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First Look at Injection Turn by Turn

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Abstract

This document shows a first look at injection turn by turn measurements made using the upgraded Tevatron BPM system. There are some outliers in the data but there are strong features which roughly correspond to my expectations for the synchrotron and betatron lines. This work is still preliminary and the Echotek TBT configuration has yet to be fully certified on the bench. There are probably some artifacts in the frequency spectra which are introduced by the method used to fix the outliers in the data.

1 The Data

The data shown here are from the first 8192 turns following the start of proton injection at 04:13:51 AM January 25, 2005, the start of a long HEP store. The data were taken on BPMs HA32 and VA33. They were read out by Luciano, who e-mailed them to me. Only the proton data will be presented here. The BPM electronics were configured to make 8192 consecutive single turn measurements, triggered by a signal that injection is imminent.

The sum and position information were computed on the front end. The position is given by,

$$P = 26\frac{|A| - |B|}{|A| + |B|} \tag{1}$$

where $A = (I_A, Q_A)$ and $B = (I_B, Q_B)$ The sum is given by $|A| + |B|$.

The red points in Figure 1 show the proton sum signal for the first few turns. The vertical scale for these points is on the right hand side of the plot. Each point corresponds to a measurement for one turn of the Tevatron. The upper plot shows information for BPM VA33 while the lower plot shows information for BPM HA32. The beam first arrives on turn 16. The blue data points show the proton position and the vertical scale for these points is on the left side of the plot

The gross features of this data are: the arrival of the beam at point 16; the sawtooth in the sum signal; the outliers in the position signal. At present the last two features are not understood. The pattern continues for all 8192 data points, modulated by beam motion.

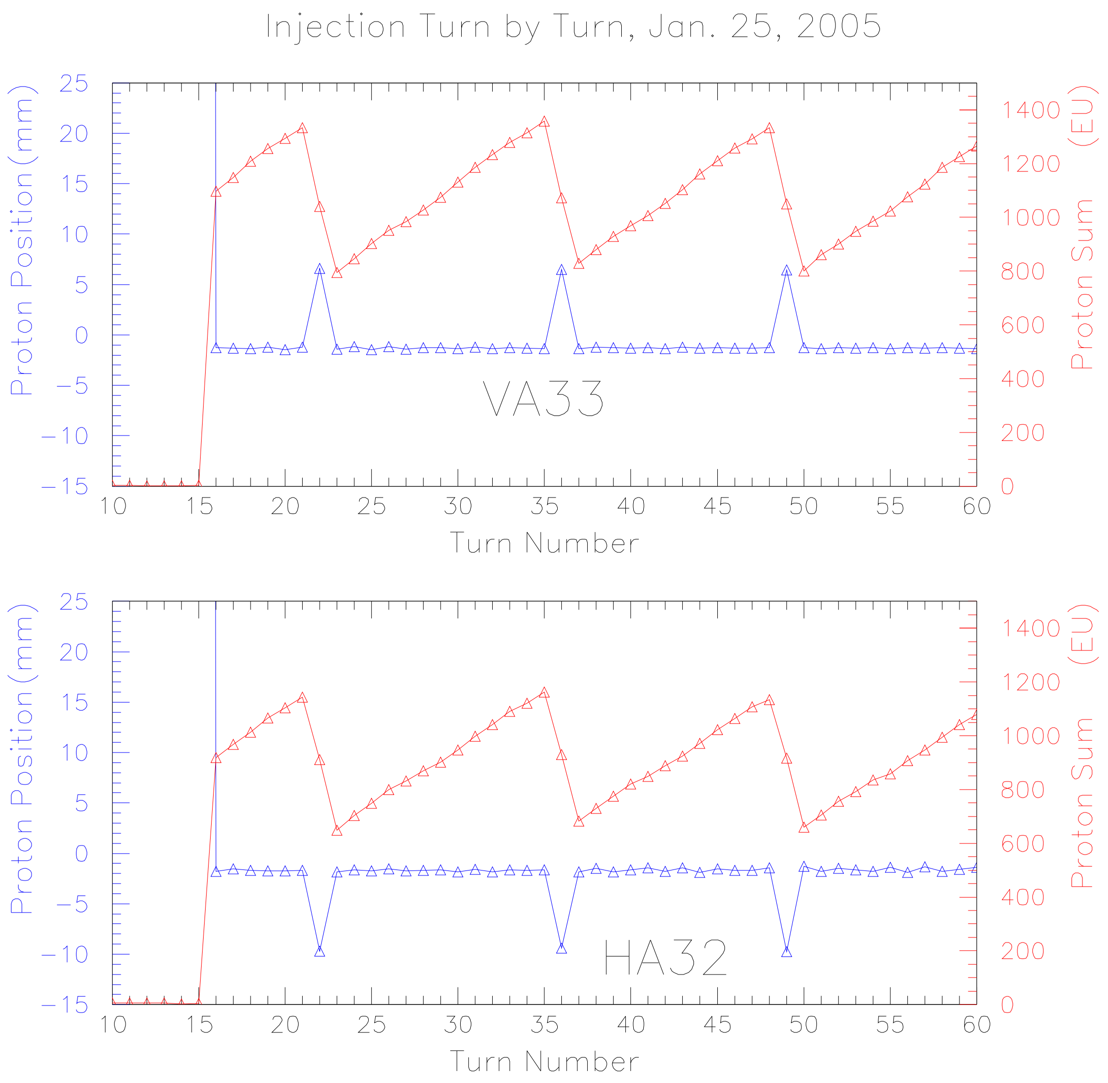

Figure 1: The red points show the measured proton sum signal at VA33 and HA32 as a function of turn number for the first few turns of the shot at 04:13:51 AM, Jan. 25, 2005. The beam arrives at turn number 16. The blue points show the measured proton positions for the same turns. The features of the data are discussed in the text.

2 Fixing the Outliers

In order to measure the frequency content of these data, the outliers were fixed by replacing them with the mean of their neighbors. I have not yet checked to see what sort of artifacts this will produce — but at low frequencies there should be few artifacts. Figure 2 shows the fixed beam positions as a function of turn number. In this figure, the data points before the beam arrived were dropped, leaving 8177 points.

3 Fourier Transforms

In order to look at the frequency content of the position data, the following transform was computed,

$$FT(f) = \sum_{n=0}^{N-1} (P_n - \bar{P}) e^{iwt_n} \tag{2}$$

where the sum runs over the N turns with beam present (8177), f is the frequency at which the transform is evaluated, $w = 2\pi f$, P_n is the measured position for the n^{th} turn, $t_n = nT_{\rm rot}$ is the time at the start of the n^{th} turn, $T_{\rm rot}$ is the rotational period of the Tevatron, and where $\bar{P}$ is the mean position, averaged over the N turns with beam present.

In the above transform, the purpose of subtracting $\bar{P}$ is to remove the alias of the digitizing frequency which appears at 0 Hz and would dominate the transform. Also, care has not been taken with the normalization, so the transform is expressed in arbitrary units.

In this analysis I used a nominal RF frequency,

$$f_{RF} = 53.104 \text{ MHz} \tag{3}$$

This value is not quite correct but the conclusions should stand when the correct value is used. From this I derived, a Tevatron rotational frequency of

$$f_{\rm rot} = f_{RF}/1113 = 47.712 \text{ kHz}, \tag{4}$$

and a Tevatron rotational period of,

$$T_{\rm rot} = 1/f_{RF} = 20.9589\ \mu\text{s}. \tag{5}$$

Figure 3 shows histograms of $|FT(f)|$ for VA33 and HA32 data; the transform for each bin was evaluated using the center frequency of the bin. Each transform was computed in N bins between 0 and half of the Tevatron rotational frequency. Therefore the width of a frequency bin is

$$\delta f = \frac{f_{\rm rot}}{2}\frac{1}{N} = 2.917 \text{ Hz} \tag{6}$$

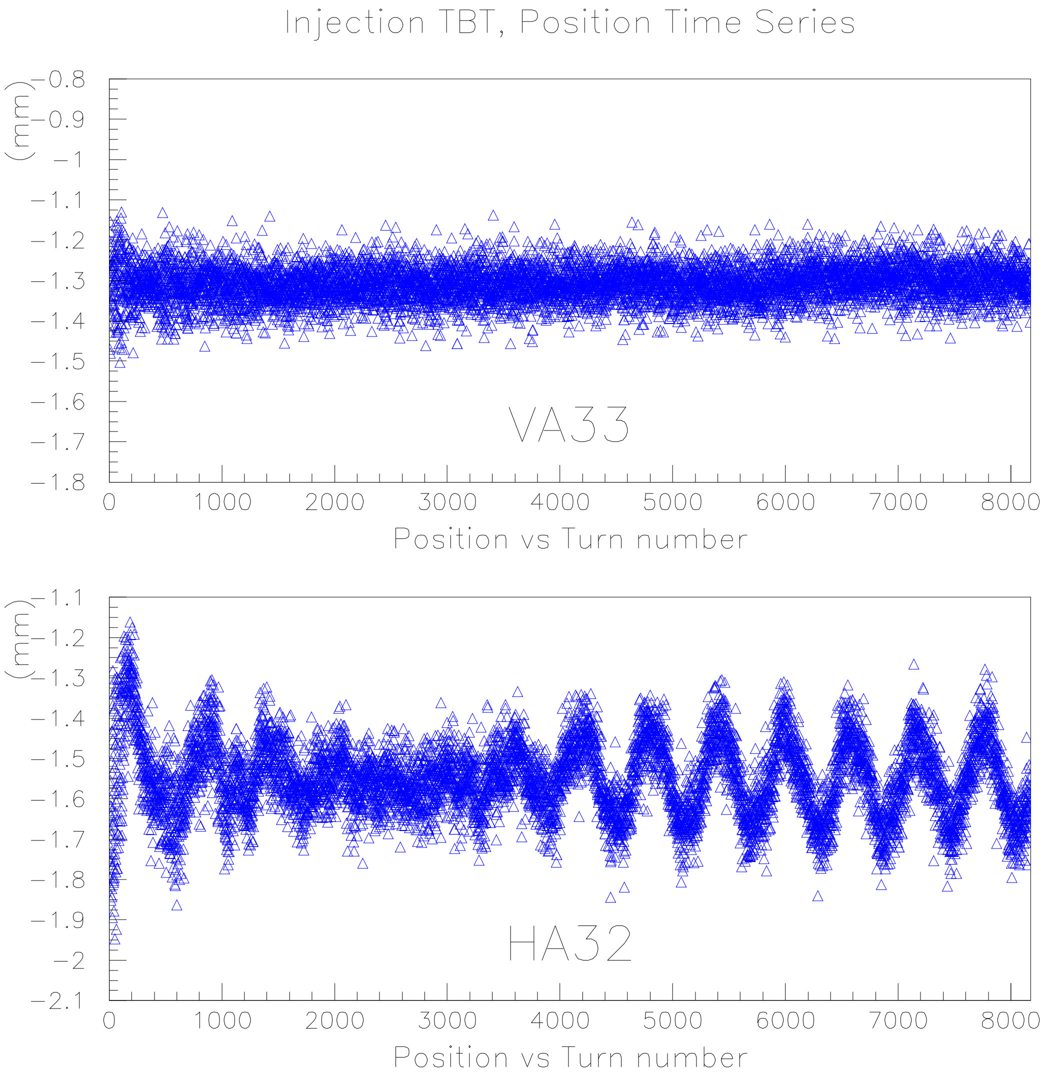

Figure 2: Measured proton positions at VA33 and HA32 as a function of turn number for the full 8177 turns. This plot was made after the outliers were repaired, as described in the text. On both plots the full vertical scale is 1 mm. Clear oscillations can be seen in the data for HA32.

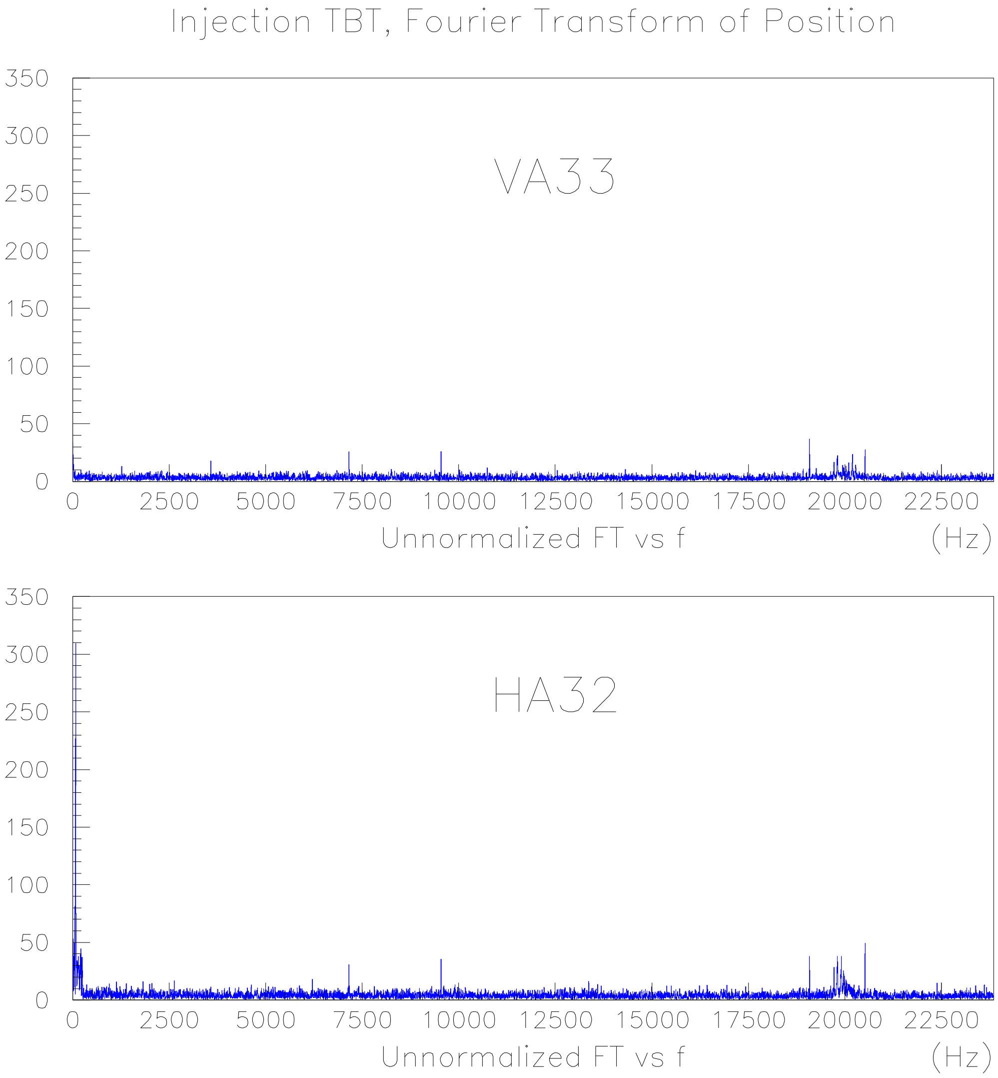

Figure 3: Frequency content of the position data shown in Figure 2. The vertical scale is arbitrary and the mathematics of the transform are described in the text. There is a prominent feature in the HA32 data near 80 Hz and there are prominent features in both plots near 20 kHz. The next plots will show these features in detail.

Frequency (Hz)	δ Frequency (Hz)	Tune	TeV Tune
19715	-90.	0.58680	
19805		0.58491	0.5830
19910	+105	0.58271	
20193		0.57678	0.5780
20278	+85	0.57410	

Table 1: The first three columns give information about the features in Figure 5 that are marked by vertical lines. The properties are the frequency, the difference in frequency from the most prominent line in the group, and the tune corresponding to the frequency. For comparison, the last column records the measured Tevatron horizontal and vertical tunes, recorded in the Tevatron machine e-log at 04:17:05 AM, a few minutes after this data was taken.

In the two plots there are prominent features near frequencies of 80 Hz and 20 kHz. The following plots will focus on these features.

Figure 4 shows a detail of Figure 3 at low frequencies. There is a prominent feature near 80 Hz which is present in the HA32 data but absent in the VA33 data. This data was taken at injection when the energy of the Tevatron is 150 GeV. At this energy the synchrotron frequency is about 80 Hz. So it seems likely that the observed feature is the synchrotron line.

Figure 5 shows a detail of Figure 3 near 20 kHz, where the betatron lines are expected. At these frequencies, there could be artifacts of the procedure for fixing the outlying data points. I have not investigated what those artifacts might look like.

In the lower plot there is a group of three strong lines centered near 19800 Hz. I eyeballed the center frequency of each line and drew a vertical dashed red line at that frequency. The center frequencies are recorded in Table 1. That table also records the difference in frequency between the outer two lines and the center line. And the table records the tune corresponding to each frequency, computed as,

$$\text{tune} \quad = \quad 1. - f/f_{\text{rot}}. \tag{7}$$

Finally the table records the measured horizontal and vertical tunes of the Tevatron, taken from the Tevatron e-log. I don't have any intuition for judging the quality of the agreement between the tune determined here and the tune taken from the machine log.

I had expected the frequency difference between either of the two sidebands and the central peak to be the synchrotron frequency of 80 Hz. My guess is that the errors on each frequency measurement are maybe 4 MeV and the error on the difference about 6 MeV. So the upper sideband peak is well off from my expectations.

The red vertical lines were also drawn on the top plot at the same frequencies

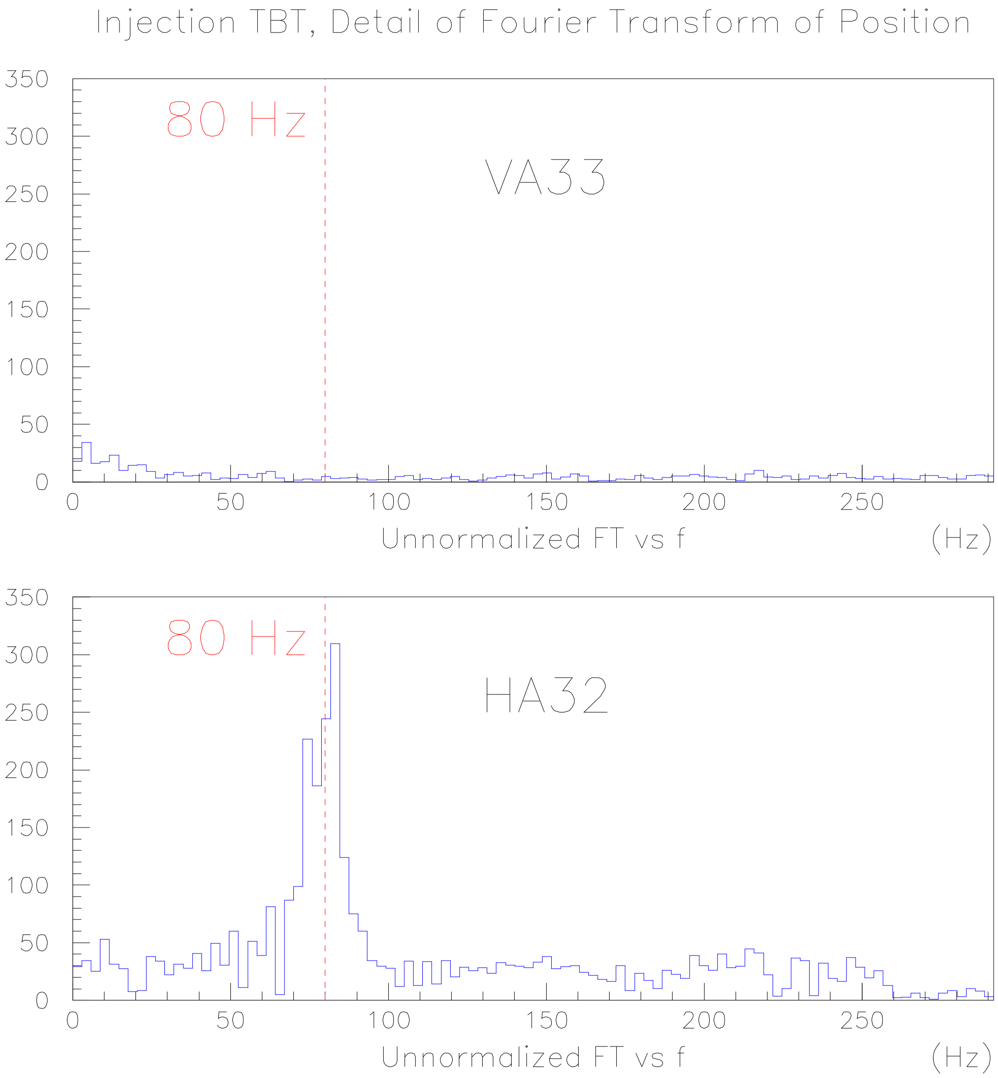

Figure 4: Detail of Figure 3 for low frequencies. The feature near 80 Hz in the horizontal data is likely the synchrotron line.

as on the lower plot. There are features at two of these three frequencies in the upper plot. Is this a useful measure of horizontal-vertical coupling in the Tevatron?

I don't yet understand the two very narrow lines at the edge of the plot. These lines are resolution limited.

I had expected to find a triplet of lines in the upper plot, corresponding to the vertical betatron oscillations and its two sidebands. I don't see this. I guess that the line near 20200 Hz is the vertical betatron line and the line near 20280 Hz is its upper sideband. Maybe there is some destructive interference which reduces the lower sideband? The frequencies and tunes for these two lines are recorded in table 1. The splitting between the two lines agrees well with the expectation of being the synchrotron frequency.

Green lines were drawn on the lower plot at the same place as in the upper plot. There are no features in the lower plot at these frequencies. I have no idea if this is consistent with the hypothesis of coupling which I suggested for the appearance of the horizontal tune lines in the vertical data.

4 Summary

The sawtooth pattern in the BPM sum signal is not yet understood. There remains a problem with outliers in the injection TBT position data. When these outliers are fixed by hand, the data shows features which are roughly consistent with the expectations of a synchrotron line near 80 Hz and betatron lines near 20 kHz. I have not been able to make a quantitative comparison of how well the spectra agree with expectations.

There are some narrow structures in the frequency spectra which are not yet explained.

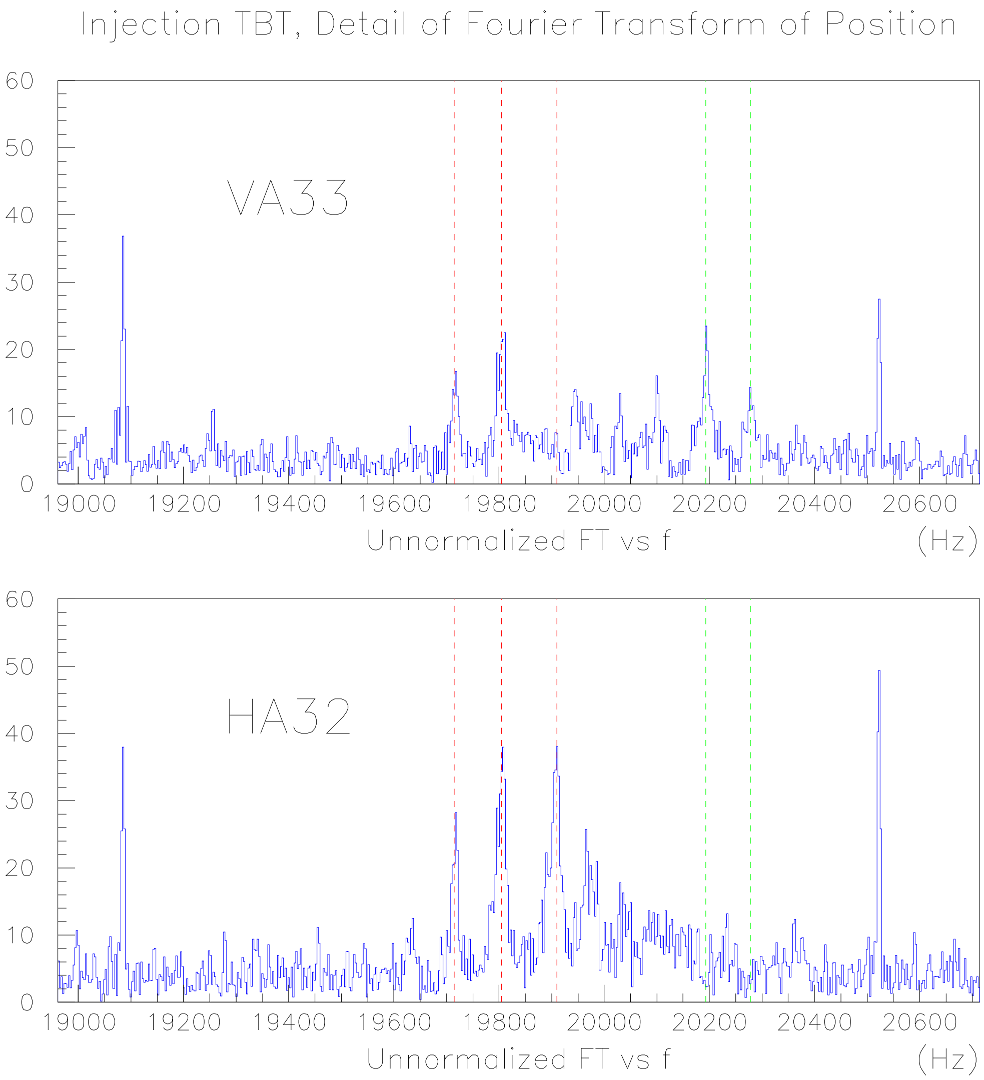

Figure 5: Detail of Figure 3 for frequencies hear the expected betatron lines. The vertical scales are the same on the two plots. The red dashed vertical lines are drawn through the three main features in the HA32 data and are repeated on the VA33 plot The green dashed vertical lines are drawn through two of the features in the VA33 data and are repeated on the HA32 plot. The frequencies of these lines are recorded in Table 1. The features are further discussed in the text.