TEVATRON STUDY REPORT: MEASURING PBAR TUNES WITH TAN'S-SYSTEM, BEAM SEPARATION, AND PBAR REMOVAL 12/03/02

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Abstract

During a dedicated machine study on December 03, 2002, we measured tunes of all individual pbar bunches by exciting them with the tune meter and detecting the resulting signals on the pbar Schottky monitors. We found that the horizontal tune is significantly lower for the first bunch in each train, and some evidence that the vertical tune of the last bunch is also below the average. This behavior is exactly opposite to the theoretical prediction. Separating the beams at B0 and D0, we could infer the head-on beam-beam tune shift experienced by the pbars. The horizontal tune shift was consistent with the expectation, about 0.006 at this intensity. Vertically the measured tune shift was significantly smaller than expected. Finally, we made a new attempt of cross-calibrating the available beam-size detectors by scraping. After removing 10% of the pbars, this experiment was terminated by a quench.

1 SEQUENCE OF EVENTS

The study started at the end of a store. At 6:08 CDF and D0 detectors were ready, and C.Y. Tan started the set up of the noise source. At 6:43 all pbar bunches were excited vertically, which led to about 10-20% blow up in their transverse emittance. The TevArray display with flying-wire emittances and pbar intensities is shown in Figs. 1 and 2, before and after tickling all bunches, respectively. The blow up is evident. Figure 3 shows the emittances from the synchotron light monitor recorded at an intermediate time. The emittance values from the synchrotron light monitor are roughly consistent with the flying-wire numbers.

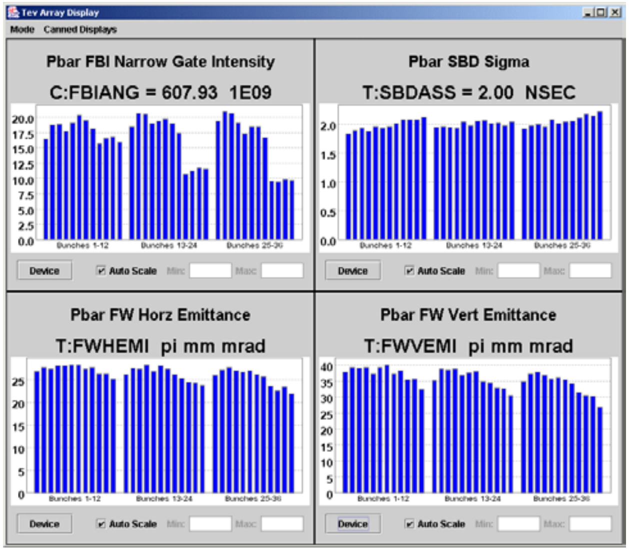

Figure 1: Pbar intensity, bunch length, and flying-wire emittances at the start of the study.

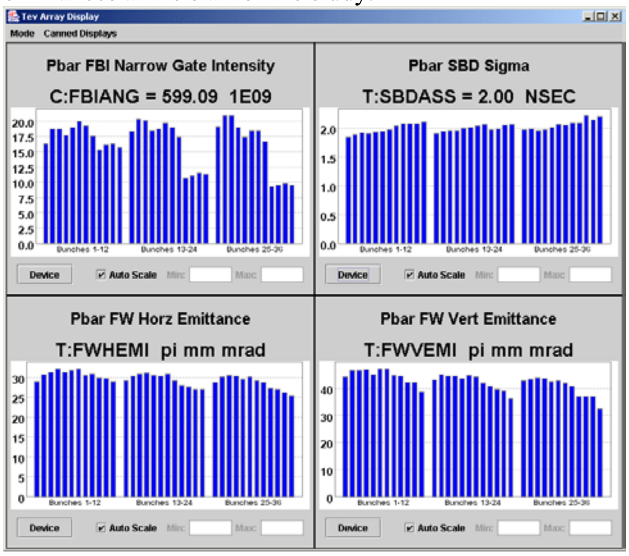

Figure 2: Pbar intensity, bunch length, and flying-wire emittances after tickling all bunches for a few minutes, during the set up.

*visiting from CERN

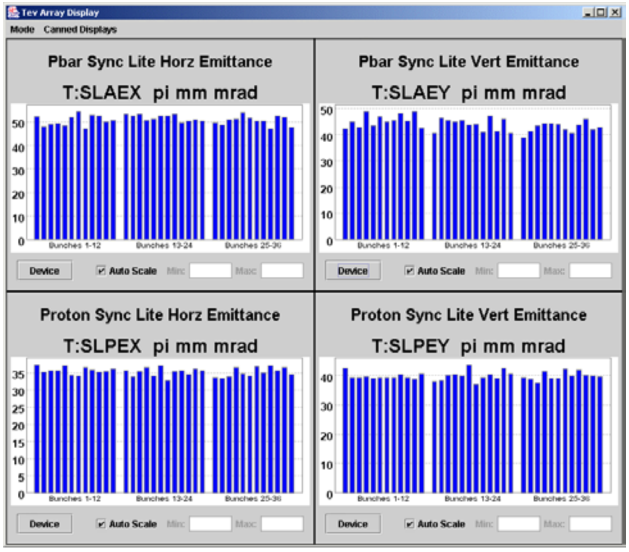

Figure 3: Proton and pbar emittances recorded from synchrotron light monitor at an intermediate time (between the previous two figures).

The excitation was then gated to individual bunches. At 7:00 bunch A1 was excited. The bunch identification was confirmed by a visible slow emittance growth on the TevArray display. At 7:13 we switched the excitation to bunch A13. A final adjustment to the excitation level was performed at 7:18. The horizontal Schottky spectra of pbars and protons during this initial set-up period are displayed in Figs. 4 and 5.

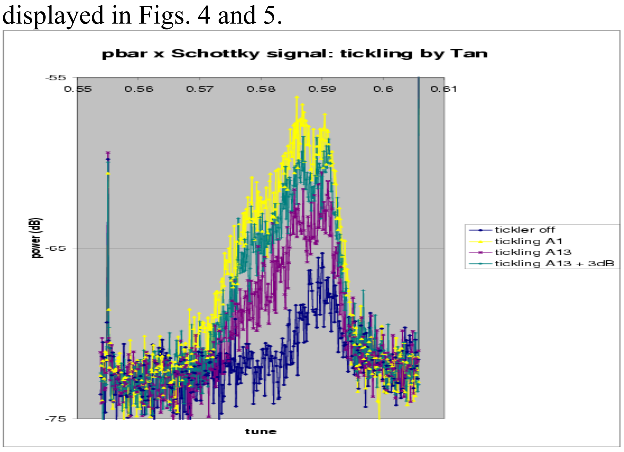

Figure 4: Horizontal pbar Schottky spectrum without any excitation, and with the 'tickler' gated to pbar bunches A1 or A13, before and after the final gain adjustment.

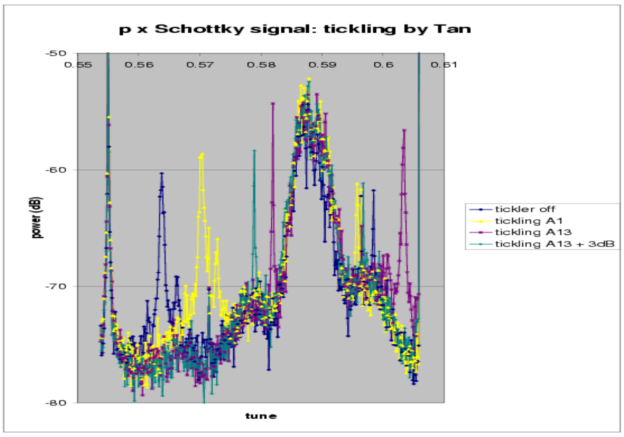

Figure 5: Vertical proton Schottky spectrum without any excitation, and with the 'tickler' gated to pbar bunches A1 or A13, before and after the final gain adjustment.

The excitation noise was random with 20 kHz center frequency and 1 kHz span (input 0 dB, 5 W power). From 7:18 to 8:33 we scanned successively bunches A13 to A24 recording first the horizontal Schottky signals for protons and pbars in each case, and afterwards, moving downwards from A24 to A13, saving the vertical Schottky signals. The bunches were always 'tickled' vertically. Sometimes we observed 1 or 2 coherent 'ghost' lines), moving across the horizontal or vertical betatron tune. An example is visible in the proton spectrum of Fig. 2. The amplitude of these lines appeared to be independent of the tickler excitation. Another complication was that often three tune peaks were observed instead of two. Therefore, to unambiguously identify of the pbar tunes, from 8:35 to 9:30, on bunch A15, we varied the pbar horizontal tune knob, comprising the feeddown sextupoles, by +0.002 and +0.0034, and detected the effect on the horizontal Schottky spectrum. Subsequently, we changed the pbar vertical tune by –0.0012 and +0.002, and observed the change in the vertical spectrum. We then tickled all bunches, A2 to A26, A13 to A24, and A1 to A12, one by one, and read the lines on the Schottky monitor by eye (V. Shiltsev). Around 10:50, we started the preparation for separating the beams. We flew the wires, and saved Schottky spectra. At 10:59, the collimators were retracted. The beams were separated at the two crossing points horizontally and vertically, respectively, by inverting the 'initiate collision' process (J. Annala). When the beams were separared the horizontal pbar tune was clearly lower than the horizontal proton tune (A6). The difference was about –0.005, close to the value expected from the settings of the feeddown sextupoles. We then tickled again all pbar bunches, one by one, and read the tunes for each bunch from the two pbar Schottky monitors. Spectra were saved with tickler on and off. At 12:45, the tune study was completed. We now attempted a pbar removal. The collimators were set back to their original position. A single vertical collimator, F49VCP, was used for the scraping. A variety of variables were monitored by a fast time plot (F49VCP, C:FBIANG, R:SLASBV, T:SLASBH, T:SLAABV, T:SLAABH, T:SBDAIS, T:SBDASS, T:F49VCP). The collimator was moved in steps of 2 mils at a time. Initial step position was at position –3 steps. For the step –163, the loss was about 1%. At 13:00 a quench occurred at position –184.

2 PBAR TUNES

The horizontal pbar Schottky spectra taken when the pbar bunches A13 to A24 were excited with the vertical tickler are superimposed in Fig. 6. Most of the pbar bunches have similar tunes, and only the first and last bunch in each train differ significantly. In Figs. 7 and 8 we compare the horizontal spectra of two different bunches near the centre with those of the first and last. The spectrum of the first bunch appears to have a double peak; the maximum of the last bunch lies somewhere between these two peaks. Figures 9 and 10 show the individual spectra for an excitation of the bunches A24 and A13, respectively. Figures 11 to 15 present the analogous data from the vertical Schottly pick up. On the vertical pick up the amplitude of the left-hand peak is enhanced, confirming that this is the vertical tune.

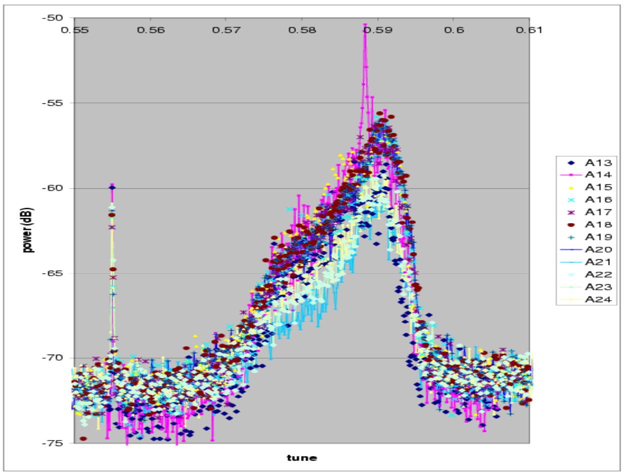

Figure 6: Horizontal pbar Schottky spectra obtained by (vertically) exciting pbar bunches A13 to A24 one by one.

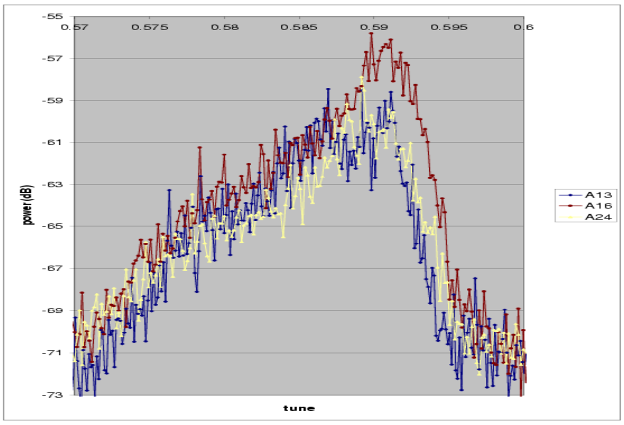

Figure 7: Horizontal pbar Schottky spectrum when pbar bunches A13, A16 and A24 were excited vertically.

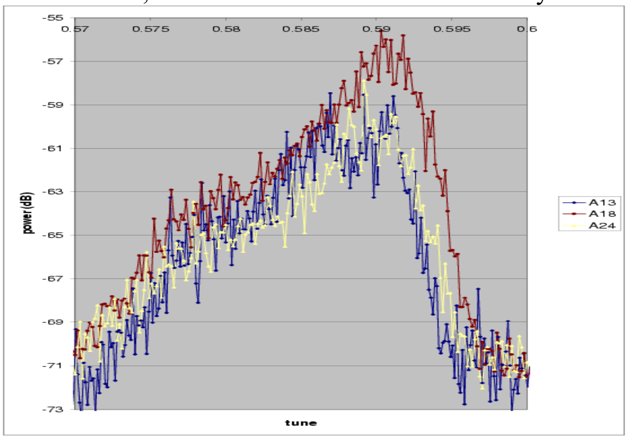

Figure 8: Horizontal pbar Schottky spectrum when pbar bunches A13, A18 and A24 were excited vertically.

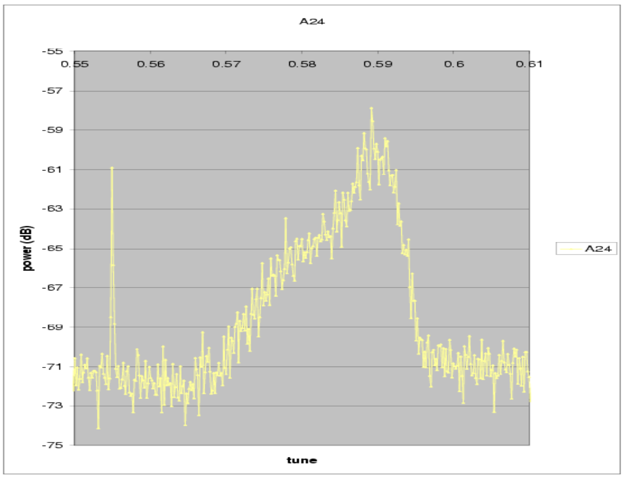

Figure 9: Horizontal pbar Schottky spectrum for the excitation of pbar bunch A24.

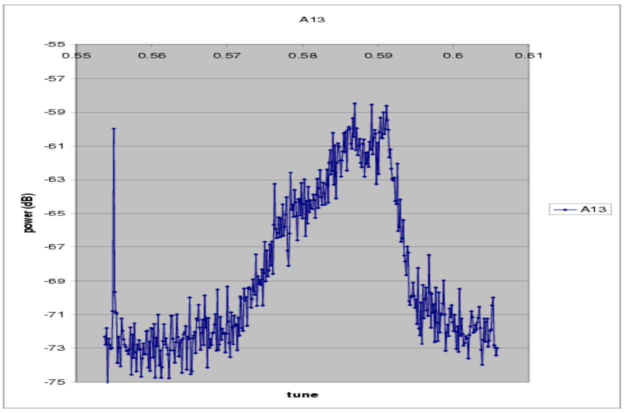

Figure 10: Horizontal pbar Schottky spectrum for the excitation of pbar bunch A13.

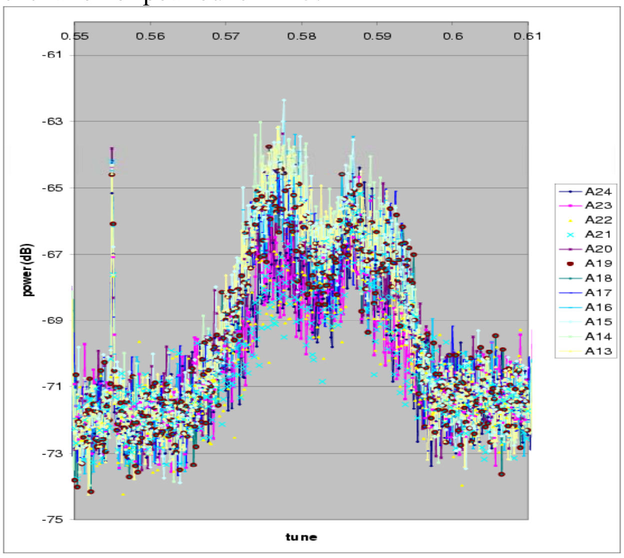

Figure 11: Vertical pbar Schottky spectra obtained by (vertically) exciting pbar bunches A13 to A24 one by one.

Figure 12: Vertical pbar Schottky spectrum when pbar bunches A13, A16 and A24 were excited vertically.

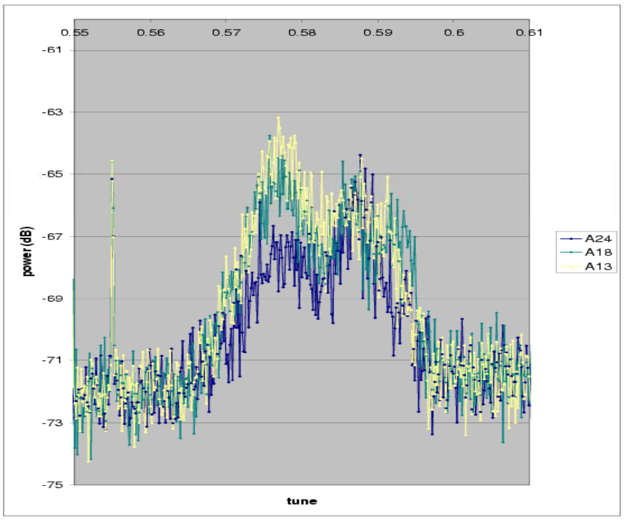

Figure 13: Vertical pbar Schottky spectrum when pbar bunches A13, A18 and A24 were excited vertically.

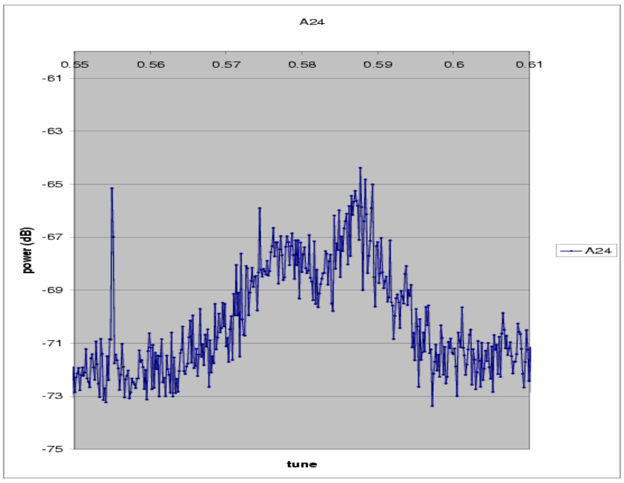

Figure 14: Vertical pbar Schottky spectrum for the excitation of pbar bunch A24.

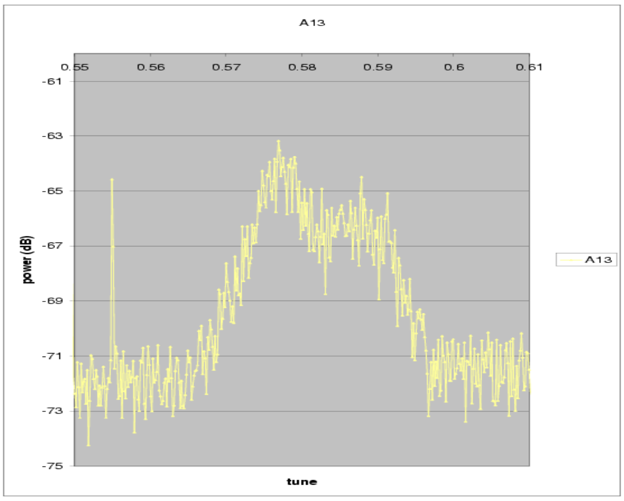

Figure 15: Vertical pbar Schottky spectrum for the excitation of pbar bunch A13.

Figure 16 shows the change in the horizontal Schottky spectrum for pbar bunch A15, which resulted from changing the pbar horizontal tune by +0.002 and +0.0034 units via the feeddown sextupoles. The right peak moved in the expected direction, from initially 0.5906 to about 0.5930, which is roughly the correct magnitude. Figure 17 displays a similar measurement for the vertical tune on the vertical Schottky spectrum. Here, the tune could be moved downwards by –0.0012 only, at which point the losses increased dramatically. The left peak moves roughly as expected, but the right peak also appears to move slightly (due to linear coupling and/or due to non-orthogonality of the pbar tune knobs?).

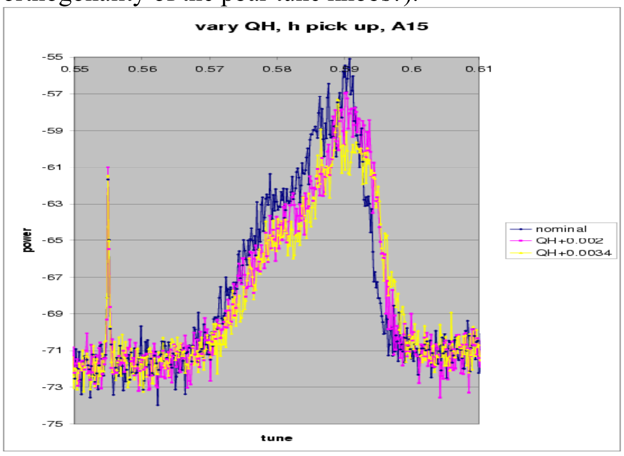

Figure 16: Change of the horizontal pbar Schottky spectrum for bunch A15 when the horizontal pbar tune was varied by +0.0020 and +0.0034.

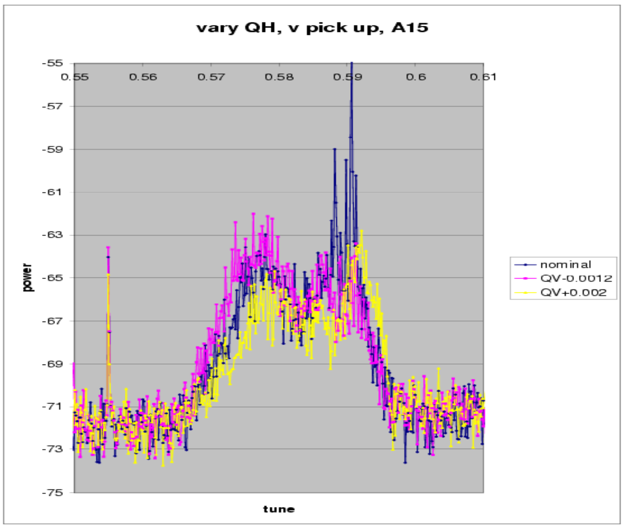

Figure 17: Change of the vertical pbar Schottky spectrum for bunch A15 when the vertical pbar tune was varied by -0.0012 and +0.002.

We next separated the two beams at B0 and D0. The intensities and flying-wire emittances for all bunches of both beams at this time are displayed in Figs. 18 and 19. Figures 20 and 21 show the Schottky spectra of the pbars before and after the separation, with and without the vertical tickler. In Fig. 20, the horizontal spectrum is much wider and extends further to the left (location of the vertical tune) whenever the vertical tickler is on. If the beams are separated, the peak amplitude is shifted towards the left, as expected from the vanishing head-on beam-beam tune shift. In collisions without tickler, the Schottky power is much reduced (see, e.g., the bottom blue curve in Fig. 20), which demonstrates the stabilizing effect of the beam-beam force. Also in Fig. 21 we observe a downward shift in the (now vertical) tune, when the beams are separated.

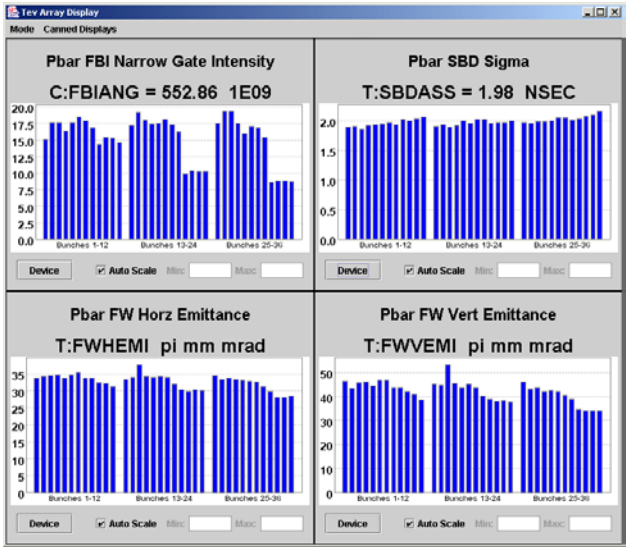

Figure 18: Pbar intensities, bunch lengths, and flying-wire emittances prior to beam separation.

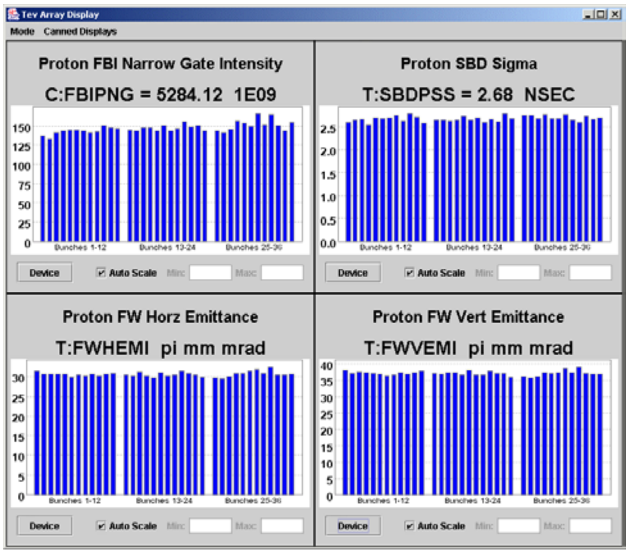

Figure 19: Proton intensities, bunch lengths, and flying-wire emittances prior to beam separation.

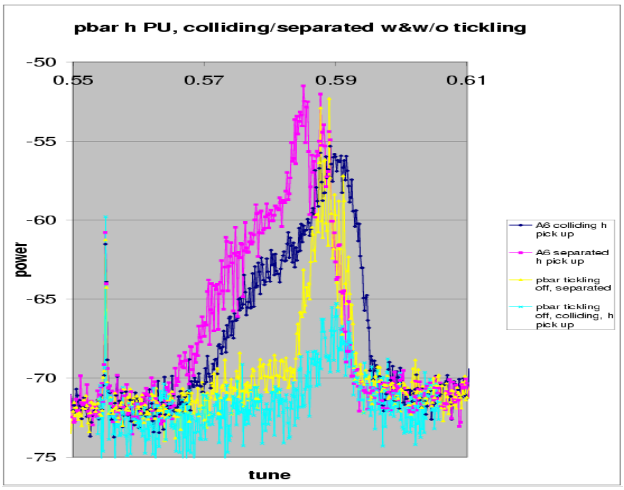

Figure 20: Pbar horizontal Schottky spectra in collision and separated at D0 and B0 with and without the vertical tickler, for pbar bunch A6.

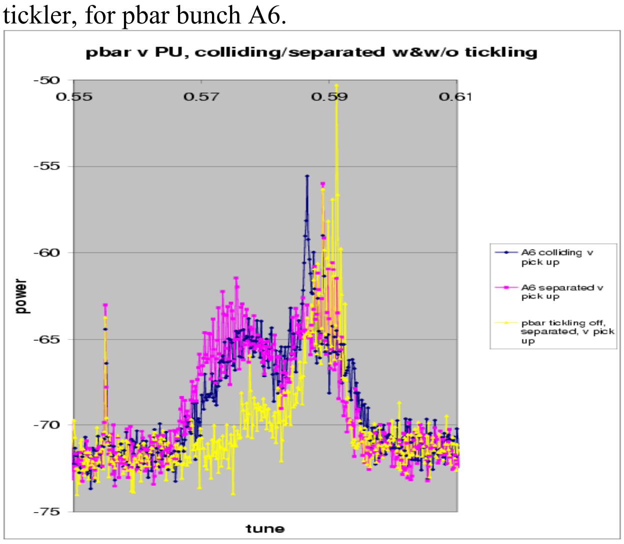

Figure 21: Pbar vertical Schottky spectra in collision and with separation at D0 and B0 when the vertical tickler was on, and separated without tickler, for pbar bunch A6.

Figures 22 and 23 show the corresponding spectra for the protons. The separation hardly affected their spectrum, presumably because the tune shift experienced by the protons is much smaller thanthat for the pbars. However, in the vertical plane we do see a change when the tickler is turned off. This may indicate that the proton vertical Schottky channel is sensitive to the pbar beam.

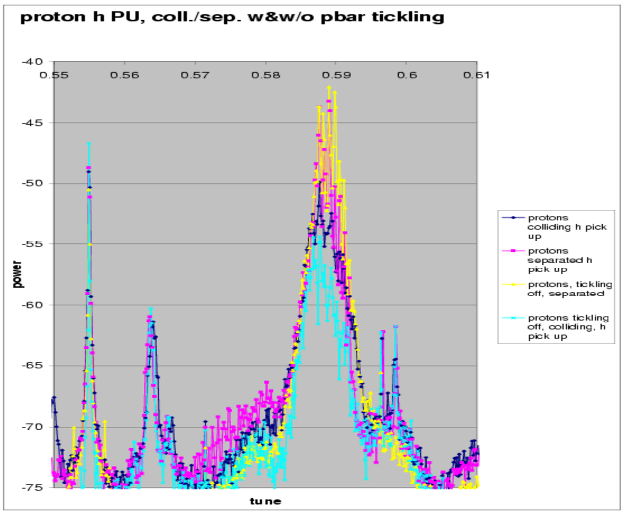

Figure 22: Proton horizontal Schottky spectra in collision and separated at D0 and B0 with and without the vertical tickler, for pbar bunch A6.

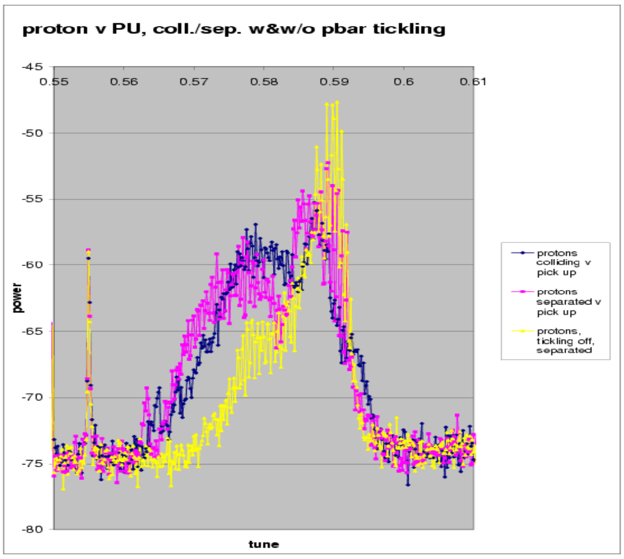

Figure 23: Proton vertical Schottky spectra in collision and with separation at D0 and B0 when the vertical tickler was on, and separated without tickler, for pbar bunch A6.

Figures 24 and 25 illustrate the tunes for all pbar bunches, which we inferred 'by eye' from the Schottky monitors. Often there are two peaks in the horizontal and/or vertical spectrum. The second peak might represent the average 'background' tune of the non-excited pbar bunches. In such cases both upper and lower lines are displayed. Figure 24 refers to the case including head-on collisions, Fig. 25 to the situation after separating the beams in B0 and D0. A striking feature in either figure is that the horizontal; tune is lower for the first bunch in each train. The theoretical prediction, independently computed by D. Shatilov, Y. Alexahin, T. Sen, and (earlier, for a different optics) by P. Bagley [1], is that the horizontal tune should be low for the last bunch in each train, and not the first.

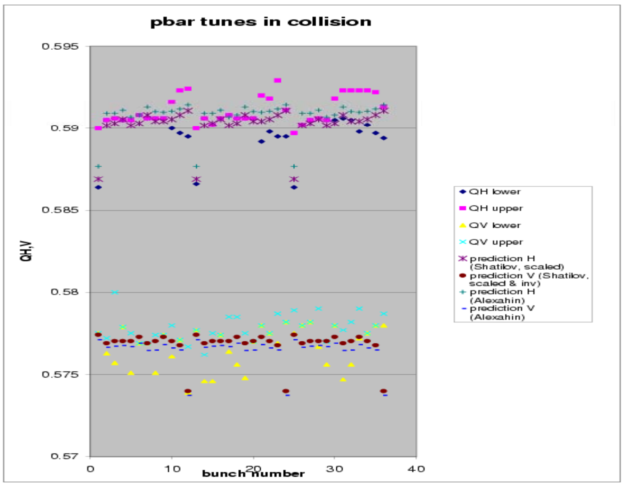

Figure 24: Horizontal and vertical pbar tunes as a function of bunch number, measured in collision for all bunches, and comparison with the variations predicted by D. Shatilov and Y. Alexahin at zero amplitude (here the tune of bunch no. 6 was adjusted to be the same as the measured one, the tune shifts were scaled with the proton intensity, about $1.4x10^{11}$ per bunch, and all bunch numbers were inverted along each train).

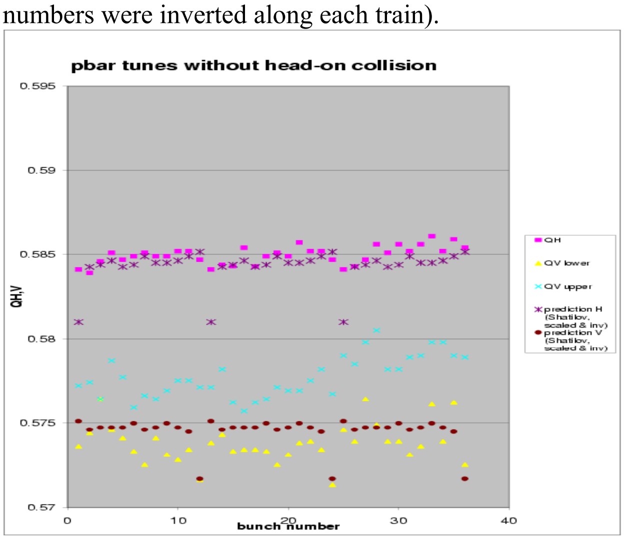

Figure 25: Horizontal and vertical pbar tunes as a function of bunch number, measured after separation for all bunches, and comparison with the variations predicted by D. Shatilov and Y. Alexahin at zero amplitude (here the tune of bunch no. 6 was adjusted to be the same as the measured one, the tune shifts were scaled with the proton intensity, and all bunch numbers were inverted along each train).

Conversely, there is some evidence, e.g., in Fig. 25, that the last bunch in each train features a low vertical tune, whereas according to the prediction it is the first bunch in each train for which the vertical tune should be low. The magnitude of both measured horizontal and vertical tune shifts agrees however perfectly with the prediction for the tune at the other end of the train. We thus suspect that the ordering of the bunches along each train must be inverted either in the measurement or in the simulation. In Figs. 24 and 25 we have modified the theoretical predictions accordingly.

By subtracting the tune values of Fig. 24 and Fig. 25, we can infer the tune shift induced by the two head-on collisions. Subtracting the upper and lower values individually, we obtain the results in Fig. 26. The head-on tune shift is about +0.006 horizontally, and 0.000-0.003 vertically (the two numbers for the vertical direction refer to the upper and lower tune lines). The horizontal value is roughly consistent with the expectation for 1.4×10^{11} protons per bunch and normalized $6\sigma^2$ emittances of about 35 μm vertically and 25 μm horizontally; see Table 1. The remaining rather large discrepancy in the vertical plane could perhaps be attributed to uncertainties in the emittance measurement or to the contribution from the parasitic collision points nearest to the main IPs, where the beam-beam distance may also have been changed by the beam separation.

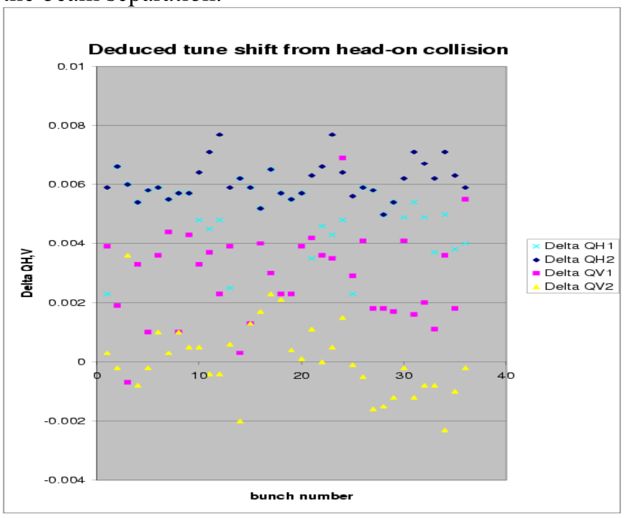

Figure 26: Tune shift induced by the two head-on collisions as a function of bunch number, deduced by subtracting the tune values of Figs. 24 and 25.

Table 1: Measured and expected tune shifts from the two head-on collision points. The expected value on the right refers to the incoherent tune shift from two collision points, $\Delta Q_{x,y}=6Nr_p/(\pi\ \varepsilon_{Nx,y}\ \ (1+(\varepsilon_{Nx,y}/\varepsilon_{Ny,,x})^{1/2}))$, using ε_{Nx}=30 μm, ε_{Ny}=35 μm, and $N_b=1.4 \times 10^{11}$.

tune shifts	measured	expected
ΔQ_x before/after separation	0.005-0.006	0.0066
ΔQ_y before/after separation	0.000-0.003	0.0061

3 EMITTANCE FROM SCRAPING

At the end of the study we scraped the beam using a single vertical collimator jaw. Figure 27 shows the beam current, loss rates, and collimator position as a function of time.

If the distribution is Gaussian, the logarithm of the lost beam fraction, *f*, should be a parabolic function of the collimator position *x*. Denoting the (a priori unknown) position of the beam center by x_0 this relation is $\ln f = -1/(2\sigma^2)\ (x^2-2xx_0+x_0^2)$, where σ is the beam size at the collimator. Thus plotting ln *f* versus *x* and applying a parabolic fit yields both the beam size and the beam center x_0. The three coefficients of the general parabolic fit $\ln f = ax^2+bx+c$ are related via $b=-2\ (ac)^{1/2}$, since there are only two independent variables (the one constraint is that the curve has a maximum at $x=x_0$). This allows for a convenient cross check of the fit validity. The fit for the present experiment, in Fig. 28, fulfils this condition (actually we adjusted the initial point of the fit so that it did; for data points at the very beginning of the scraping, where the losses are still within the error of the beam-current measurement, the fit is poor.). From the fit we obtain a beam size of σ=0.34 mm. With β=43 m, this corresponds to a $6\sigma^2$ normalized emittance of 17 μm. For comparison, the flying wires reported an emittance of 40 μm, and the synchrotron light monitor 50 μm (in a previous pbar removal study on November 17, the synchrotron light emittances were a factor of two smaller than the flying-wire emittances; in the meantime a correction factor of 1.8 was added to the pbar synchrotron-light beam size).

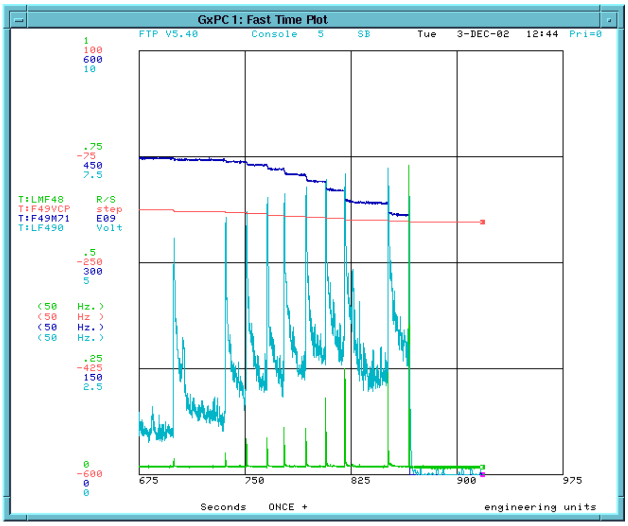

Figure 27: Collimator position, beam current, pbar loss rates as a function of time, during the scraping attempt.

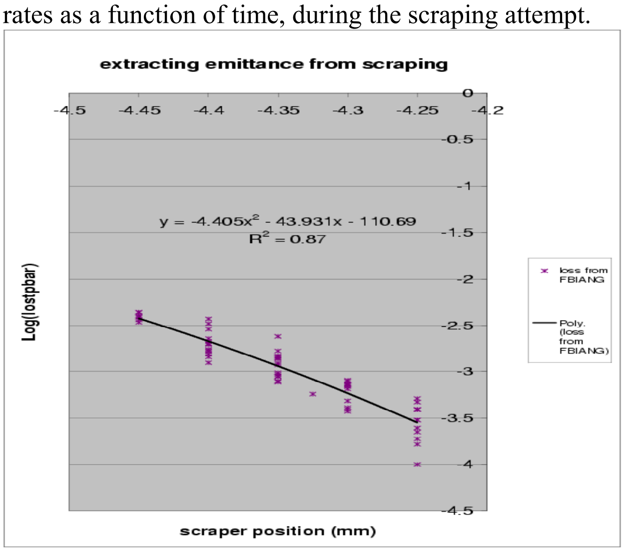

Figure 28: Logarithm of lost fraction of pbars as a function of scraper position and parabolic fit, from which the rms beam size at the collimator can be inferred.

4 CONCLUSIONS

We have measured the horizontal and vertical tunes of all pbar bunches, using the tune meter excitation and the Schottky monitor. The horizontal tune was lower by about 0.003-0.004 for the first bunch in each train, and there is some evidence (especially in the case when the beams were separated) that the vertical tune of the last bunch is lower by a similar amount. The proton intensity in this study was $1.4\text{x}10^{11}$ per bunch. If the variation is due to long-range beam-beam effects, the tune difference should grow linearly with intensity, and it would be about 0.007 at the start of a store. Our observation is exactly the opposite of what was predicted in calculations by D. Shatilov, Y. Alexahin, T. Sen, and (for a different helix in 1996) by P. Bagley. The last case agreed with measurements [1]. Possible explanations for the discrepancy would be a reverse polarity of the helix or the excitation of the wrong bunches. Both are unlikely.

Comparing the pbar tune spectra with and without collisions in D0 and B0, we inferred a measured pbar tune shift from the two head-on collision points of 0.005-0.006 horizontally and 0.000-0.003 vertically. This should again scale linearly with the proton intensity, and also inversely with the proton emittance. The horizontal number agrees with the expected incoherent tune shift. The measured vertical tune shift is too low.

An attempt to determine the pbar vertical emittance by scraping terminated prematurely due to a quench. Only 20% of the beam was removed. Fitting the dependence of the beam loss on the collimator position to the expected relation for a Gaussian profile, we obtain an estimate of the beam emittance which is 2 or 3 times smaller than the value reported from synchrotron-light monitor and the flying wires. Removing the entire beam by scraping would reduce the error bar of this type of emittance measurement.

5 ACKNOWLEDGEMENTS

Many thanks to the Tevatron operations crew for the reliable assistance and friendly help. We also thank Y. Alexahin and T. Sen for useful discussions and informations.

REFERENCES

[1] P. Bagley, `Beam Beam Tune Shifts for 36 Bunch Operation in the Tevatron', EPAC'96, Sitges (1996).