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Correction of the LEP beam loss monitors for known saturation effects

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Abstract

The beam loss monitors installed in LEP cannot measure higher loss rates than the bunch passage frequency if they are not corrected for saturation effects. With certain assumptions about the detector efficiency it is possible to raise this threshold by almost one order of magnitude applying Poisson statistics.

This paper explains how to apply Poisson statistics to the problem. The necessary assumptions are given. Data supporting these assumptions and the results of measurements of the gain due to the enlarged range of sensitivity are shown.

1 Assumptions about detector efficiency

1.1 PIN diodes as detectors for charged particles

The beam loss monitors using PIN diodes were developed at DESY [1]. A loss monitor consists of two diodes which are sensitive to charged particles. A charged particle passing through the diode ionises the material along its track and thereby produces a signal. To suppress electronic noise and background due to synchrotron radiation only a coincidence signal from the two diodes is used.

At DESY the detection efficiency for minimal ionising particles (MIPS) was measured. The efficiency was measured to be $\epsilon_{BLM} = 0.348 \pm 0.019$ [2].

1.2 Assumptions

Most of the loss monitors in LEP are installed close to collimators in order to measure the rate of particle losses at these collimators. Usually they are installed such that they are sensitive to only one particle type[1] as can be seen in Fig. 1.

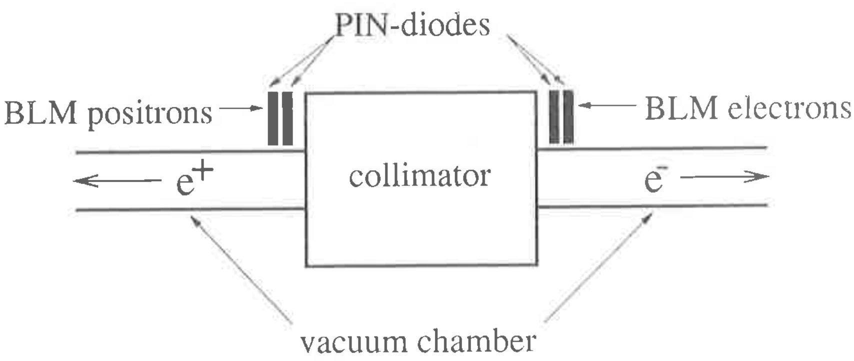

Figure 1: Schematic drawing of a collimator with the two beam loss monitors (BLM).

A particle hitting the collimator jaw will produce a shower. The energy is sufficient that some charged particles may reach the loss monitor installed behind the collimator. We assume that the probability of being detected is the same for all lost particle wherever they hit the collimator.

To apply the Poisson statistics we have to make an additional assumption: If the probability to detect one lost particle is p then the probability to get a signal if two particles are lost at the same time must be exactly $2 \cdot p$. This means that it is not possible that the two particles each produce a shower such that alone it would not be detected but together it can be detected. Experimental results given below support this hypothesis.

[1] The crosstalk is much less than 10%; in most cases of the order of 1 or 2%; it was measured with a single positron beam at 20 GeV.

2 Applying Poisson statistics

During the integration time for one measurement (typically 1 s) a certain number of particles is lost at the collimator. Only a fraction of these particles produces a shower which can be detected by the PIN diodes. The number of detectable particles l which are lost during the integration time can be between 0 and more than the number of bunch passages F during that time.

The number of observed hits h is less or equal l because two particles can be lost at the same bunch passage and therefore are not resolved as two separate losses[2]. The limit of the detector resolution is reached if $h = F$ [3].

If F is sufficiently large (typically $F \approx 45000$)[4], a mean number of losses per bunch passage μ can be defined:

$$\mu := \frac{l}{F} \tag{1}$$

Depending on collimator settings and beam conditions μ can vary between 10^{-5} and more than 1.

For a given μ the probability that n detectable particles hit the diode at one bunch passage is given by Poisson statistics as

$$f(n,\mu) = \frac{\mu^n \cdot e^{-\mu}}{n!} \tag{2}$$

The probability to have at least one detectable particle at a certain bunch passage and therefore a signal is given by

$$1 - f(0,\mu) = 1 - e^{-\mu} \tag{3}$$

where $f(0,\mu)$ is the probability to have no detectable particle and therefore no signal. From this follows that the number of observed hits during F bunch passages is given by

$$h = F \cdot \left(1 - e^{-\mu}\right) = F \cdot \left(1 - e^{-\frac{l}{F}}\right) \tag{4}$$

For small μ one can use $e^{-\mu} \approx 1 - \mu$ and therefore $h \approx F \cdot \mu = F \cdot \frac{l}{F} = l$ which is what one would expect (the few lost particles are lost at different bunch passages).

Equation 4 can be solved to get the total number of detectable particles in dependence of the number of observed hits h and the number of bunch passages F:

$$l = -F \cdot \ln\left(1 - \frac{h}{F}\right) \tag{5}$$

[2] The time resolution of the loss monitors is 50 ns. Therefore it is possible to distinguish between the bunches in a train, but not between different particles lost from the same bunch.

[3] As a 16bit ADC is used to read the data, F should not exceed 65536.

[4] in MDs we usually use four bunches per particle type.

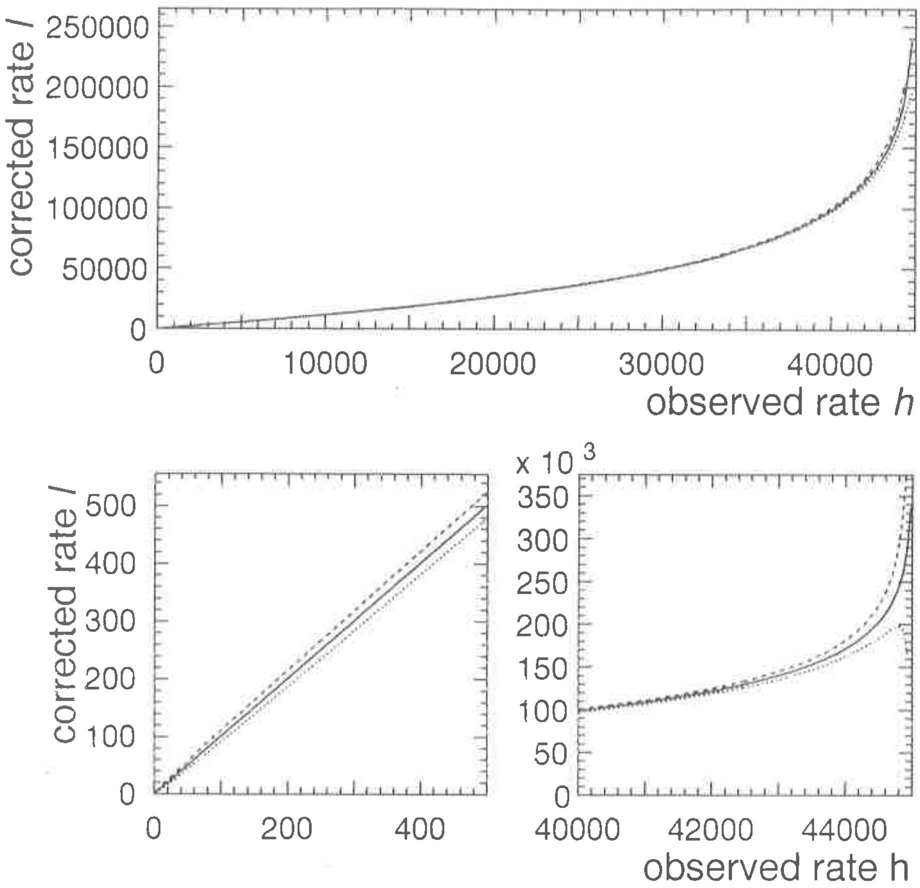

Figure 2: The real loss rate l as a function of the measured loss rate h for $F = 45000$ bunch passages. The two lower plots show an enlarged view of the upper and lower end of the curve. The errors are shown as dashed lines.

Figure 2 shows the relation between h and l including the errors as derived below. In addition Table 1 gives some values for different loss rates. To rewrite this equation in a different form we introduce the number of bunch passages without a hit $\overline{h} := F - h$. We then get

$$\begin{aligned} l &= F \cdot \ln\left(\frac{F}{\overline{h}}\right) \\ &= F \cdot \left[\ln F - \ln \overline{h}\right] \end{aligned} \tag{6}$$

From Eq. 5 follows that the exact knowledge of the number of bunch passages and therefore of the integration time is very important for high loss rates which are used for the calibration of the loss monitors (otherwise the lifetime of the beam is not small enough). Therefore the integration time of each measurement is stored together with the number of hits. This has to be done because the integration time varies for technical reasons.

observed hits	h	10	500	10000	44000
no hits	$\overline{h}$	44990	44500	35000	1000
corrected rate	l	10.001	503	11309	171300
statistical error	$(\Delta l)_{stat}$	3.163	23	129	9439
error due to ΔF	$(\Delta l)_F$	$1.1 \cdot 10^{-6}$	$6.3 \cdot 10^{-5}$	2	40
total error	$(\Delta l)_{total}$	3.163	23	129	9439
	$(\Delta l)_{total}/l$	32 %	4.6 %	1.1 %	5.5 %

Table 1: Examples for $F = 45000$ bunch passages which corresponds to four bunches and an integration time of about 1 s.

2.1 Error estimation

The statistical error of l due to the statistical error on the number of hits $(\Delta h)_{stat} = \sqrt{h}$ is given by

$$(\Delta l)_{stat} = (\Delta h)_{stat} \cdot \left| \frac{d\,l}{d\,h} \right| = \sqrt{h} \cdot \frac{F}{F-h} \tag{7}$$

For small loss rates ($h \approx l$) the total loss rate can be approximated to

$$l = h \pm \sqrt{h} \tag{8}$$

For large loss rates the number of bunch passages without a hit is $\overline{h} \pm \sqrt{\overline{h}}$. Using Eq. 6 one obtains[5]

$$\begin{aligned} l &= F \cdot \ln\left(\frac{F}{\overline{h} \pm \sqrt{\overline{h}}}\right) \\ &= F \cdot \left[\ln\left(\frac{F}{\overline{h}}\right) - \ln\left(1 \pm \frac{1}{\sqrt{\overline{h}}}\right)\right] \\ &\approx F \cdot \left[\ln\left(\frac{F}{\overline{h}}\right) \pm \frac{1}{\sqrt{\overline{h}}}\right] \end{aligned} \tag{9}$$

The error of the loss rate due to an error of the number of bunch passages is small. The integration time of the loss monitors is known with an uncertainty of less than 1 ms [6]. Therefore the error on the number of bunch passages assuming four bunches (typical MD conditions) is $\Delta F \approx 45$.

[5]The last line in Equation 9 is obtained using $\ln(1+\epsilon) \approx \epsilon$.

[6]If necessary this value could be given with an accuracy of the order of 10 to 100 μs.

The error $(\Delta l)_F$ is given by

$$(\Delta l)_F = \Delta F \cdot \left|\frac{d\,l}{d\,F}\right|$$
$$= \Delta F \cdot \left|-\ln\left(1-\frac{h}{F}\right) - \frac{h}{F-h}\right| \quad (10)$$

Using $\overline{h}$ one can rewrite Eq. 10 to

$$(\Delta l)_F = \Delta F \cdot \left|\ln F - \ln \overline{h} - \frac{h}{\overline{h}}\right| \quad (11)$$

For small h the expression given in Eq. 10 can be approximated to[7]

$$(\Delta l)_F \approx \Delta F \cdot \left|\frac{h}{F} - \frac{h}{F}\right| = 0 \quad (12)$$

For big h it is not possible to give a simple approximation. For typical integration times it can be shown numerically that $(\Delta l)_F$ stays smaller than the statistical error. Table 1 gives the errors for different loss rates. The total error is also indicated in Fig. 2 as dashed lines.

3 Results from measurements

3.1 Description of the measurements

The data shown in the following plots are from tail scans done partially during MDs and partially during physics. The tail scan collimators are equipped with two loss monitors per particle type which have different sizes of diodes and therefore different sensitivities.

In addition scintillators are used to have an independent measurement. The data from the scintillators is not updated as fast as that from the loss monitors. Therefore there is less data available per scan to compare the two instruments than there is to compare the two loss monitors.

3.2 Comparing different PIN-diode sizes

At the collimators which are used for the tail scans there are two loss monitors installed on each side of the collimator (one side measures the electrons, the other the positrons). The two monitors are glued together and put into a lead box with a thickness of 5mm to protect them from synchrotron radiation.

The smaller diodes have a size of 7.5625 mm^2, the larger ones of 100 mm^2 [3]. Therefore theoretically the sensitivity should be different by about a factor

[7]Using $\ln(1-\epsilon) \approx -\epsilon$.

of 13. In practise it can be larger because the two small diodes are so small, that the effective size of the detector, i.e. the overlap of the sensitive area of the two diodes, is even smaller. We expect the difference to be of the order of 15 to 20.

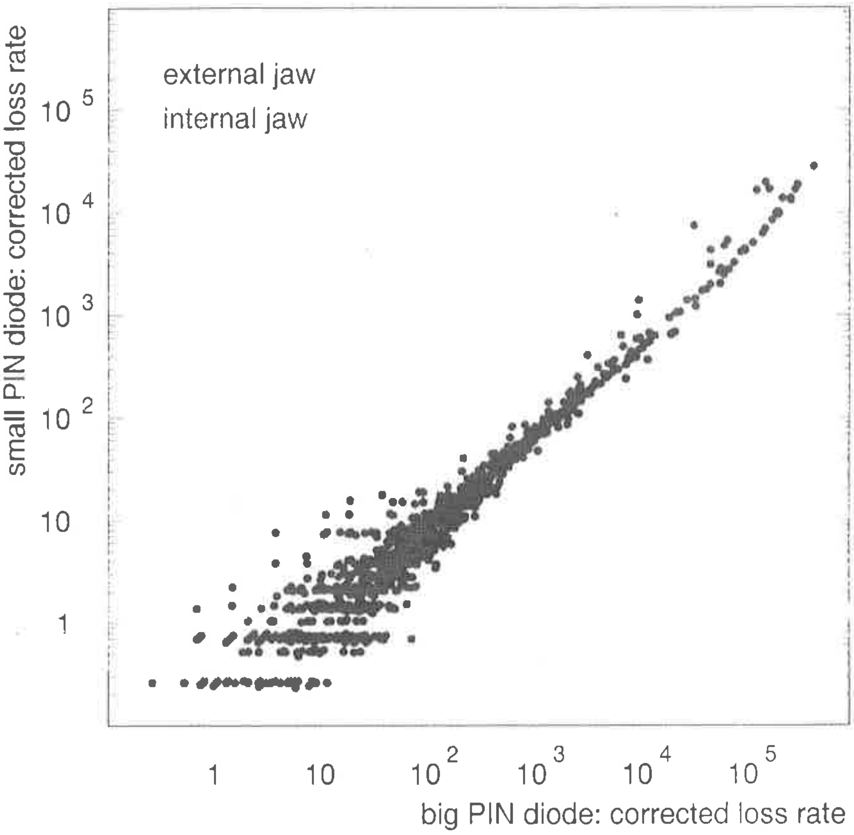

Figure 3: Comparison between corrected loss rates for small and big diodes.

Figure 3 shows data from some tail scans. The curve shows no saturation effects at the upper end. At the lower end the loss monitors are at the limit of their resolution. If one does not include the correction the curve changes slope for high loss rates.

The linearity over the whole range is very important for the calibration of the loss monitors. To get an absolute value of the loss rate they are calibrated using the lifetime as calculated from the measured bunch currents. This is only possible for the small diodes as the big ones saturate at lifetimes of about 20 hours. To extrapolate the calibration to the big diodes one must assume that they are linear.

3.3 Comparison with another instrument

The scintillators which are used are described in [4]. They are installed at the collimators which are used for tail scans. As they work in a different way they are ideal to check the linearity of the loss monitors (or vice versa).

In 1995 the scintillators could not give data with the same rate as the loss monitors. Only for every third to fourth point of a tail scan there is also a measurement from the scintillator. In addition there were still some slight problems with the synchronisation of the two instruments. Nevertheless the measurements were useful to check the linearity of the loss monitors.

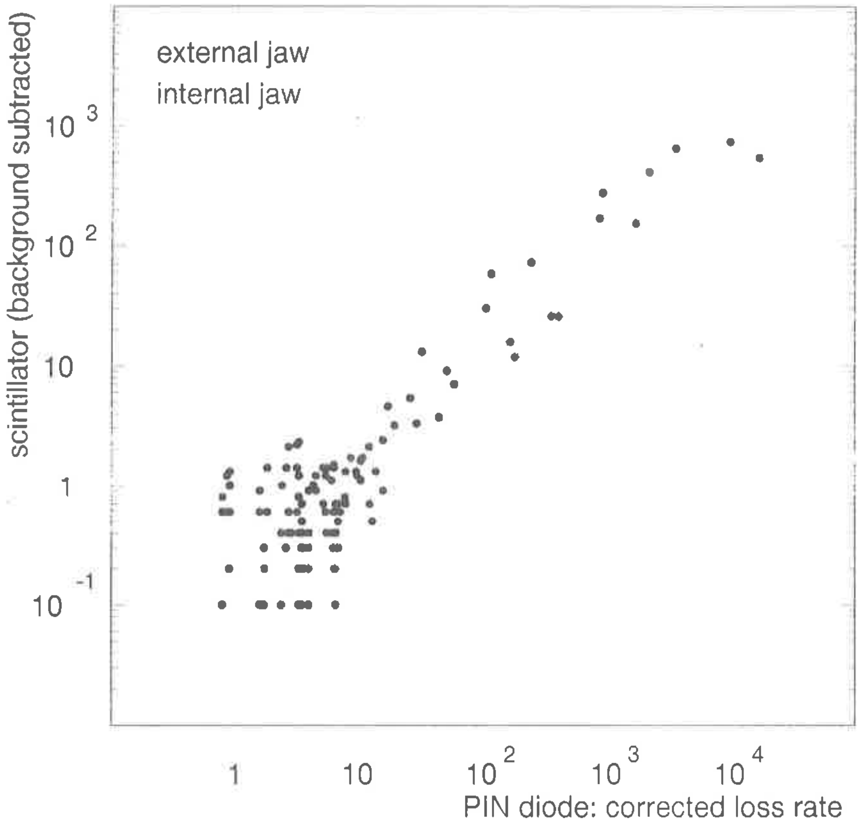

Figure 4: Comparison between corrected loss rates for the beam loss monitors and the rates measured with the scintillator. For the scintillator a constant background due to synchrotron radiation has to be subtracted.

Figure 4 shows the data from some tail scans taken during one fill. The corrected loss rate from the loss monitors is plotted versus the rate measured with the scintillator. The agreement between the two instruments is very good. The larger scatter at the lower end is due to the fact that at these low rates both instruments are at the limit of their resolution. The good linearity supports the assumptions made to apply the correction.

4 Conclusion

Applying Poisson-statistics has improved the resolution of the beam loss monitors by almost one order of magnitude. The correction can be easily implemented into the software.

Comparisons between the different sizes of the loss monitors and the scintillators showed that (after applying the correction) both instruments are linear over the range of sensitivity of the loss monitors.

References

[1] K. Wittenburg W. Bialowons, F. Ridoutt. Electron beam loss monitors for HERA. In *Proceedings of the 4th European Particle Accelerator Conference*, 1994.

[2] F. Ridoutt. Das Ansprechvermögen des PIN-Strahlverlustmonitors. PKTR Note No. 91, DESY, 1993.

[3] H. Schmickler, private communication.

[4] K. Cornelis et al. Commissioning of a Scintillator at the Aperture Collimators for the Study of Beam Tails. SL-MD Note 60, CERN, 1992.