Fermilab

Tevatron beam study report

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A. Jansson *et al*

COLLIMATOR SCANS TO MEASURE TEVATRON EMITTANCE

Introduction

Lately, several beam studies were made removing either the proton or antiproton beam using a single scraper/collimator. The primary motivation for these measurements was the differences in emittance values reported by the synchrotron light (SL) monitor and flying wire (FW) monitors. By scraping the beam, an independent third emittance value is obtained, to help evaluate which monitor (if only one) is at fault.

The scraping measurements done so far where:

- Vertical scraping of antiprotons (with protons still in the machine) on 12.17.2002.
- Horizontal scraping of protons (with antiprotons still in the machine) on 12.21.2002.
- Vertical scraping of a single bunch of protons on 01.07.2003.

The two first measurements were end-of-store studies, whereas the last one was a dedicated study.

Emittance measurement by scraping the beam

If the beam has a 2D Gaussian distribution in transverse phase space, the betatron amplitude distribution is

$$\rho_{\varepsilon}(r_x) = \frac{N_0\ r_x}{\sigma^2}\ e^{-\frac{r_x^2}{2\sigma^2}}$$

If there is no x-y coupling or dispersion at the location of the scraper, and the scraper is properly aligned (either horizontally or vertically), it will act only in one plane and remove all particles that have betatron amplitudes larger than the distance from the beam center to the scraper edge. Assuming that the scraper velocity is slow compared to the betatron frequency, so that doomed particles have time to hit the scraper, but fast compared to diffusive processes that tend to reduce beam lifetime in the presence of a collimator, the intensity drops as

$$N(x) = \int_0^{x-x_0} \rho_{\varepsilon}(r_x)\ dr_x\ = N_0\left(1 - e^{-\frac{(x-x_0)^2}{2\sigma^2}}\right)$$

as a function of scraper position. This simple function can be fitted to the intensity data to obtain the beam size, and thus the emittance.

If, on the other hand, there is coupling or dispersion at the scraper location, the functional form is more complicated. For example, in the case of dispersion, the scraper will remove all particles that have a combined maximum excursion (betatron and dispersive) larger than the distance between beam center and collimator. Hence, ρ_p is the synchrotron amplitude distribution (expressed as a function of maximum momentum), which is also assumed to be Gaussian, then

$$N(x) = \int_0^x \int_0^{\frac{x-r_x}{D}} \rho_x(r_x)\,\rho_p(r_p)\, dr_p\, dr_x =$$

$$1 - \frac{\sigma_x\, e^{-\frac{x^2}{2\sigma_x^2}}}{\sigma_x^2 + D^2\sigma_p^2} - \frac{D\sigma_p\, e^{-\frac{x^2}{2D^2\sigma_p^2}}}{\sigma_x^2 + D^2\sigma_p^2} -$$

$$\sqrt{\frac{\pi}{2}}\, \frac{D\,\sigma_p\,\sigma_x\, e^{-\frac{x^2}{2(\sigma_x^2+D^2\sigma_p^2)}}}{(\sigma_x^2 + D^2\sigma_p^2)^{3/2}}\, x \left[\mathrm{erf}\left(\frac{x\,\sigma_x}{\sqrt{2}\, D\sigma_p \sqrt{\sigma_x^2 + D^2\sigma_p^2}} \right) + \mathrm{erf}\left(\frac{x\, D\sigma_p}{\sqrt{2}\,\sigma_x \sqrt{\sigma_x^2 + D^2\sigma_p^2}} \right) \right]$$

where the beam center x_0 has been set to zero for convenience. A very similar function is obtained for the case of x-y coupling. When $\sigma_x = D\,\sigma_p$, this simplifies to

$$N(x) = 1 - e^{-\frac{x^2}{2\sigma_x^2}} - \frac{e^{-\frac{x^2}{4\sigma_x^2}}\sqrt{\pi}}{2\sigma_x}\, x\, \mathrm{erf}\left(\frac{x}{2\sigma_x} \right)$$

It should be noted that the above equation is symmetric under the exchange $\sigma_x \leftrightarrow D\,\sigma_p$. Therefore, it is impossible to extract both σ_x and the product $D\sigma_p$ from scraping data. However, if the $D\sigma_p$ is known it can be input in the fit function in order to determine the emittance.

The scraping profile with dispersion present resembles the non-dispersive case, with the exception that the former is much flatter close to the beam center, giving the impression of a position shift with respect to the non-dispersive scraping. Since the derivative is zero at the extinction point, it is very hard to tell from the scraping profile alone if there was dispersion or not at the location of the scraper.
Also, the measured width is very sensitive to the detection of the beam center (extinction

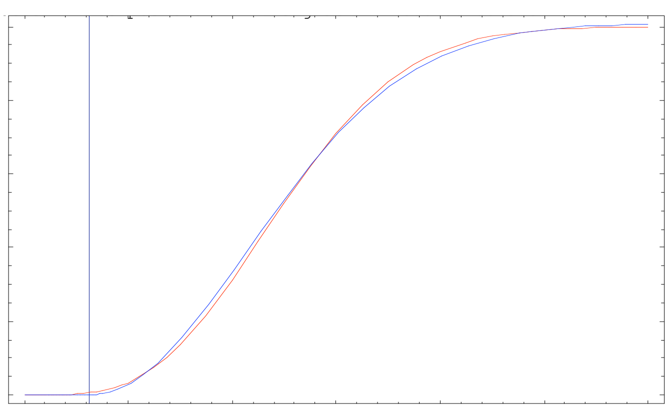

Fig1. Scraping profile for dispersive (red) and non-dispersive (blue) case. The non-dispersive case have been translated in the x direction to minimize the rms difference between the two curves. The vertical line marks the point where the blue line goes to zero.

point).

Vertical scraping of antiprotons (12.17.02)

Study 1011 was performed at the end of physics store 2078. In order not to quench the machine while scraping, 30 of the 36 antiproton bunches where removed using the Tevatron electron lens (TEL). This also had the effect of blowing up the emittance of the remaining 6 bunches by about 10π, according to the FW.
Once only six pbar bunches remained, the F49V collimator was moved in several steps, and the wires were flown at approximately 100%, 75%, 50%, 25%, 1% and 0% of initial pbar intensity. It was noted that the scraping did not only reduce the horizontal emittance (as measured by the FW), but also both the vertical emittance and the momentum spread. The reduction in momentum spread was confirmed by a reduction in bunch length as measured by SBD. The reduction in momentum spread indicates a non-vanishing vertical dispersion at the collimator location, and the horizontal scraping hints that there was coupling either at the scraper or monitor position (or both).

This function derived for 1D scraping fits well to the data, and yields an emittance of about 20-24 pi, depending slightly on which of the available intensity measurements that

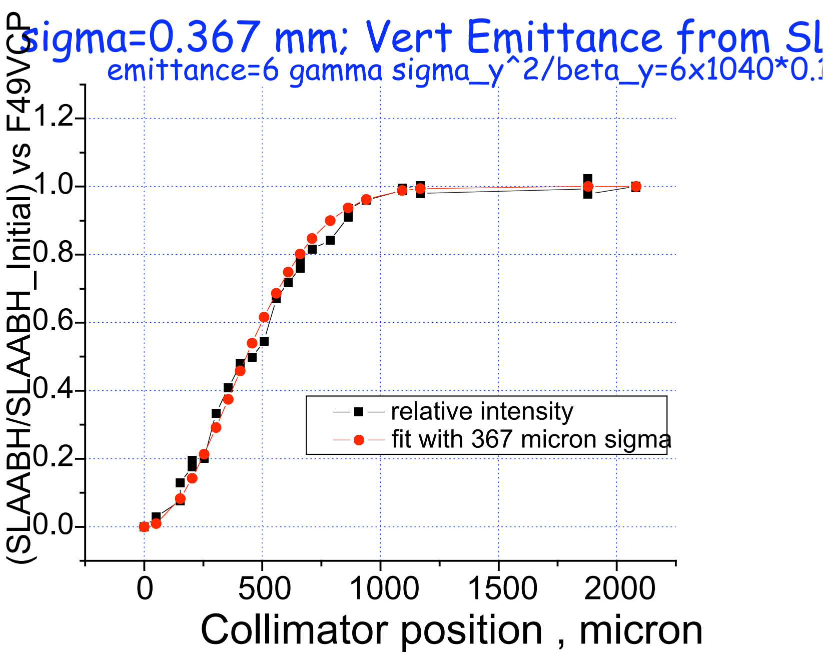

Fig 2. Scraping profile for pbar vertical collimator scan.

is used (SL, FBI, IBEAM), and what constraints are put on the fit (e.g. whether one fixes the endpoint or not).

The emittance measured by scraping is about a factor 1.8 smaller than the initial emittance as measured by the FWs. The reason for this is not properly understood, and merits further study.

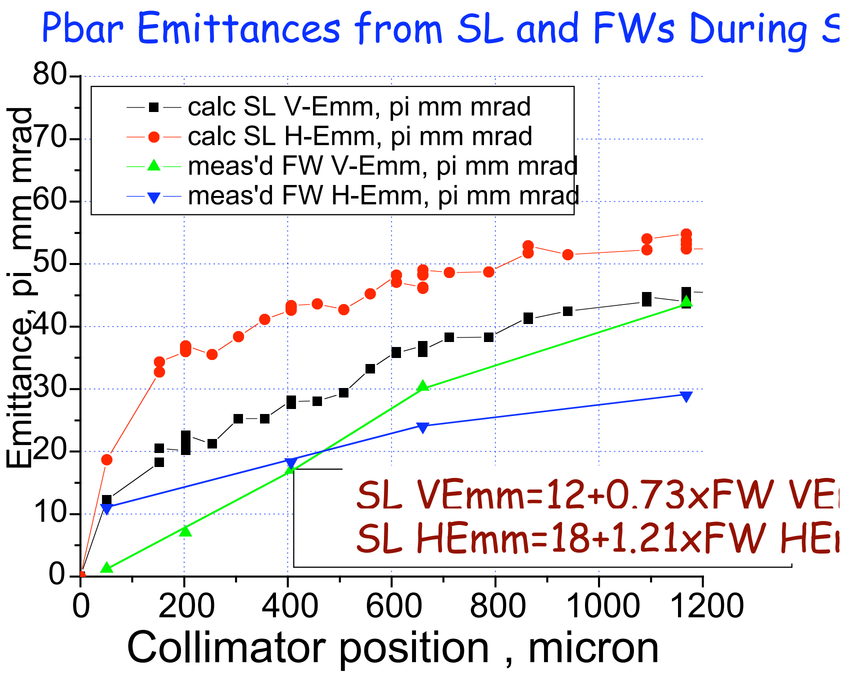

Fig 3. Emittance measured by FW and SL (recalculated from logged beam sizes) during scraping. The tracking is not very good.

A second observation is that the emittance as measured by the SL did not decrease at the same rate as the same quantity measured by the wire scanners

This MAY be attributed to aberrations in the SL optical system, causing a smearing of the light and broadening of the measured profile. Such an effect is expected to add in quadrature to the measured beam size and hence mainly affect the measurement of small beams. The smallest vertical beam size measured was 0.32 mm, giving an upper bound for the magnitude of any such effect (note also that there are few data points towards the end of the scraping).

However, there may be other causes for this. It was observed that the pbar beam ellipse was tilted at the location of the SL detector, which is a clear sign of coupling. If one assumes that the scraper location is uncoupled, so that the scraper only affects the SL emittance, the measured vertical beam size at the SL location would be (in a simple approximation)

$$\sigma_v = \sqrt{\varepsilon_h \beta_{v0} \cos^2\theta + \varepsilon_v \beta_{h0} \sin^2\theta}$$

where (is the tilt angle. Here, the horizontal emittance adds in quadrature to the vertical beam size, in much the same was in the case of optical aberrations. Hence, further studies are required to draw clear conclusions. The tilt effect could be quantified and separated from optical aberrations by studying the raw 2D data from the SL detector.

Horizontal scraping of protons (12.21.02)

During store 2091, the TEL filed, causing DC beam to build up in the abort gaps. To avoid a quench on abort, the proton beam was slowly scraped away using a horizontal collimator. Part of the reason for this was to test the future pbars recycling mode (which requires protons to be removed without touching the pbars). During the scraping, the FWs were flown regularly, and the SL data stored at an increased rate.

Comparing the FW sigmas to the SL sigmas show that the two track each other nicely. There is no hint of a resolution limit, as was observed for the pbar SL. The ratios between SL and FW sigmas are within about 10% of what's expected from the lattice functions at th

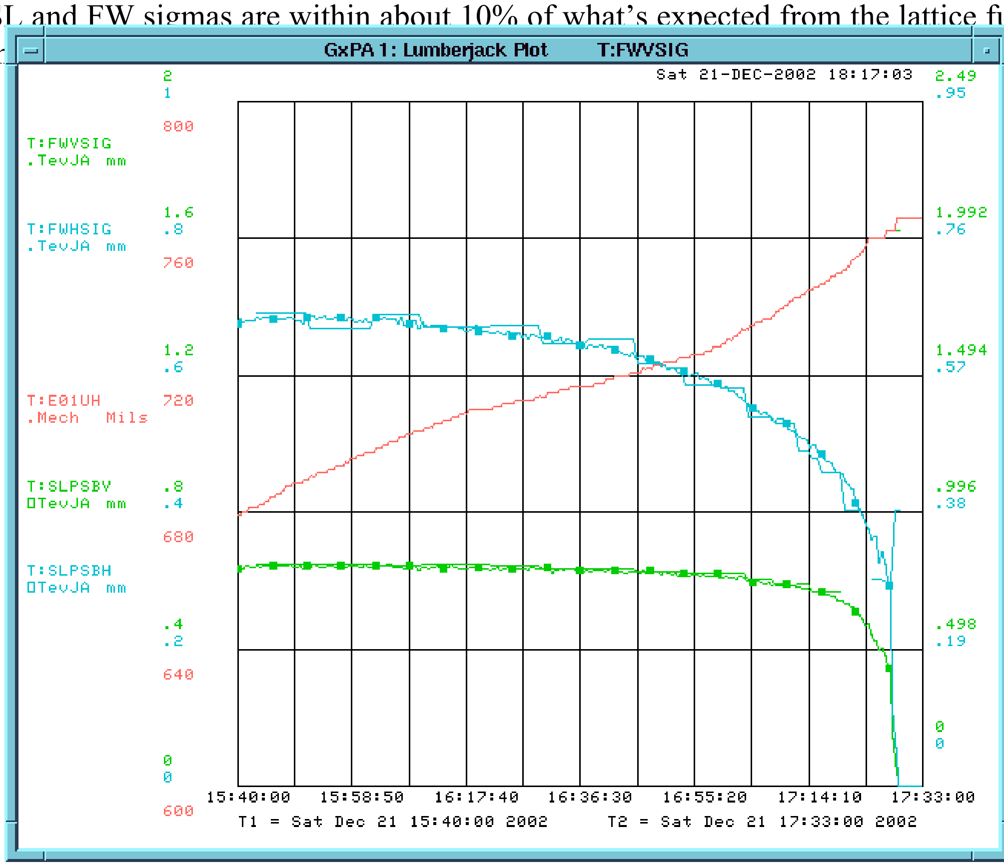

Fig. 4 Emittances measured by SL and FW, as well the collimator position

Plotting the total proton current (C:FBIPNG) versus collimator position yields an emittance of 33.0 using the 2D scarping model with fixed momentum spread. Using the

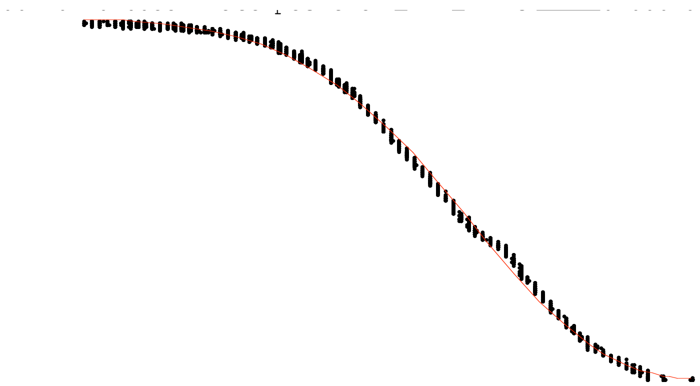

Fig 5. Scraping profile during horizontal proton collimator scan, with fitted 2D scraping model.

1D model and subtracting off the dispersive contribution to the beam size yielded an emittance of 31.1.

Vertical scraping of protons (01.07.03)

Study 1059 was a dedicated study, designed to cross check the earlier results. Since the

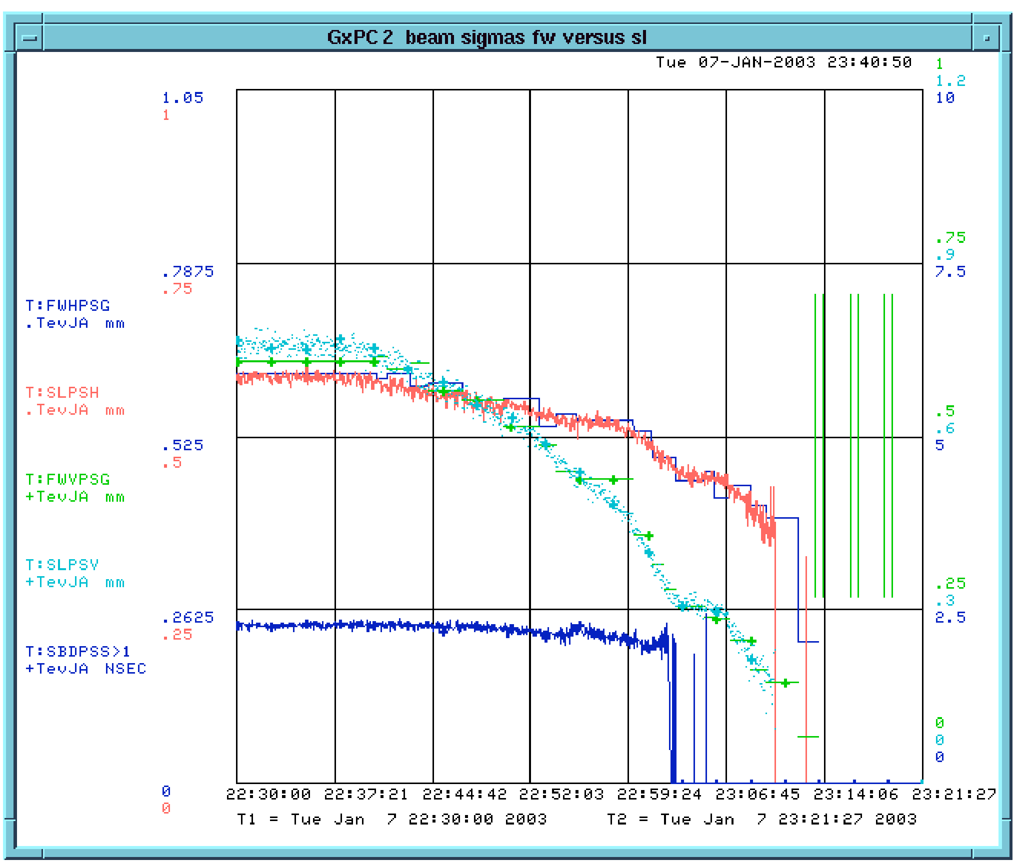

Fig. 6 Emittances measured by SL and FW, as well as bunch length measured by the sample bunch display (SBD)

FW mechanism is common for pbars and protons (apart from the scintillator), the calibration can be checked with either particle. A single bunch was injected into the Tevatron and accelerated to 980 GeV, where it was scraped vertically. The SL and FW emittances tracked nicely during the scraping, with no hint of a minimal resolution.

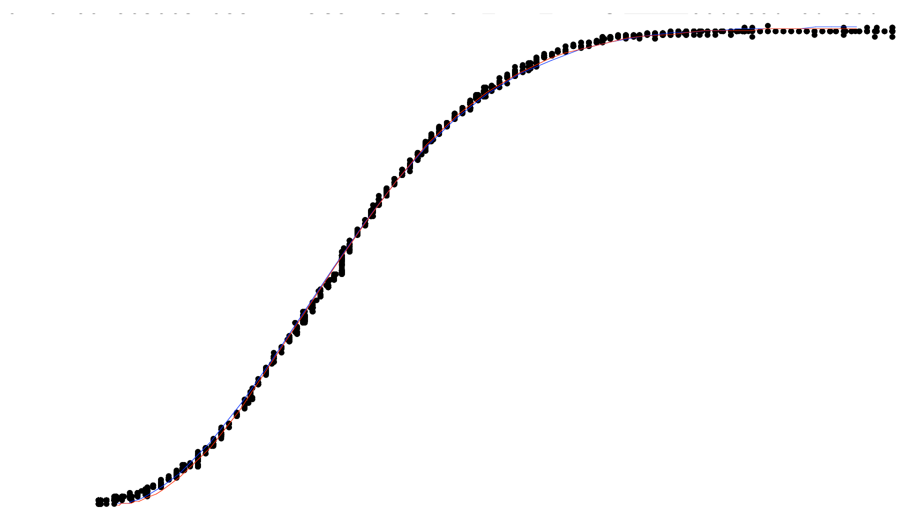

Fig. 7 1D Gaussian scraping profile fitted to the data from vertical proton scraping. The emittance obtained was 25.6 ± 1.5 π mm mrad, depending on the restrictions of the fit.

Summary and Conclusions

The emittance values obtained from the different instruments are summarized below

	Collimator scan	Flying wires	SL
Pbar vertical	22 ± 2	42.3	43.8
Proton horizontal	31.1 (1D model) 33.0 (2D model)	25 ± 3 (FW+SBD 18.6)	34.0
Proton vertical	25.6 ± 1.5	29.5	33.5

The errors only reflect the variations in final value

Overall, the differences in emittance value reported by SL and FW in the measurements can be explained by uncertainties in lattice parameter values (beta function and dispersion), which can be of order 10-20%. The obvious exception is the vertical pbar scraping, where both SL and FW disagree with the collimator scan by a factor almost two. This measurement should therefore be repeated. Also, efforts should be made towards verifying the lattice functions.

Proposals for future measurement:

There are a number of actions and studies that could improve our understanding of the Tevatron emittance, including

- Installing k-modulation quadrupoles to measure beta function at FW, SL, Schottky and Collimators.
- Calibrating collimator movements.
- Upgrade BPM system to have multi-turn measurement capability at each pick-up to measure local coupling and beta function around ring.
- Exchange vertical and horizontal emittance by crossing the coupling resonance, and scrape horizontal emittance with a vertical collimator avoiding dispersive effects.
- Measure dispersion at instruments, either using the position readout, or a separate pick-up.
- Install dedicated BPMs to measure local coupling at FW, SL, Schottky and Collimators.