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On the Calibration of TEVATRON Beam Position and Intensity Monitors Used in E778

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I. INTRODUCTION

In the second run of E778 two sets of electronics were used to record the motion of the center of mass of the beam. The first, the standard Fermilab Beam Position Monitor (BPM) front end, gives direct horizontal, vertical and intensity signals. The second is a peak sensing circuit which gives signals from the separate plates of two horizontal and one vertical pickup.

This note addresses the question of calibration of the signals from the standard Tevatron beam position (HF42 and HF44 in the case of E778) and intensity monitors (I_45).

In a different note the calibration of the peak detectors will be addressed. In principal, it is possible to cross calibrate the two sets of electronics. It has not yet been attempted.

Following is the summary of this study:

Calibration Constants

Position Monitors : .0083 mm/mV

$$\textbf{Intensity Monitors}\begin{cases}\textbf{Smear data :} & \mathbf{-147}\ \dfrac{\text{LSB}}{\mathbf{10^{10}}\ \text{particles}}\\ \textbf{Resonance island data :} & \mathbf{(-134 \pm 7)}\ \dfrac{\text{LSB}}{\mathbf{10^{10}}\ \text{particles}}\end{cases}$$

II. POSITION MONITORS

Here we want to determine the conversion factor from Least Significant Bits (LSB's) to mm of displacement at the location of the BPM's used to record the data (HF42 and HF44).

Chris Saltmarsh's program *plinf*, when applied to a given dataset, gives, among other information, a scale factor which is the number of μV per LSB. For example, a scale factor of 2.5 100 μV implies .250 mV/LSB. Notice that the scale factor may vary among various datasets but it can only assume the following values: 100 μV/LSB, 250 μV/LSB, 500 μV/LSB, 1 mV/LSB, 2.5 mV/LSB, 6.25 mV/LSB, 12.5 mV/LSB and 25 mV/LSB.

What remains to be determined is the calibration factor from mV to mm. On this issue we have two independent sources of information. The first comes from the knowledge of the hardware and the second from direct observation.

1. Hardware

The calibration of the position (as well as the intensity) signal involves three components: the detector, the cable and the rf module.

1a. The Detector

If (A/B) is the ratio of the rf signal amplitudes out of the two detector output ports on either side of the vacuum chamber, then the response of the detector as given in IEEE NS Vol NS-28 #3 (1981) pg 2290, is

$$.67 \text{ x} = 20\log_{10}\left(\frac{A}{B}\right) = \left(\frac{A}{B}\right)_{db}$$

where x is in mm.

1b. The Cable

In this case we can ignore the cable since both signals, A and B, are treated alike.

1c. The rf Module

Let v denote the output of the rf module in Volts; one can convince oneself that (see ref. IEEE NS Vol NS-28, pg 2325-5):

$$\left(\frac{A}{B}\right)_{db} = \frac{20}{\ln(10)}\ln\left[\tan\left(\frac{\pi}{10}v + \frac{\pi}{4}\right)\right] = .67 \text{ x}$$

Now we are going to linearize this expression. First using

$$\tan(\alpha + \beta) = \frac{\tan\alpha + \tan\beta}{1 - \tan\alpha\tan\beta}$$

we get

$$.67 \text{ x} = \frac{20}{\ln(10)}\ln\left[\frac{1 + \tan(\frac{\pi}{10}v)}{1 - \tan(\frac{\pi}{10}v)}\right]$$

Then expanding $\ln\left(\frac{1+z}{1-z}\right)$, $z = \tan(\pi v/10)$ and keeping only the first term, yields:

$$\text{x} = \frac{20}{.67\ln(10)}2\tan\left(\frac{\pi}{10}v\right)$$

which, in the small angle approximation becomes

$$\text{x} = \frac{20}{.67\ln(10)}2\frac{\pi}{10}v$$

or

$$x = 8.14v$$

or

$$\text{calibration constant} = .00814\ \frac{\text{mm}}{\text{mV}}$$

Note that if we limit ourselves to excursions of about ±4mm, then $v = .5$ and $\frac{\pi}{10}v = .157$ so the approximations used above are valid.

In calibrating the data taken for the smear measurements, we actually used a slightly different value of the calibration constant (.0083 mm/mV). This value though, came from a more precise evaluation of some of the system constants (See Fermilab, BPM Design Note #4).

2. Direct Observation

The second source of information is the 2 plots attached here. In fig. 1, (a) and (c) are the outputs of two neighboring beam position monitors (HE24 and HE26) for 1024 turns. The vertical axis is in mm. Fig. 2 is the plot of the same data as recorded by the BPM's at HF42 and HF44. Here the vertical axis is in bits (data was recorded by the SUN Workstation; the file, which is called *calibr*, is on Myrtle in the directory *camac/safe*). In both figures, a synchrotron motion of period 600 turns is apparent. From fig. 1(a) we can see that the peak to peak variation of the centroid of the beam during the first 100 turns after the kick is 4.35 mm. (This is the difference between the amplitudes after and before the kick. Unfortunately the only dataset we recorded for calibration purposes happened to be damaged by noise. This was actually an unusual situation. The majority of the data we took look like fig. 2(b)). From fig. 2(a) the corresponding quantity is 1150 bits (again here the amplitude after the kick is 1550 bits while before the kick it is 400 bits). So the conversion is .0038mm/LSB if the beta functions at the two BPM's (HE24 and HF42) are equal. From *plinf* we find that these data were taken with a scale factor 500 μV/LSB. The combination of the above gives .0038mm/LSB × 2 LSB/mV or .0076 mm/mV. Now we should correct this number for the fact that the beta functions at the locations of the 2 BPM's are not the same. The design values of the two betas are $\beta_{\text{HE24}} = 100.555$m and $\beta_{\text{HF42}} = 100.143$m. The correction factor is the square root of the ratio of the two betas. The final value of the calibration constant is still

$$\text{calibration constant} = .0076\ \frac{\text{mm}}{\text{mV}}$$

Both methods we described above are likely to have errors of the order of 5%. The use of the design values of betas, for example, introduces an error. Within this error the two methods agree. Notice that in the analysis of the smear data we used the number .0083 mm/mV, being aware of its inaccuracy at the 5% level.

III. INTENSITY MONITORS

In this case we want to be able to translate bits into particles per bunch. Again *plinf* in principal provides us with the scale factor, the number of μV per LSB, for the particular dataset. So what remains to be specified is the conversion between mV and number of particles per bunch. The same three factors, as before (detector, cable, and RF module) enter the calibration of the intensity signal.

1. Hardware

1a. The Detector

If V_d is the detector output in Volts, then the intensity in particles per bunch is:

$$I\ (\mathrm{ppb}) = 2.17 * 10^{10} V_d$$

1b. The Cable

For a cable of length L in feet,

$$V_C = \frac{V_d}{e^{L/668}}$$

(According to a catalog, the attenuation along a 100′ cable is 1.3 dB at 53 MHz)

1c. The RF Module

$$V_{RF} = \frac{V_C}{.356}$$

If we take all these factors into account and use $L = 150'$ we arrive at

$$V_{RF\ \mathrm{mod}} = \frac{I(\mathrm{ppb})}{9.7 * 10^9}$$

In view of a bug discovered in the data reading program we can not rely on the scale factors given by *plinf*. So we have to drop this method for calibrating I_45 altogether. At the moment, it seems that the most reliable way of calibrating the intensity signal is to relate it with the recordings of the Tevatron device T:IBEAM, which gives us the number of particles in the machine at 39 seconds within the supercycle (1 second before the kick occurs).

2. Direct Observation

The intensity signal is noticeably affected by a self-excited coherent oscillation at the synchrotron frequency of approximately 800 turns as fig. 3 shows. We should remark that 2048 bits correspond to 0 intensity. The kick here occurs at turn number 8240. In order to extract the value of the intensity signal, as given by I_45 in LSB's we average over 800 turns, before the kick. In fig. 4 and 5 we plot the I_45 signal versus the reading of T:IBEAM from the smear and the resonance island data correspondingly. Different symbols correspond to different tapes. LE and HE denote low and high emittances. Next we do least-squares fits to a line with one end fixed (the line passes through 2048) to deduce the slopes for each tape.

On fig. 6 we summarize the results by plotting the slope *i.e.* the calibration constant in LSB's per 10^{10} particles, for each tape.

From here we can extract the calibration constant to be used on the resonance island data (tapes 12-17) by averaging over the constants from the 6 tapes:

$$\text{calibration constant} = (-134 \pm 7)\frac{\text{LSB}}{10^{10}\ \text{particles}}$$

For the smear data we did not need to know the value of I_45 in particles per bunch. For reference purposes, though, we quote that for the smear data

$$\text{calibration constant} = -147\ \frac{\text{LSB}}{10^{10}\ \text{particles}}$$

This value comes entirely from the data of tape 18. The reason we did not use other data is that for tapes 8 and 9 the intensity signal was saturated, and for tapes 6 and 7, I_45 depends on T:IBEAM in an abnormal way.

Acknowledgments

We are deepply indebted to Chris Saltmarsh for all his help during the E778 experiment including his almost successful attempt to stretch our debugging abilities to the limit.

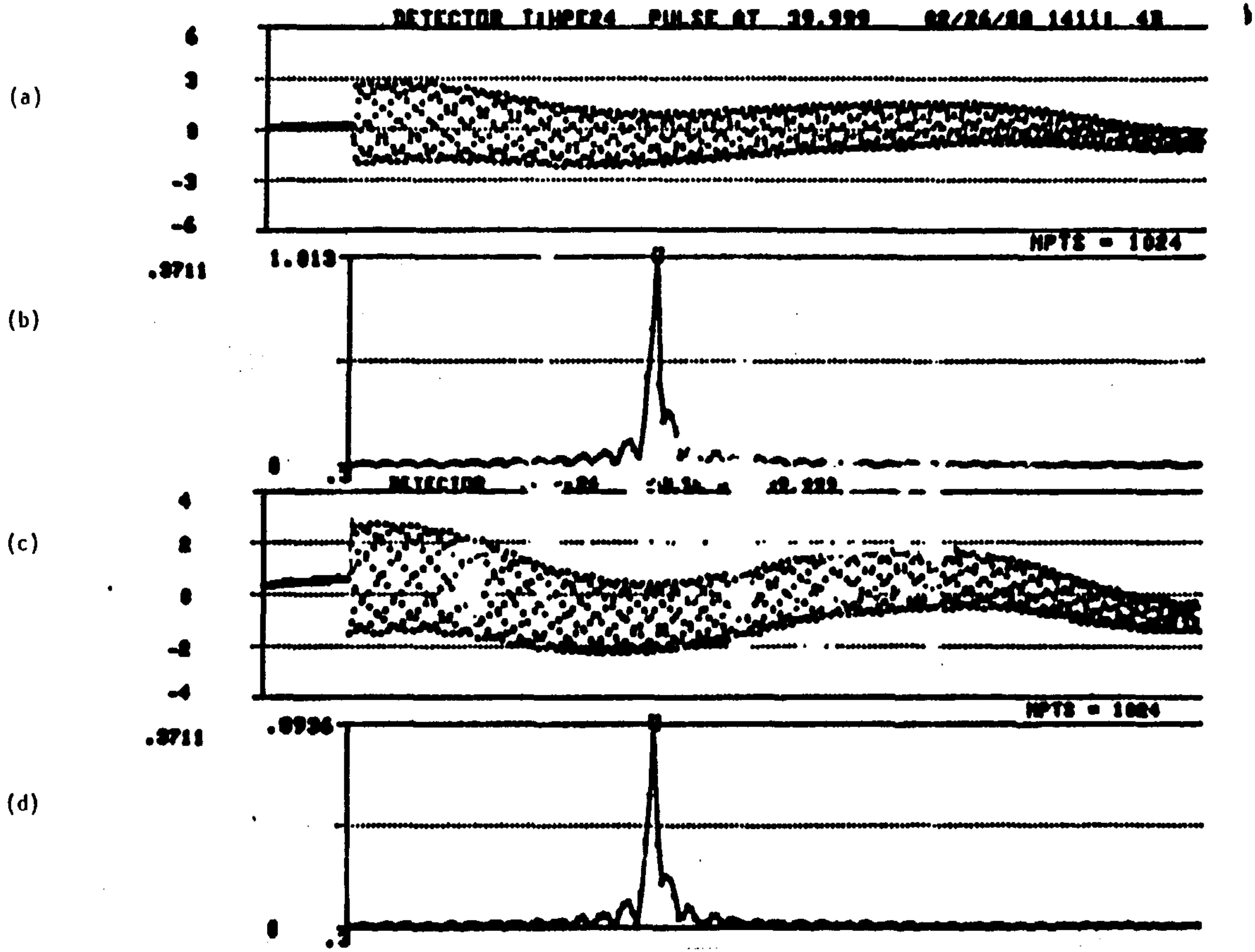

Fig. 1. (a) and (c) are the output of two neighboring Tevatron BPM's (HE24 and HE26) for 1024 turns. The vertical axis is displacement in mm.

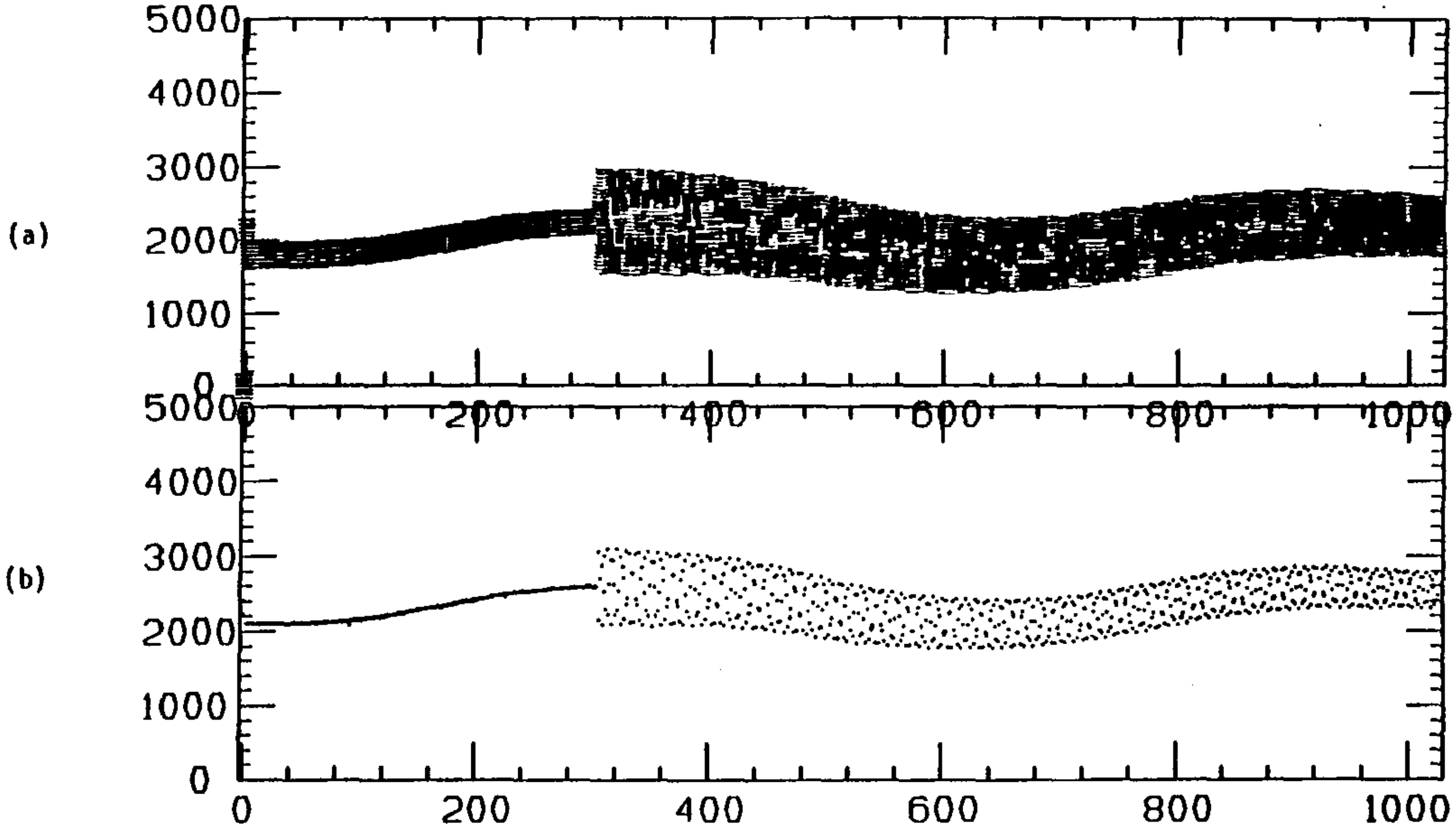

Fig. 2. (a) and (b) are the output of two Tevatron BPM's (HF42 and HF44) recorded by the SUN Workstation. The vertical axis is in bits.

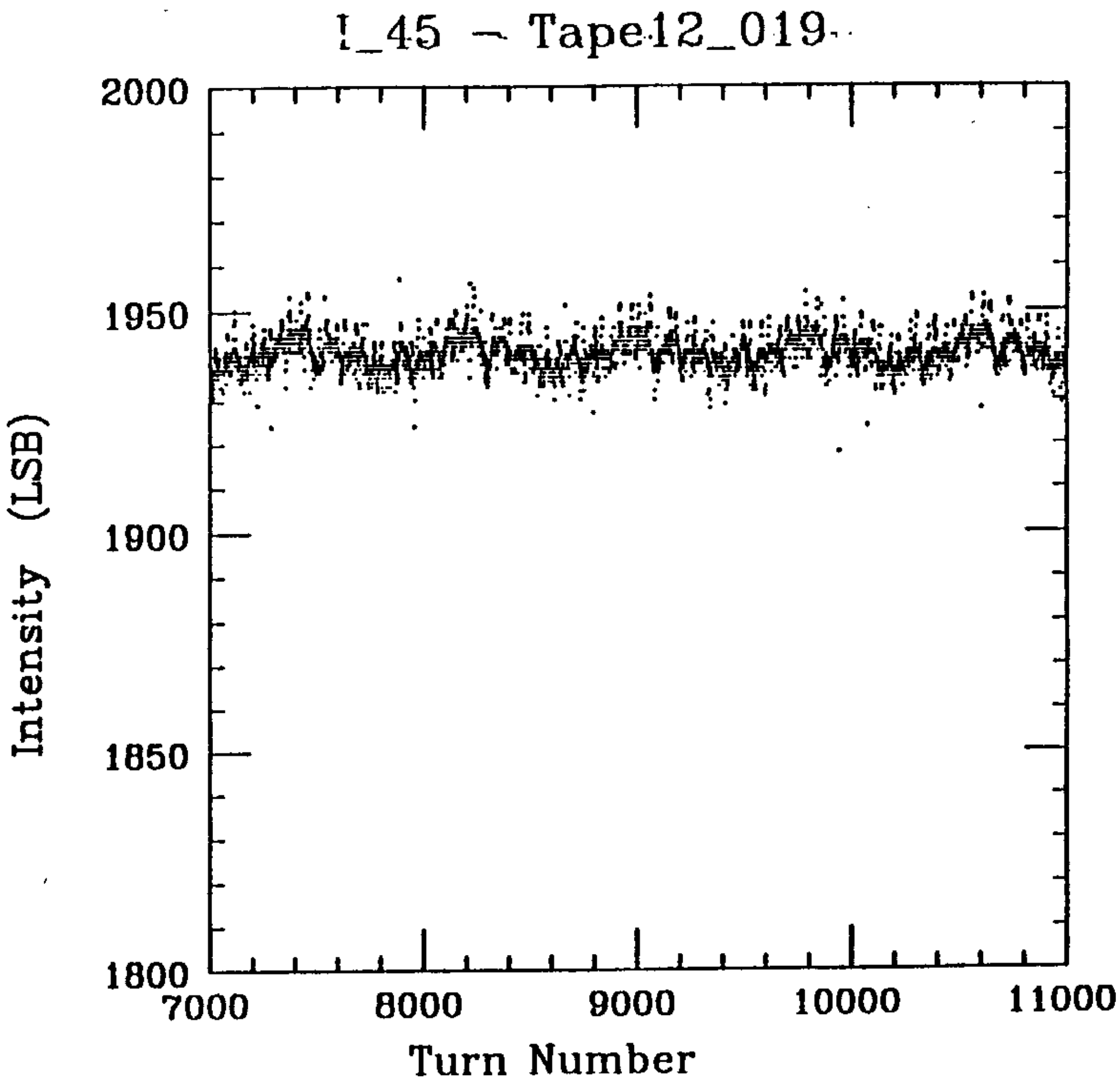

Fig. 3. The intensity signal (in bits) as given by the Tevatron beam intensity monitor I_45. 2048 bits correspond to 0 intensity.

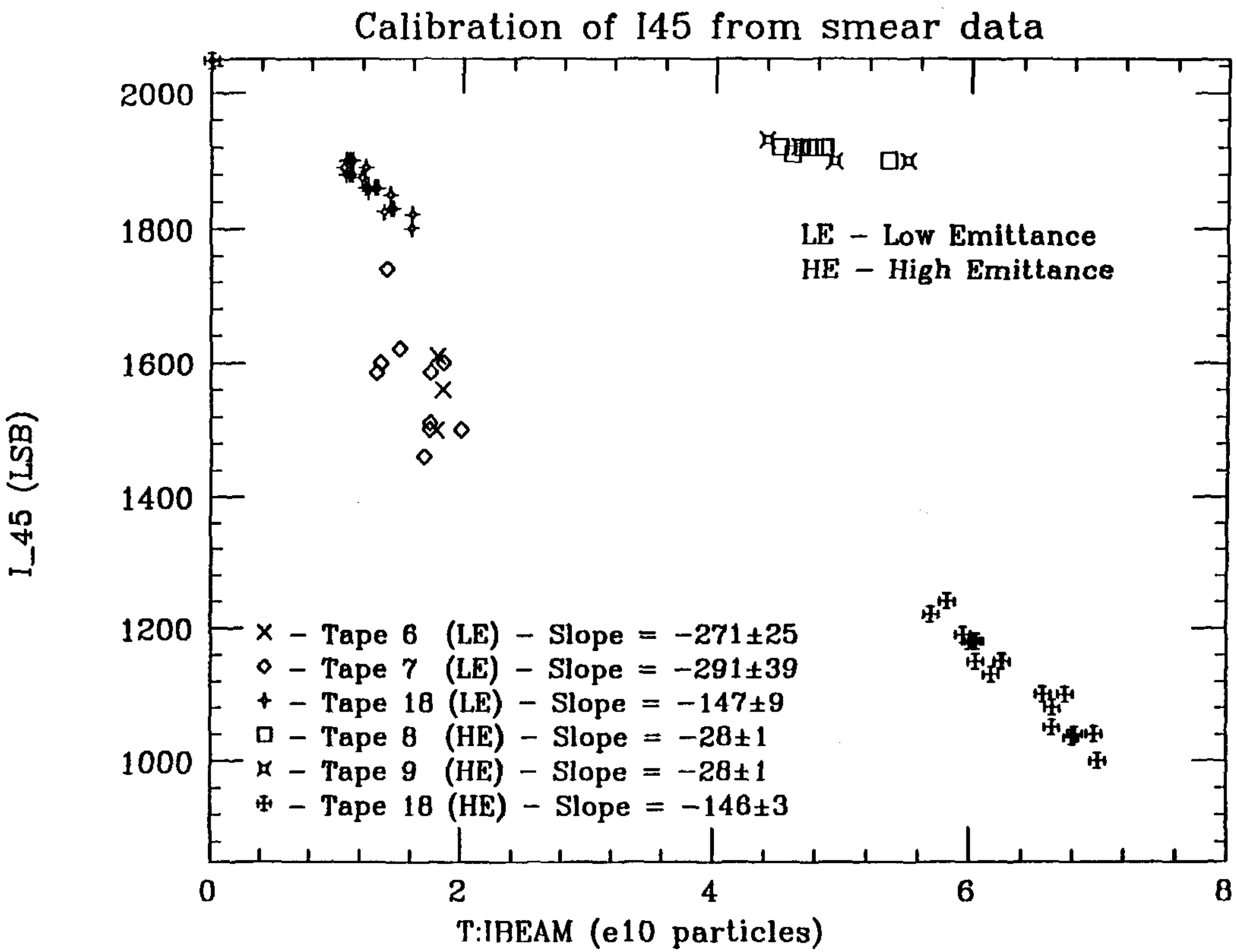

Fig. 4. Plot of the intensity signal as a function of the recordings of the Tevatron device T:IBEAM extracted from the smear data only.

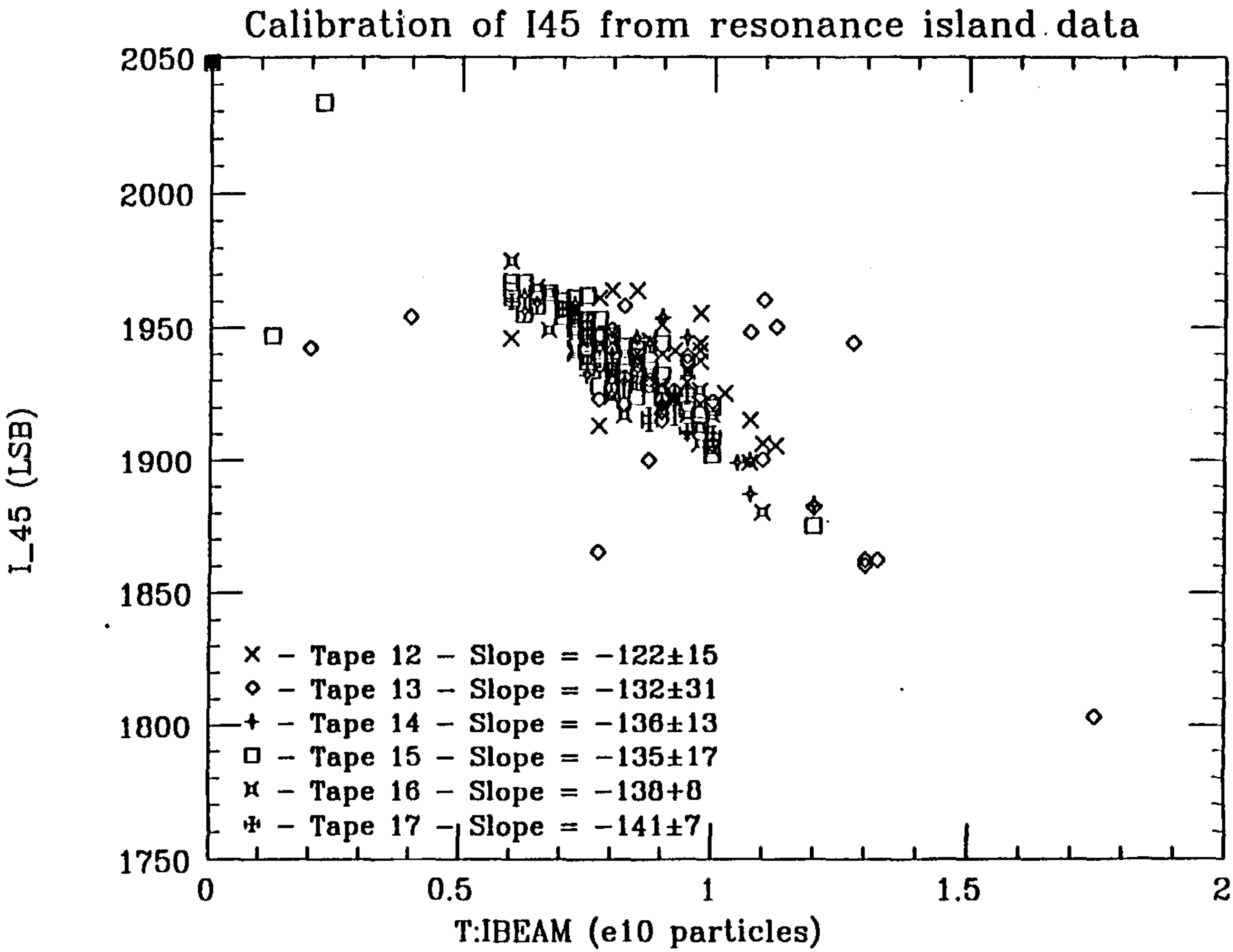

Fig. 5. Plot of the intensity signal as a function of T:IBEAM extracted from the resonance island data only.

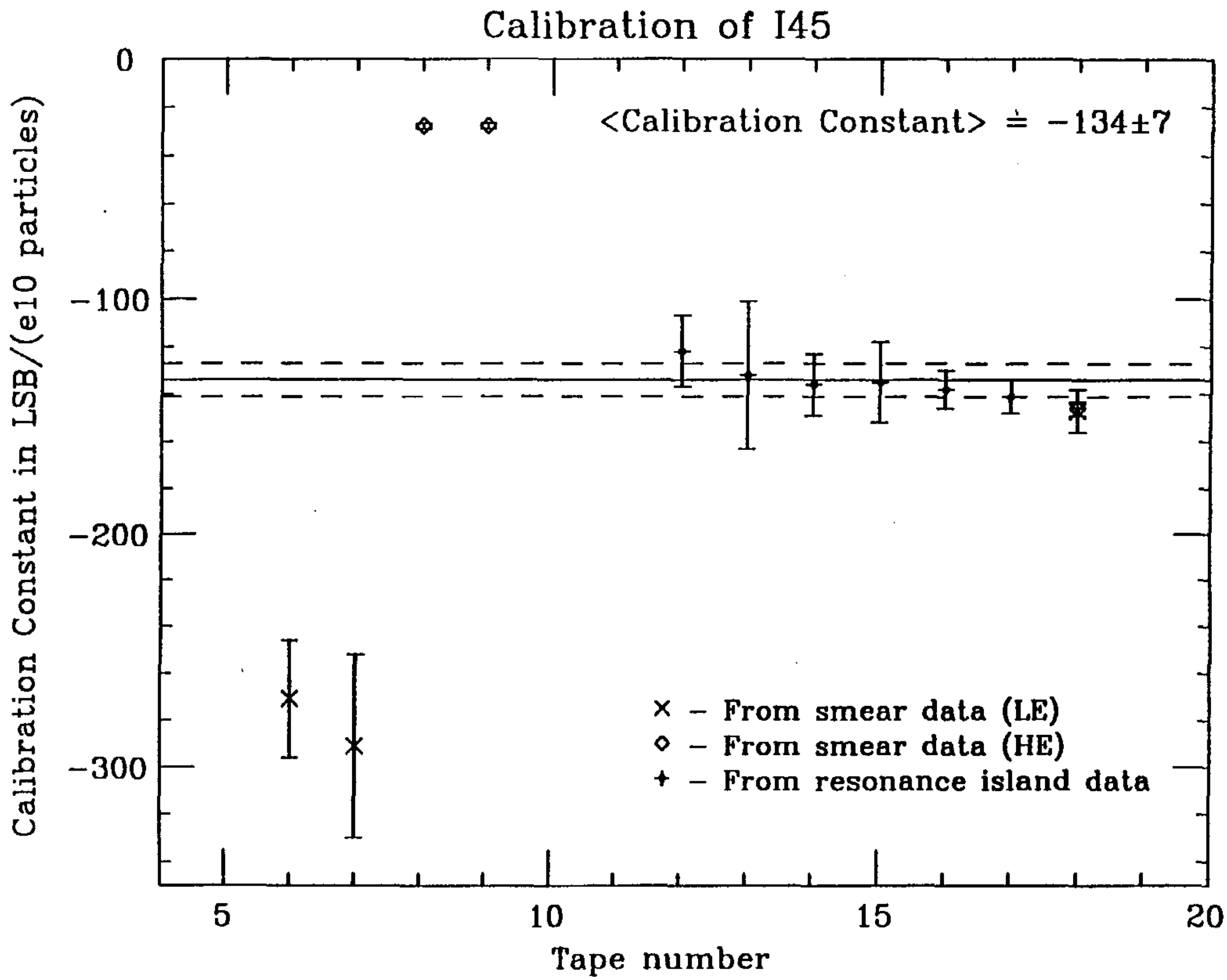

Fig. 6. Calibration constant for each tape separately. The average value, (-134±7) LSB/(10^{10} particles) is for the resonance island data.