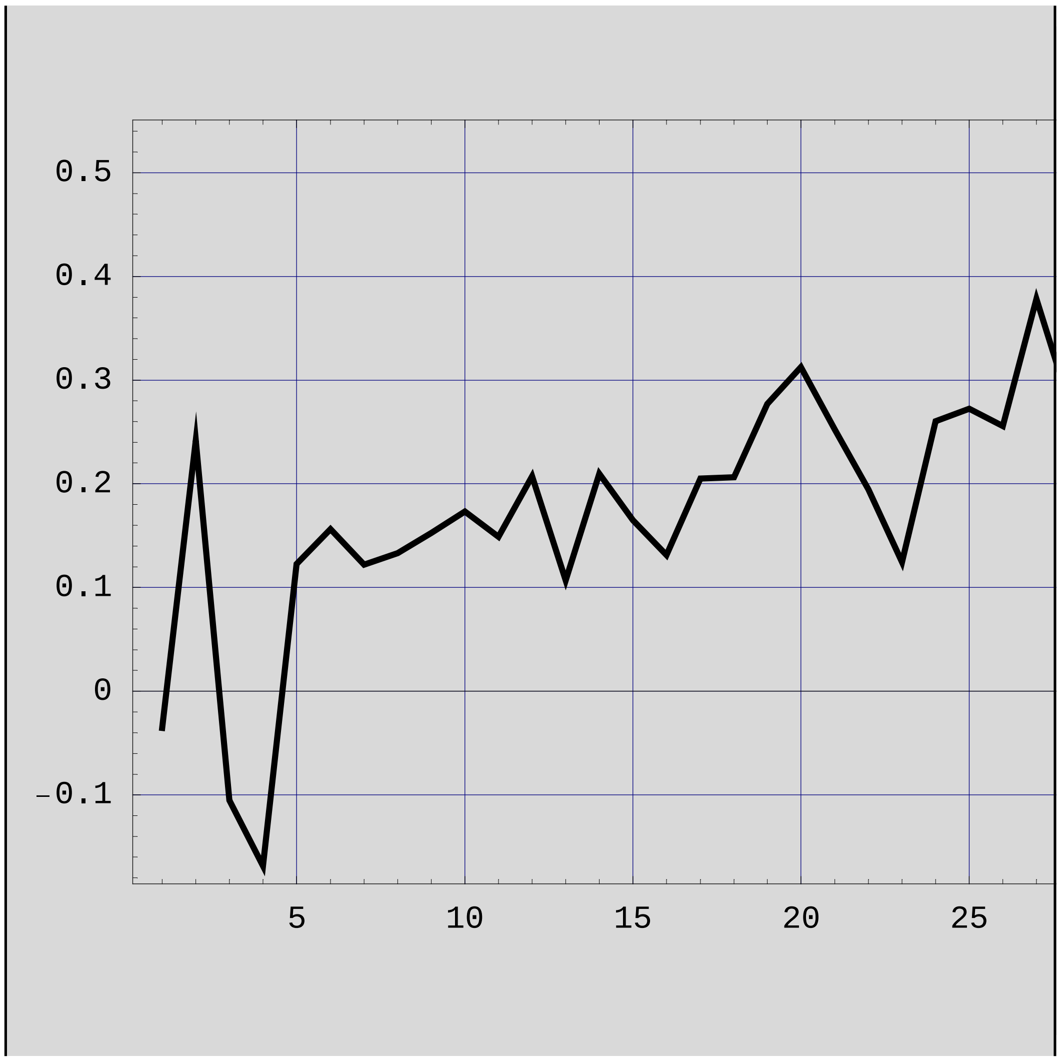

Figure 7. This figure shows the (t(n) - t(1) $)_{150}$ - (t(n) - t(1) $)_{980}$ vs bunch number. The 0.4 ns difference is just what is expected from the difference in velocity at 150 GeV/c and 980 GeV/c.

The rms error is around 50 ps. This very accurate determination of the time allows us to superimpose the bunches by the following technique. First a 3rd order interpolation function is constructed so that instead of the output being discrete points at 0.5 ns intervals, we have a continuous function of time. Since the time of each bunch is known (from the gaussian fit mentioned above), this function can be cut into pieces and superimposed. The result gives an ensemble of protons that represents the overall behavior of the whole set of bunches. The following figure show the result of this procedure for run 2667 for the protons at 150 GeV/c. The sum has been divided by 36 to give an "average" pulse.

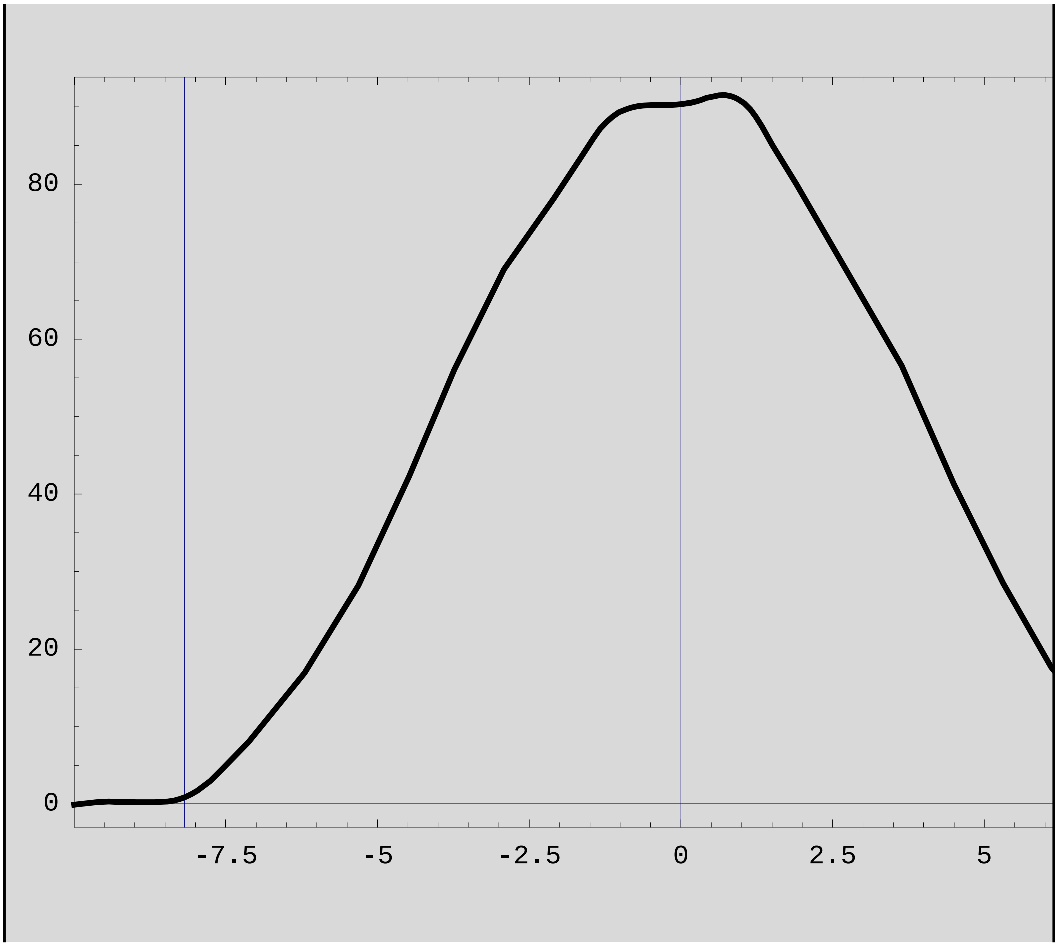

Figure 8. The superposition of all 36 proton bunches at injection for run 2667. The vertical lines represent the phase space edges of the phase that can be successfully accelerated to 980 GeV/c. The bucket edges are at +/- 9.53 ns.

The fact that the bucket is a little "bumpy" is due to the fact that the individual bunches are "dancing". However this is an excellent approximation to the ensemble of protons that must be accelerated. To see how well the dispersion and base line correction are working, we can fold the pulse about its center and compare the front and back halves. The next figure shows an expanded view of these curves. (A larger scale view of the pbars treated the same way follows.)

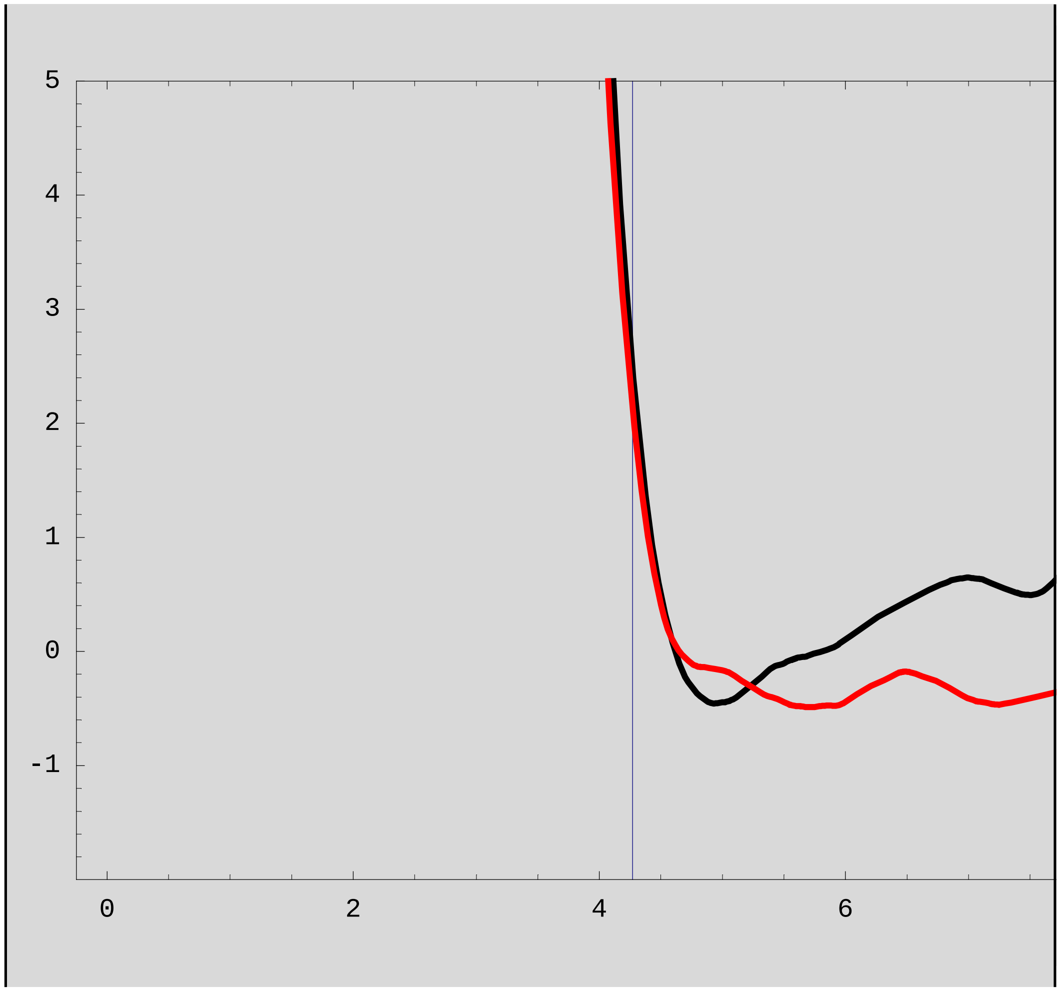

Figure 9. An expanded view of the folded protons at 980 GeV/c for store 2667. The vertical line is the edge of the space that can successfully be accelerated from 150 GeV/c to 980 GeV/c with no growth of emittance. A small expansion of the bunch during acceleration can be seen. The fact that the front and back edges match so well indicates that the cable dispersion is being handled correctly. The noise on the base line can also be seen. The horizontal scale is nano seconds

A similar plot for the pbars at injection is shown in figure 10.

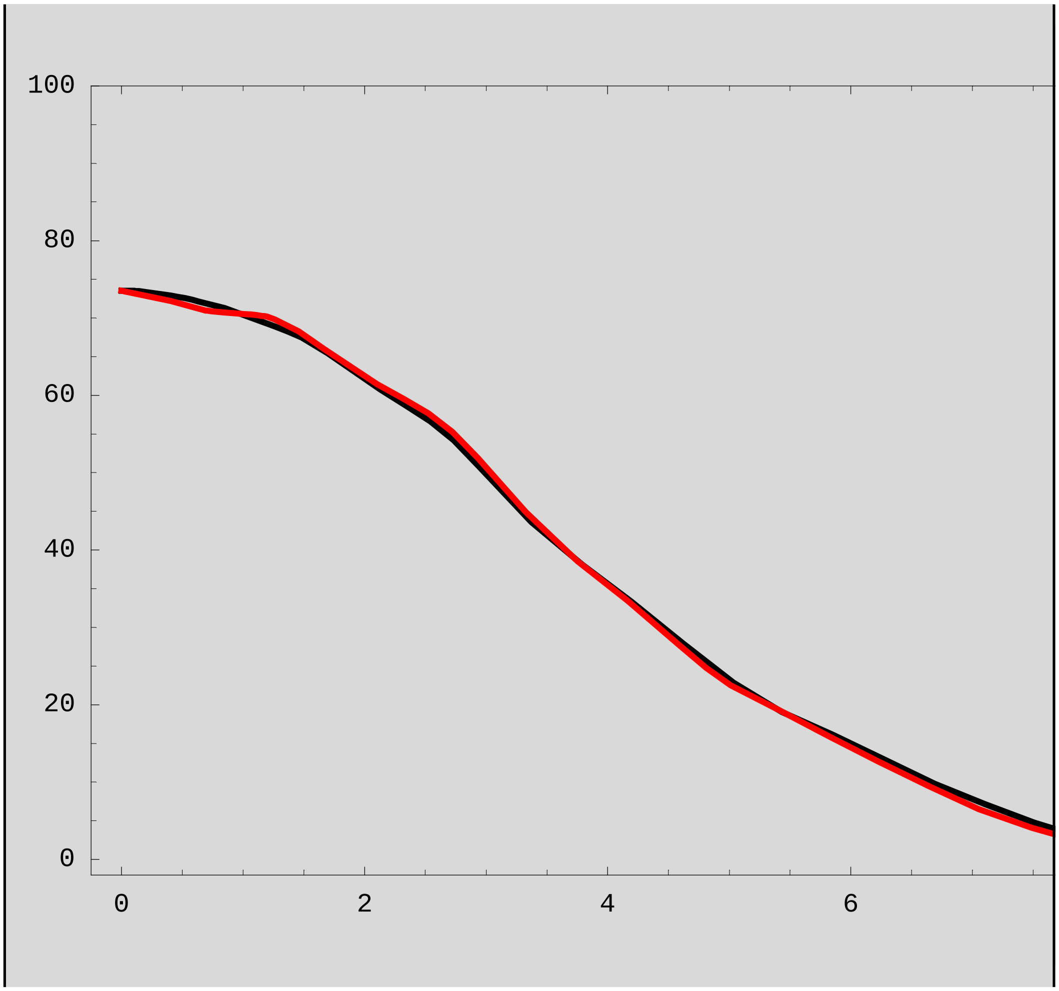

Figure 10. A similar plot to Figure 9 for pbars at injection for run 2667.

■ SBD stability

The calibration of the SBD has been followed over about 20 stores. The calibration constant is plotted in Figure 11.

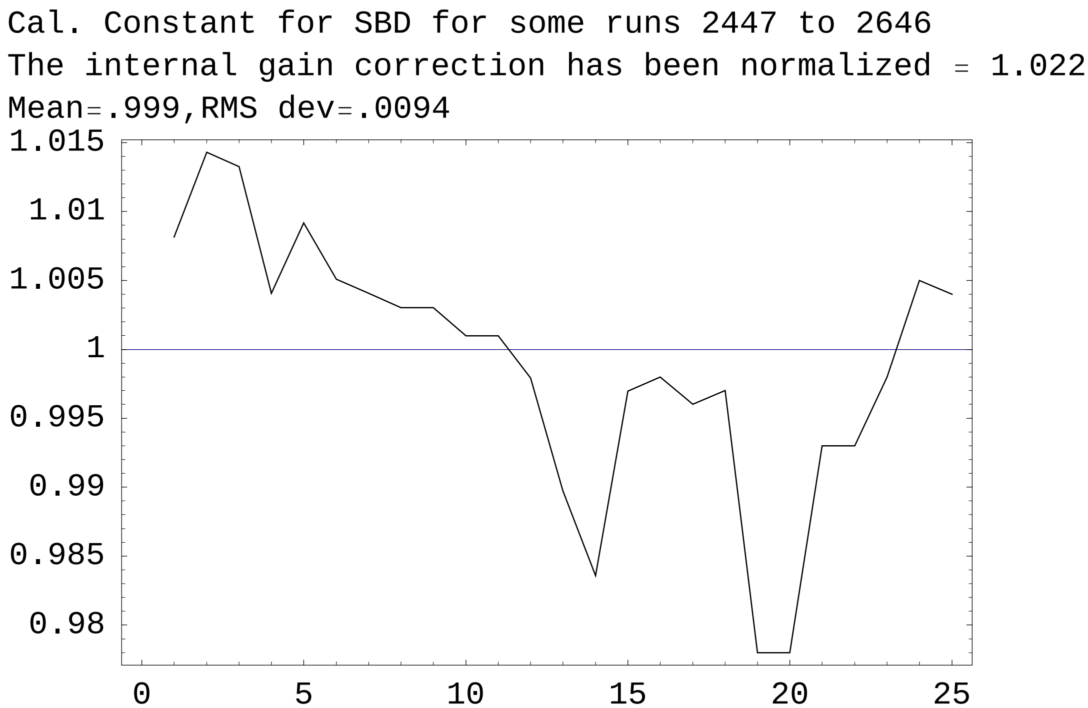

Figure 11. The variation of the calibration constant between Stores 2447 and 2646. During this period there were changes to the internal SBD gain. These variations have been renormalized to 1.022 in order to see the variations due to external causes.

In addition to the variations shown above, there are systematic variations during a store that are still not understood. The most conspicuous is that the wide gate number can drift down during a store and become very slightly smaller than the narrow gate result. It is thought that this is the result of internal calculations in the SBD program due to switching between integer and floating point arithmetic. It will be fixed and at present is in the few tenths of a percent range.

Online check of calibration

There is an easy way to check the calibration of the SBD. A signal T:SBDTWG has been generated that is the sum of the proton and pbar wide gate signals. If there is no dc beam in the machine, this signal should just equal T:IBEAM. A plot is shown below.

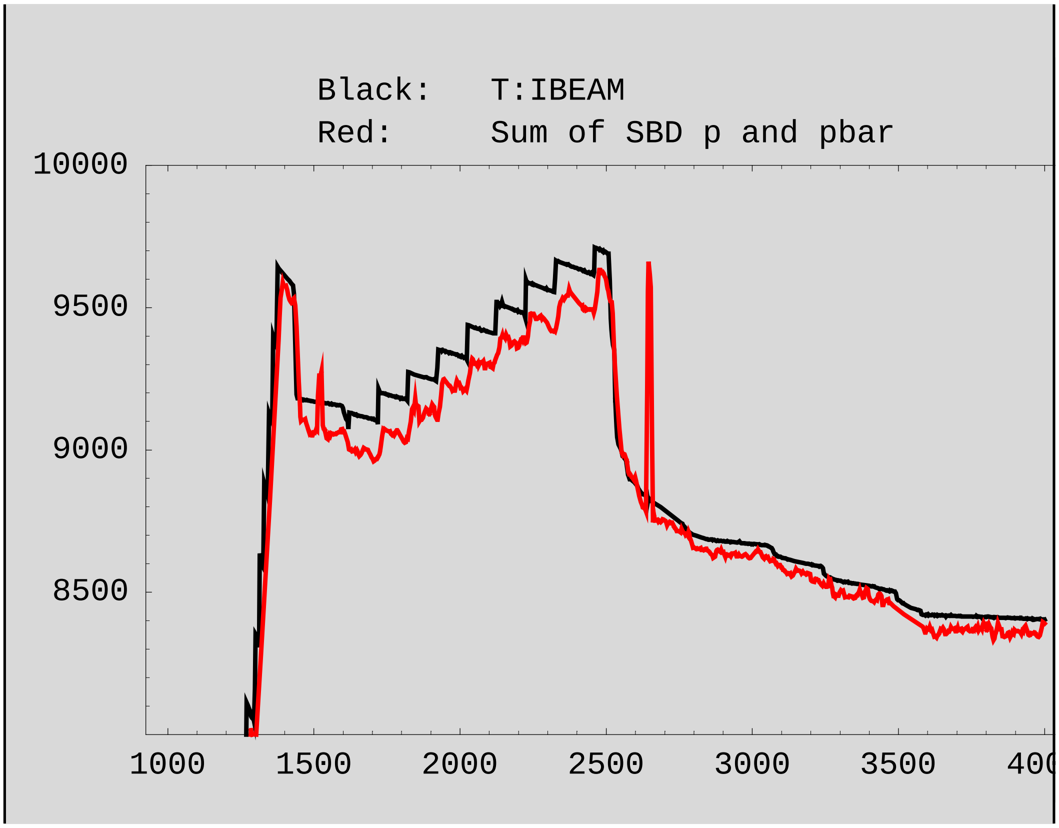

Figure 12. The black curve is T:IBEAM and the red is T:SBDTWG during pbar injection. The match is good thru proton injection but differs during pbar injection. This difference goes away as soon as acceleration takes place which cleans out the dc beam and the two curves come together.

That the difference during pbar injection is not caused by a pulse width dependence has been carefully investigated. Detailed examination during the first GeV/c of acceleration shows the curves coming together before any narrowing of the pulse occurs. The difference varies with stores and sometimes is not there. It is assumed that this difference is a direct measure of the dc beam.

The matching of the two variables during HEP is a good test of the calibration being correct.

■ Some information on the noise.

There is noise on the base line of the SBD. The no-signal output for both protons and pbars has been studied and it is found that the rms noise on both channels is 1.0 counts. In addition to this noise, there is apparently some additional noise source that has a period of a few microseconds. Thus it is observed that if we take a 1000 bin average (500 ns) we get the 1.0 count rms value mentioned above. However if one takes an ensemble formed from the sums of 40 adjacent bins over the whole 42,000 bins in a sweep when no beam is present, one gets an rms noise of 10.4 counts instead of $\sqrt{40}$ x 1.0 = 6.3 counts. Thus there seems to be additional noise that is present during store conditions that is not there during quiescence conditions. There is also a low frequency component that the base line subtraction removes completely.

To investigate this in an empirical way, we take run 2646 and slice out a section about 1000 seconds long after the run has stabilized. A linear fit is made to the decaying proton and pbar currents, and the fluctuations around this fit are calculated. The results are:

sbdpis	0.33%
sbdwid	0.34%
sbdais	0.33%

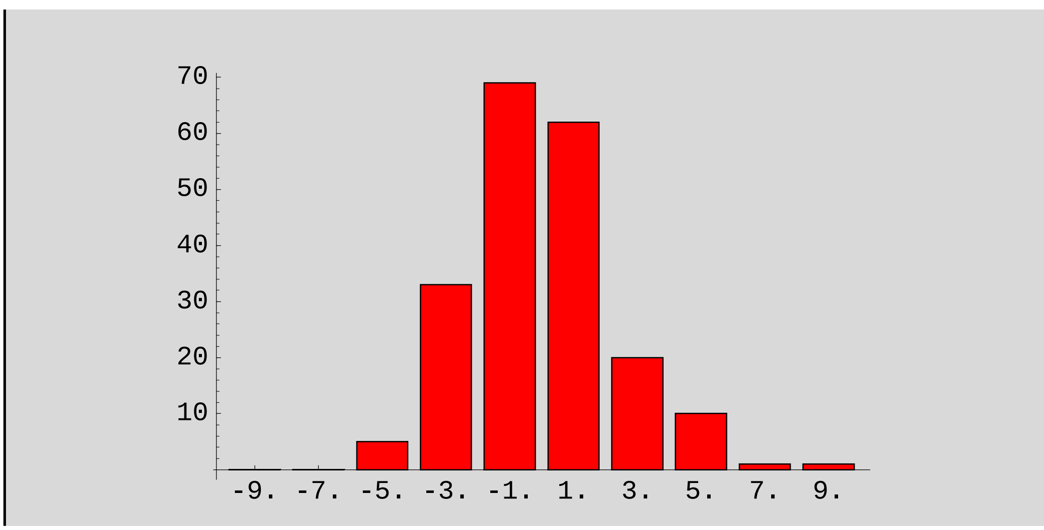

Figure 13. Histogram of sbdais minus a linear fit to account for the decay. The horizontal axis is in units of 10^9 and the beam intensity was 710 e 9. The sigma is 0.33 %.

To compare this with the base line noise measured with no signal, we use the calibration of the SBD which is about 29 e9 protons per volt ns. The proton channel is set to 12.5 mV/count and the bins are 0.5 ns long giving about 0.18 e9 per count. Using the rms for a 38 bin sum of 10.4 counts given above for the baseline noise, we calculate:

$$\text{rms sbdpis} = 10.4 \sqrt{36}\ 0.18\ 10^{9} = 11.2 \text{ e } 9$$

This is about half the 0.33% number measured above for store 2646. A similar discrepancy is noted in the difference between the SBDPIS and SBDWID. Because the wide gate value is a running average over 8 closely spaced successive sweeps, it should have a factor of $\sqrt{3}$ more noise because it includes three rf buckets rather than one but a factor of 1 / $\sqrt{8}$ less noise because of the running average making it an overall factor of 0.6 narrower than SBDPIS. The source of this noise is not known at present.

Finally, the above analysis was repeated for a single proton and a single pbar bunch in store 2718. The results were:

Single bunch sbdpis[10] rms = 0.8 %
Single bunch sbdais[10] rms = 0.73 %

A more complete analysis was made later for Stores 2740 and 2768. The agreement was within the accuracy expected and the results for 2740 are shown below:

SBD Variable	Calc Variance	Sqrt Variamce	Value Store 2740	% in Store 2740
PIS	6.7e9	13.98e9	6650e9	0.21%
AIS	0.67e9	2.23e9	630e9	0.35%
PIS5	1.12e9	2.00e9	184e9	1.08%
AIS5	0.112e9	0.212e9	15.0e9	1.41%
PWS		0.015 ns	2.12 ns	0.74%
AWS		0.030 ns	1.80 ns	1.7%
PWS5	0.062 ns	0.081 ns	2.12 ns	3.9%
AWS5	0.089 ns	0.137 ns	1.80 ns	7.6%

The calculated variance is based on the single channel noise mentioned above and its square root is shown in the second column. The actual square root variance was measured by fitting a second order polynomial to a 15000 second section of the individual variables in the middle of the store and the fluctuations around this smooth curve analyzed. The variables labeled with a "5" are for the fith bunch in the SBD display. The last column gives the percentage accuracy for this store, but note that for the intensity, the noise is a fixed value so the percentage decreases with signal size. The widths get worse the smaller the signal and the smaller the absolute width. (Note: The baseline noise does not change the average widths measured!)
The accuracy of the intensities in the table above are probably sufficient. The bunch weighted average of the widths, PWS and AWS are marginally ok. However the single bunch widths are too noisy and we need to improve them. The best way to do this is the measure multiple sweeps and employ averaging to gain in the S/N. It is not understood at this point why the measured and calculated variances disagree.

Acknowledgements

Help in obtaining the data and understanding it has come from Stephen Pordes, Jim Crisp, and Brian Fellenz. Also, it should be noted that Stephen was very helpful in getting the spelling corrected....any mistakes still present are AVT's fault.

References

Two references are useful but not complete:

1. J. Crisp and B. Fellenz, Fermilab TM 2208 describes the SBD and includes measurements of the cable dispersion.
2. W. Blokland, J. Crisp, B. Fellenz, R. Flora, A. Hahn, T. S. Meyer, S. Pordes, A. Tollestrup Fermilab Conf-03-146-E