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Calibration of BPMs in TEL2 and electron-proton alignment for tune-spread studies with Gaussian guns in the Tevatron

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1 The TEL2 BPM system

We are planning to study compensation of nonlinear head-on beam-beam interactions in colliders with electron lenses. For this purpose, we are going to search for proton or antiproton tune-spread changes in the Tevatron induced by Gaussian electron beams. In the past, it was shown that electron beam alignment is critical for effective beam-beam compensation [1]. Due to the different frequency content of electron and proton signals in the beam-position monitors (BPMs), one of the obstacles faced during operation of the first Tevatron electron lens (TEL1) was an unacceptable offset (about 1 mm) between measured electron and proton or antiproton positions. For this reason, a new type of BPM was designed and installed in TEL2 (Figure 1) [2]. Each BPM unit has 4 plates, to combine both horizontal and vertical measurements. To minimize crosstalk, the 20-cm plates are separated by ground strips. Two of these compact BPMs are installed inside the main solenoid of TEL2, one upstream (gun side) and one downstream (collector side) (Figure 2). The distance between the BPM centers is 140 cm.

Another issue is the slow readout time of the Labview-based system. It reports single position measurements every 25 s, so a full cycle of 12 measurements (horizontal and vertical, gun and collector sides, for protons, antiprotons, and electrons) takes about 300 s. A new Java-based algorithm was developed. It reads out 500 samples from the digital oscilloscope trace and reports positions according to the usual formulas

$$x = k_x \frac{A_x - B_x}{A_x + B_x}; \quad y = k_y \frac{A_y - B_y}{A_y + B_y},$$

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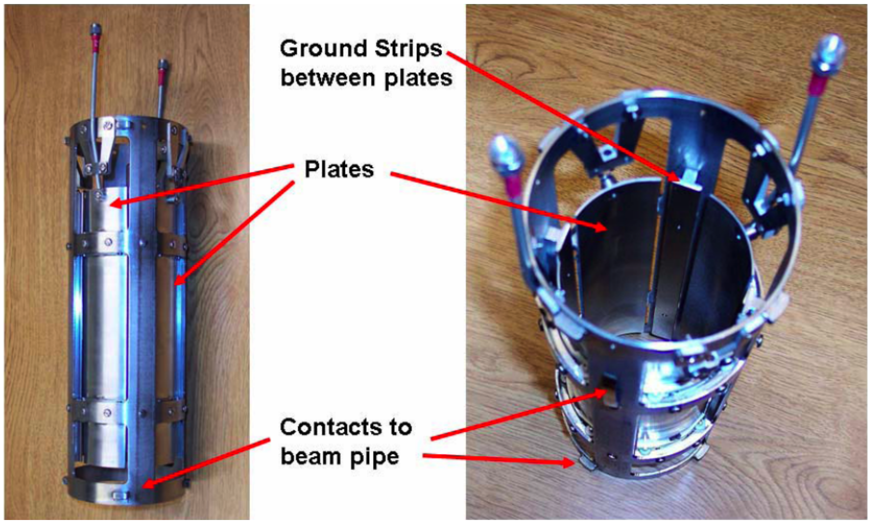

Figure 1: Photograph of a TEL2 BPM.

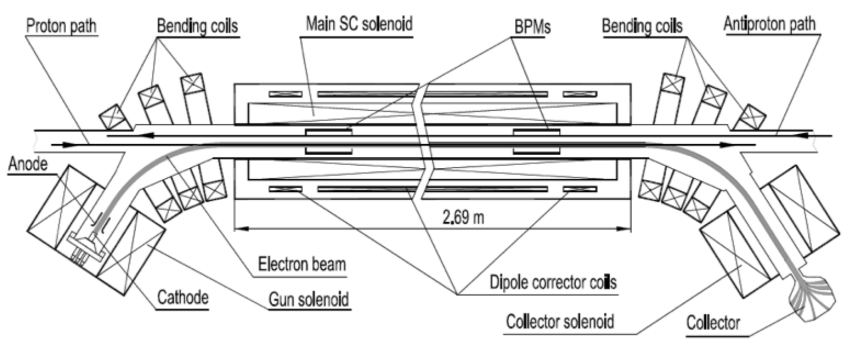

Figure 2: Layout of TEL2.

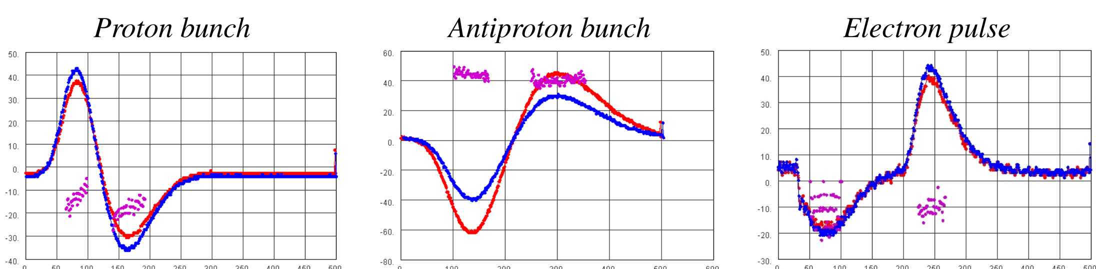

Figure 3: Sample digitized TEL2 BPM traces *A* (red) and *B* (blue). The purple dots are proportional to the sample-by-sample measured position. The full horizontal span (from 1 to 500) corresponds to 100 ns for protons, 50 ns for antiprotons, and 1000 ns for electrons.

Observable	Expected	Measured	Measured / Expected
Δx gun (mm)	2.77	-2.39 ± 0.14	-0.86 ± 0.05
Δx coll. (mm)	2.60	-2.76 ± 0.06	-1.06 ± 0.02
Δy gun (mm)	-2.69	2.68 ± 0.15	-1.00 ± 0.06
Δy coll. (mm)	-2.86	3.24 ± 0.08	-1.13 ± 0.03

Table 1: TEL2 BPM calibration with separators. Expected and measured orbit changes: (helix ON) – (helix OFF). Only random uncertainties are reported.

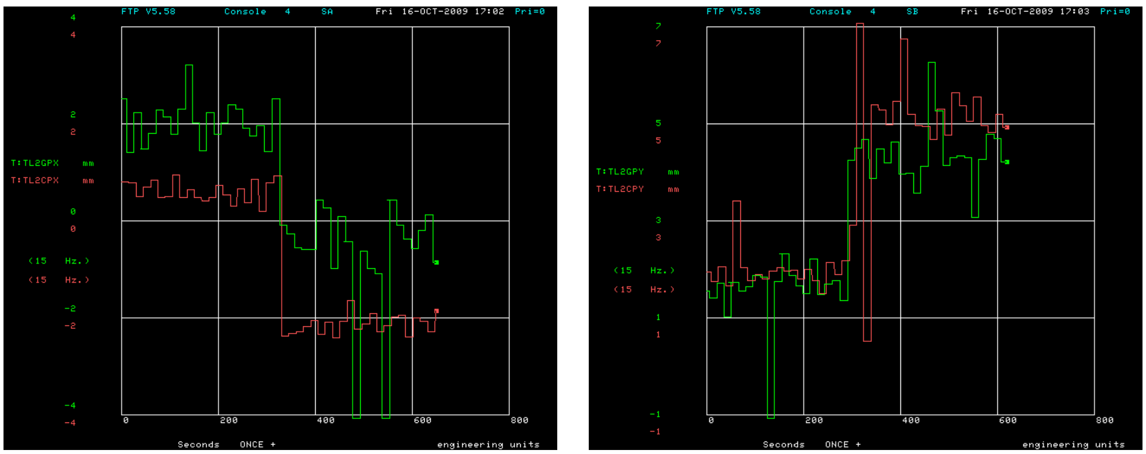

Figure 4: TEL2 BPM calibration with separators: measured horizontal (left) and vertical (right) positions of protons with separators off and then on.

where A and B are the voltage signals from the two plates in the same plane and k_x and k_y are conversion constants: $k_x = k_y = 19.9$ mm for (anti)protons, $k_x = k_y = 19.3$ mm for electrons. They are determined from stretched-wire measurements at a test bench. Sample traces are shown in Figure 3. Settings can be found in the Beam-Beam Compensation E-log (e.g., entry #275 of September 29, 2009). Each measurements takes about 2.5 s, so a full cycle of 12 measurements takes about 30 s.

2 Calibration for protons with separators

The first calibration of the new BPM system was performed on Fri Oct 16, 2009 by turning the separators on and off. This calibration relies on the accurately known helical orbits. The study was done after parsing a squeeze, so protons were uncoalesced (bunch intensity was 18×10^9) and the signals were rather noisy.

The expected orbit changes at the TEL2 location are reported in Table 1. Figure 4 shows the raw data: measured positions vs time. Separators were initially off, and they were turned on around $t = 300$ s. Results are summarized in Table 1 and in Figure 5. Here and in the following sections,

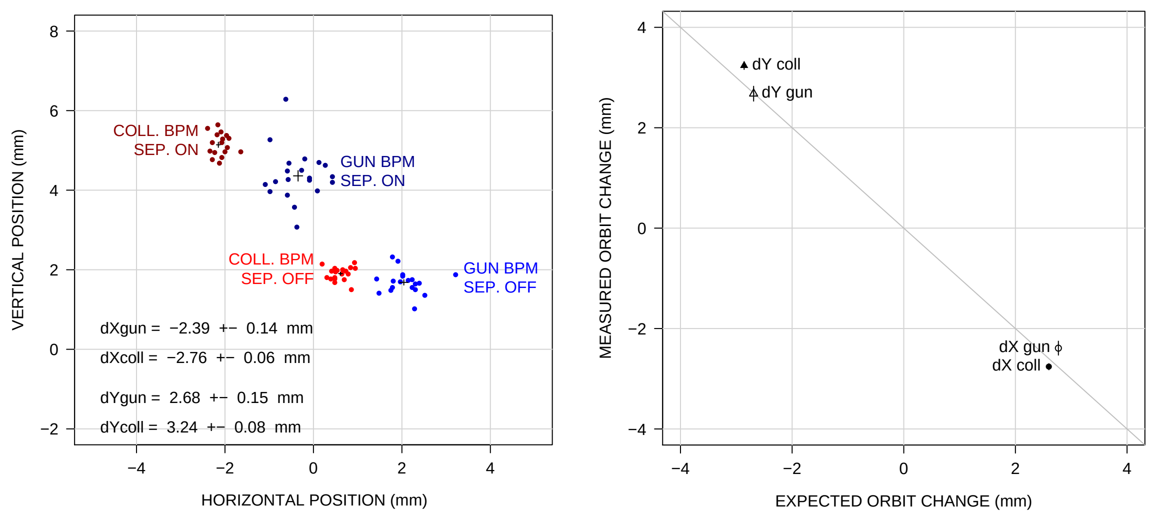

Figure 5: TEL2 BPM calibration with separators: measured positions (left) and comparison with expected values (right).

Observable	Measured / Expected Slopes
Δx gun (mm)	1.07 ± 0.01
Δx coll. (mm)	1.03 ± 0.01
Δy gun (mm)	1.028 ± 0.003
Δy coll. (mm)	1.031 ± 0.004
$\Delta x'$ (mrad)	1.10 ± 0.06

Table 2: TEL2 BPM calibration with orbit bumps.

all uncertainties are statistical only. Aside from a trivial error in the sign convention in both planes, which was later corrected, the ratios between measured and expected orbit differences are equal to 1 to within a few percent.

3 Calibration for protons with orbit bumps

On Dec 10, 2009, the TEL2 BPM readings were checked against calibrated orbit bumps (Beam-Beam Compensation E-log entry #284). This calibration relies on the Tevatron lattice measurements and the Tevatron BPMs.

Results are summarized in Figure 6 and Table 2. Linearity is good and the calibration constants are equal to 1 to within a few percent. For the angle calibration, the value of 140 cm was used as distance between BPM centers. From the standard deviation of the difference between horizontal gun and collector measurements, $\sigma = 31\ \mu$m (Figure 6, bottom left), we conclude that, at least horizontally, the resolution of the BPM system is approximately $\sigma/\sqrt{2} = 22\ \mu$m.

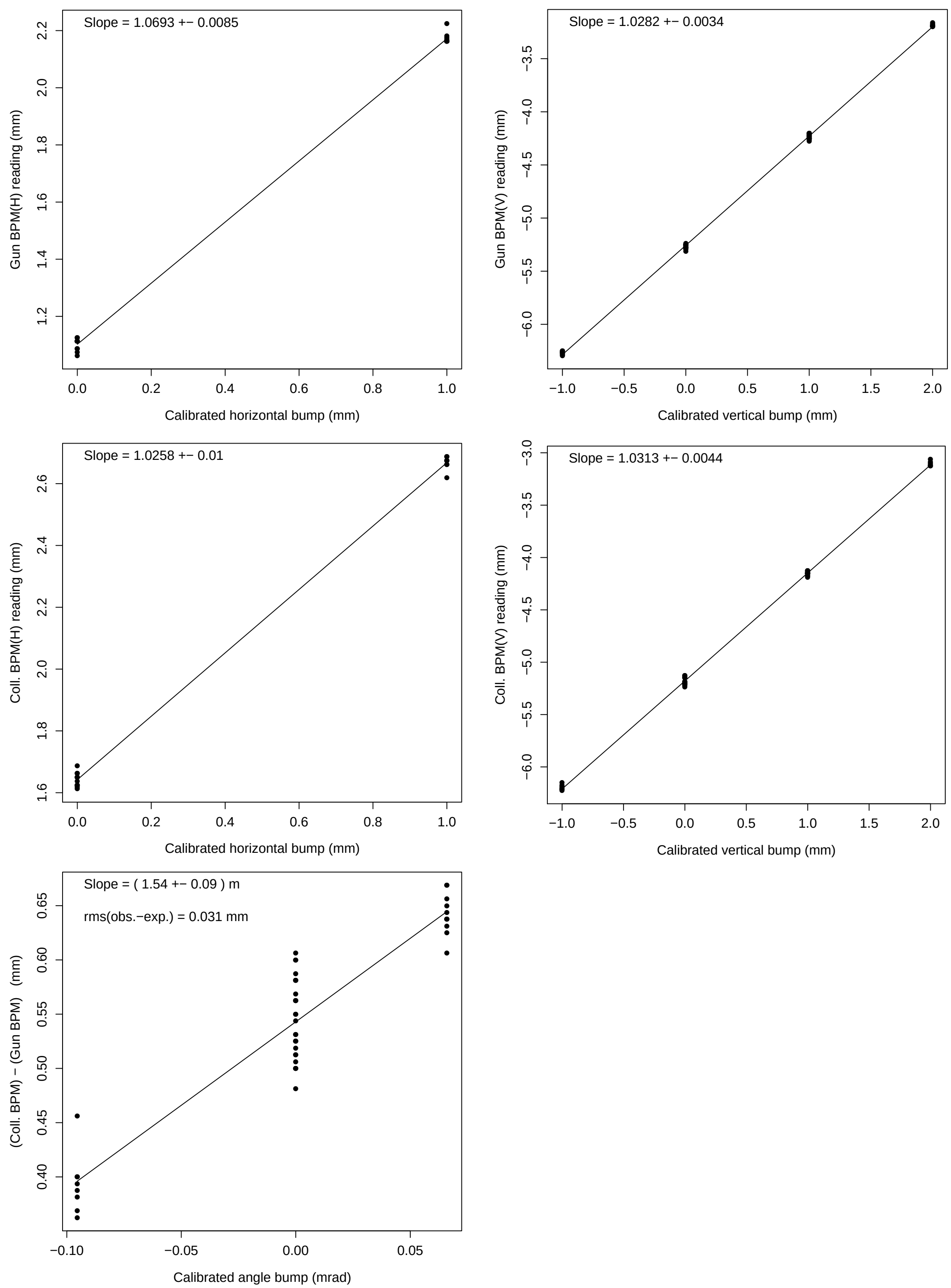

Figure 6: TEL2 BPM calibration with orbit bumps: horizontal gun, collector and angle (left column) and vertical gun and collector (right column).

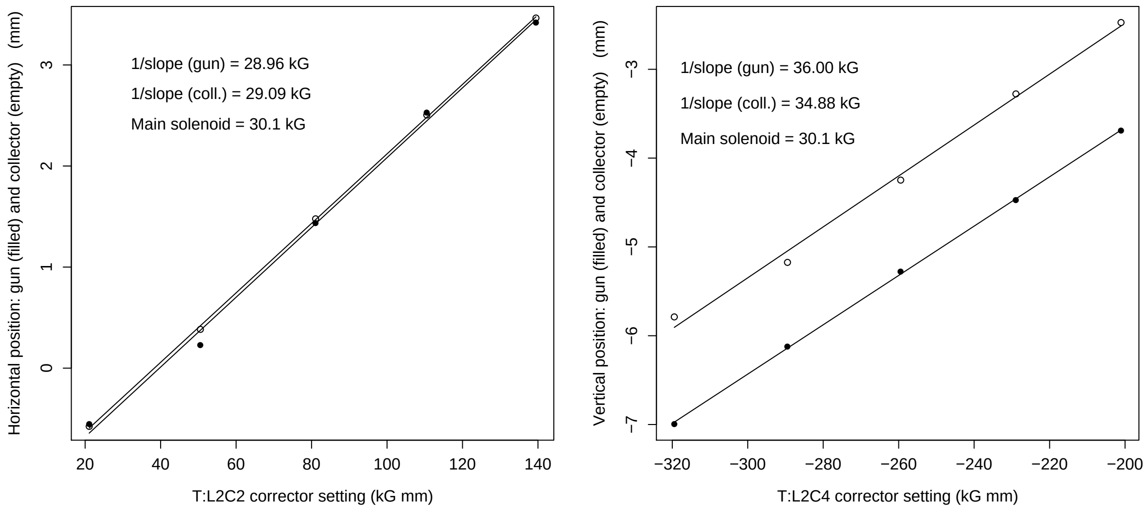

Figure 7: TEL2 BPM calibration with electrons and magnetic correctors: horizontal gun and collector (left) and vertical gun and collector (right).

Observable	Measured / Expected Slopes
Δx gun (mm)	1.04 ± 0.04
Δx coll. (mm)	1.03 ± 0.01
Δy gun (mm)	0.84 ± 0.01
Δy coll. (mm)	0.86 ± 0.04

Table 3: TEL2 BPM calibration with electrons and magnetic correctors.

4 Calibration for electrons with magnetic correctors

Calibration with electrons was carried out on Dec 14, 2009 (Beam-Beam Compensation E-log entry #285). The electron beam was timed with the abort gap. Horizontal and vertical bumps were generated by the magnetic correctors in the main solenoid: T:L2C1 and T:L2C2 for horizontal, and T:L2C3 and T:L2C4 for vertical. This calibration relies on magnetic measurements in these correctors, which are translated into strengths in kG $\cdot$ mm. The gun and collector solenoids were set at 2.93 kG (2.86 kG readback), and the main solenoid was set at 30.0 kG (30.1 kG readback).

Results are shown in Figure 7 and Table 3. The horizontal slope looks good, whereas the vertical measurements seem about 15% too low. This difference is currently not understood.

5 Estimation of proton-electron offsets from loss scans

A possible BPM offset between proton and electron position measurements was estimated on Dec 14–15, 2009 (Beam-Beam Compensation E-log entries #285 and #286) with the following procedure.

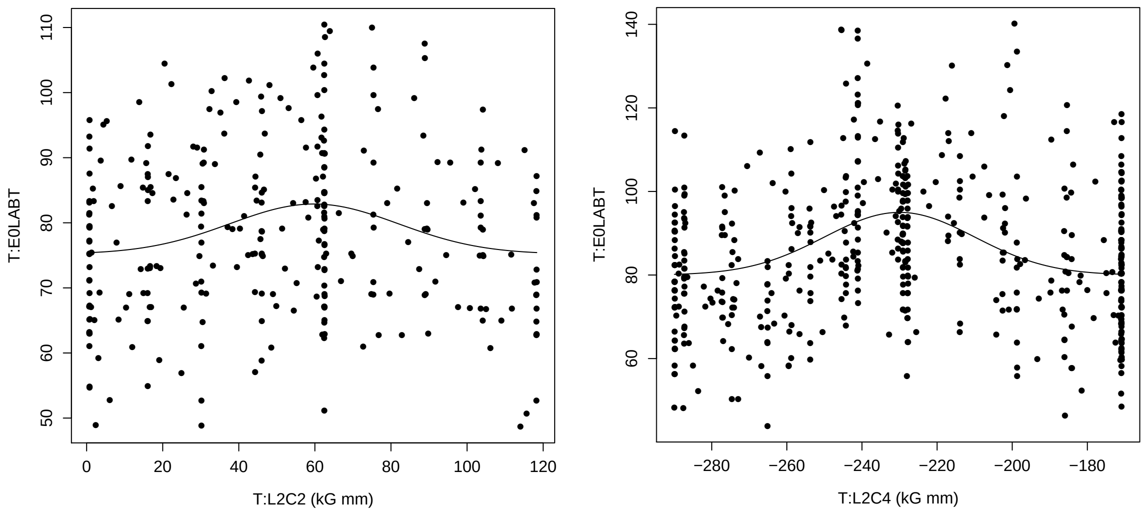

Figure 8: Results of the horizontal (left) and vertical (right) loss scans with electrons timed to the abort gap.

Proton and electron beams were aligned according to the TEL2 BPM measurements. Proton losses were then measured as the electrons beam was moved horizontally and vertically. The difference between the initial position and the position corresponding to the loss peak is taken as an estimate of the offset.

The electron beam was roughly aligned with the proton beam using the BPM readings, acting on all 6 correctors to adjust horizontal and vertical positions and angles. With the following corrector values (in kG mm)

Horizontal			Vertical		
T:L2C1	T:L2C2	T:L2C5	T:L2C3	T:L2C4	T:L2C6
−92.55	60.48	25.76	242.2	−232.6	−19.84

the corresponding 'aligned' positions were

	Horizontal		Vertical	
	gun	coll.	gun	coll.
p positions (mm)	0.930 ± 0.005	1.533 ± 0.005	-4.784 ± 0.005	-4.943 ± 0.005
e positions (mm)	0.94 ± 0.02	1.48 ± 0.02	-4.82 ± 0.01	-5.04 ± 0.01

The first loss scan was done with electrons timed to the abort gap. Horizontal positons were changed using a mult acting simultaneously on $(1\times)$T:L2C1 and $(-1\times)$T:L2C2. Similarly, T:L2C3 and T:L2C4 were used for vertical displacements. Losses were measured by the E0 Tevatron loss scaler timed to the abort gap, device T:E0LABT. Measurements are reported in Figure 8 and the results of a Gaussian interpolation are given in Table 4. The measurement was noisy, but there was indication that the offsets were indeed small, because the corrector values corresponding to the loss peaks are close to the aligned values.

Fit parameter	Abort-gap scan		P4 scan	
	H	V	H	V
Mean (kG mm)	60 ± 79	-230 ± 54	52 ± 11	-231 ± 5
Rms (kG mm)	22 ± 71	20 ± 49	52 ± 82	39 ± 25
Signal (Hz)	8 ± 26	15 ± 26	78 ± 192	75 ± 58
Background (Hz)	75 ± 21	80 ± 18	72 ± 193	55 ± 59
Input errors (Hz)	14	12	11	7

Table 4: Results of loss scans.

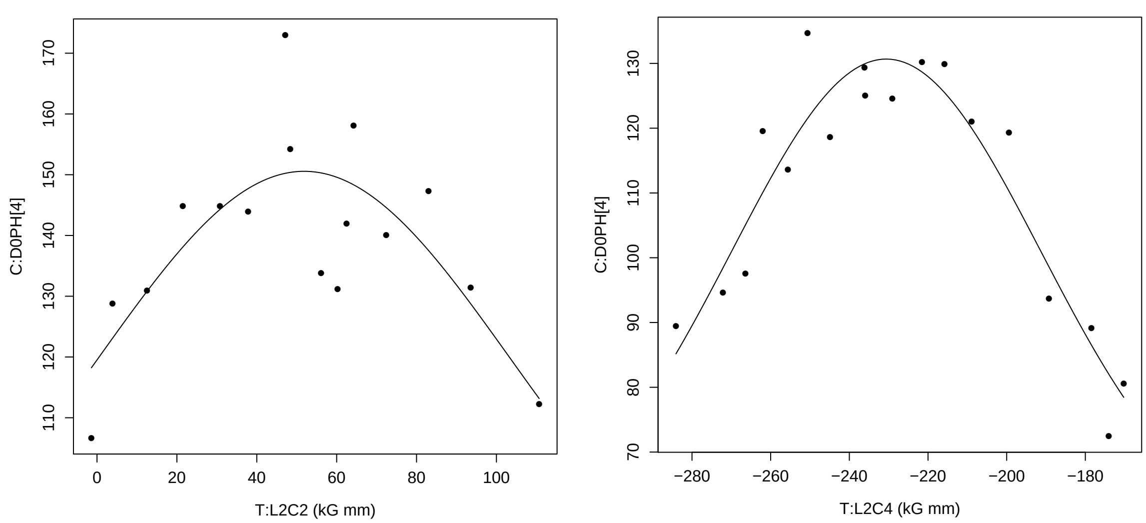

Figure 9: Results of the horizontal (left) and vertical (right) loss scans with electrons timed to proton bunch #4 (P4).

A cleaner scan was done by overlapping the electron beam with proton bunch #4 (P4) and looking at losses from the D0 proton halo monitor, device C:D0PH[4] (Figure 9). The results of the Gaussian interpolation are reported in Table 4. The electron positions corresponding to the loss peaks are determined taking the difference between the peak corrector settings (from the Gaussian fits) and their 'aligned' values from above, and then translating the results into positions using the slopes from Section 4. They are reported here together with the proton positions for comparison:

	Horizontal		Vertical	
	gun	coll.	gun	coll.
e positions at loss peak (mm)	$+0.65 \pm 0.38$	$+1.19 \pm 0.38$	-4.78 ± 0.14	-4.99 ± 0.14
p positions (mm)	$+0.930$	$+1.533$	-4.784	-4.943
Offset $(e-p)$	-0.28 ± 0.38	-0.34 ± 0.38	$+0.01 \pm 0.14$	-0.05 ± 0.14

The vertical offsets are indeed small, and consistent with the stretched-wire measurements reported in Ref. [2]. It appears that the horizontal offsets are larger, but it is difficult to draw conclusions at this stage. A more detailed scan may be useful.

Let us also compare the widths of the loss-scan curves with the expected beam sizes. From measurements of the Gaussian-gun profile in the test stand, we expect the electron beam rms to be

$$\sigma^e_{x,y} = (1.67\ \mathrm{mm})\sqrt{\frac{(2.86\ \mathrm{kG})}{(30.1\ \mathrm{kG})}} = 0.52\ \mathrm{mm}.$$

The lattice functions at the TEL2 location are

$$\begin{array}{ll} \beta_x = 66\ \mathrm{m} & \beta_y = 160\ \mathrm{m} \\ D_x = 1.18\ \mathrm{m} & D_y = -1.00\ \mathrm{m} \end{array}$$

At the end of store #7439, the beam emittances (95%, normalized) and momentum spreads were

$$\begin{array}{ll} \varepsilon^p = 30\ \mu\mathrm{m} & \varepsilon^{\bar{p}} = 15\ \mu\mathrm{m} \\ \left(\frac{\sigma_p}{p}\right)^p = 1.74 \times 10^{-4} & \left(\frac{\sigma_p}{p}\right)^{\bar{p}} = 1.5 \times 10^{-4} \end{array}$$

The expected rms beam sizes,

$$\sigma = \sqrt{\beta\varepsilon + \left(D\frac{\sigma_p}{p}\right)^2},$$

are therefore

$$\begin{array}{ll} \sigma^p_x = 0.60\ \mathrm{mm} & \sigma^p_y = 0.89\ \mathrm{mm} \\ \sigma^{\bar{p}}_x = 0.44\ \mathrm{mm} & \sigma^{\bar{p}}_y = 0.64\ \mathrm{mm} \end{array}$$

At the end of a store, when beam-beam effects are unimportant, the expected loss curve is a Gaussian convolution of electron and proton beam distributions:

$$\sqrt{(\sigma_x^e)^2 + (\sigma_x^p)^2} = 0.79 \text{ mm} \quad \sqrt{(\sigma_y^e)^2 + (\sigma_y^p)^2} = 1.03 \text{ mm}$$

From the results of the fits, one can see that vertically the measured width (according to the BPMs)

$$\frac{(39 \pm 25 \text{ kG mm})}{(35 \text{ kG})} = 1.1 \pm 0.7 \text{ mm}$$

is quite close to the expected beam convolution. Horizontally, the measured width (~ 1.7 mm) has large uncertainties, and one cannot draw conclusions at this point.

6 Conclusions

We obtained reasonable calibration constants for the TEL2 BPMs with both protons and electrons using the new Java-based readout. The offset between slow electron signals and fast proton signals is small and consistent with the stretched-wire measurements of Ref. [2], at least in the vertical plane. More accurate measurements would be useful horizontally. We are ready to start looking for proton and antiproton tune-spread changes induced by the Gaussian electron gun.

References

[1] V. Shiltsev et al. Experimental studies of compensation of beam-beam effects with Tevatron electron lenses. *New J. Phys.*, 10:043042, April 2008. doi:10.1088/1367-2630/10/4/043042.

[2] V. E. Scarpine et al. Measurements of a Newly Designed BPM for the Tevatron Electron Lens 2. In *Proceedings of the Twelfth Beam Instrumentation Workshop (BIW 2006)*, volume 868, page 481. AIP Conf. Proc., 2006. doi:10.1063/1.2401438.