EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

# MEASUREMENTS OF THE RELATIVE SENSITIVITIES BETWEEN SOME BEAM-LOSS MONITORS: PART I

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# 1    AIM

We report here on measurements made on some beam-loss detectors already in use on ion machines. The beam-loss detectors are of three types, namely: a scintillator (SCINT) coupled to a photomultiplier (PM), a P.I.N diode (PIN), and an air-filled ionization chamber (ION). In a second part we shall report on measurements made with other types of detectors. All operate under normal conditions and have almost the same time response (at least faster than 1 $\mu$s).

Measurements have been done in the laboratory with a radioactive source, and at the SPS operating with lead ions.

# 2    SHORT DESCRIPTION OF THE DETECTOR SET-UP

## 2.1    Type of detectors

a) Scintillator

Two NE102 type scintillators have been used. The first has a surface of $10 \times 10$ cm$^2$ and a thickness of 1 cm, while the other has the same thickness but a surface equal to $1 \times 1$ cm$^2$. Both are connected to a photomultiplier polarized with $U_{\mathrm{ht}} \cong 1300$ V.

b) PIN diode

We make use of the Hamamatsu S3590-03 type diode already used on another machine [1]. Its physical surface is $1 \times 1$ cm$^2$ at the depletion depth 300 $\mu$m. The polarization voltage $V_{\mathrm{bias}} \cong 25$ V.

c) Ionization chamber

Already in use at the SPS [2] it consists of a 1 litre air-filled chamber polarized at $V_{\mathrm{bias}} \cong 800$ V. Its measured sensitivity is $10^{-5}$ C/Gy.

## 2.2    Type of processing electronics

We considered two types of processing electronics which are:
the counting mode used for SCINT and PIN,
the integration mode used with the ionization chamber.

### 2.2.1 Counting mode

For the PM one should refer to Fig. 1 where the photomultiplier output signal is applied to a comparator. The pulses that have a voltage amplitude larger than an adjustable threshold voltage $V_{\mathrm{th}}$ are registered in a counter.

The circuit used for the PIN diode(s) (Fig. 2) is equivalent to that used for the scintillator except that in some cases we put in coincidence two diode signals.

### 2.2.2 Integration mode (Fig. 3)

This concerns the air-filled ionization chamber. The signal coming out of the chamber is transmitted through a cable of length $L_{\mathrm{c}}$ to an integrator (defined by its capacitance $C_{\mathrm{o}}$). The integrated signal is amplified (amplifier of gain $G$) before being acquired.

During measurements with ion beams circulating in the SPS we had: $L_{\mathrm{c}} = 300$ m, $C_{\mathrm{o}} = 5$ nF, $G = 64$, while in the laboratory we used: $L_{\mathrm{c}} = 1$ m, and the same electronics.

The integrator offset current does not exceed 75 fA so that the output voltage rate will always be less than 1.0 mV/s.

With $Q$ [C] the total charge generated by the ionization chamber, we obtain an output voltage: $V_i$ [V] $= G \cdot (Q/C_o)$ which corresponds to the number of gray deposited within the air vessel: GRAY [Gy] $= 10^5$ [Gy/C] $\cdot (V_i \cdot C_o/G)$.

In the case where the dose is time dependent we use instead $g(t) \equiv d(\text{GRAY})/dt$ [W/kg]. This will induce a charge rate $q(t) = dQ/dt$ [A] seen at the ionization chamber output. Then after the time $t$:

$$V_i(t) = \frac{G}{C_o} \int_0^t \left(\frac{dQ}{dt}\right) dt = \frac{G}{C_o} \int_0^t q(u) \cdot du .$$

A simple case occurs when $g(t) = g$ is constant and therefore $q(t) = q$ is constant. In such a case:

$$g\,[\text{Gy/s}] = 10^5\,[\text{Gy/C}] \cdot \frac{V_i(t) \cdot C_o}{G \cdot t} .$$
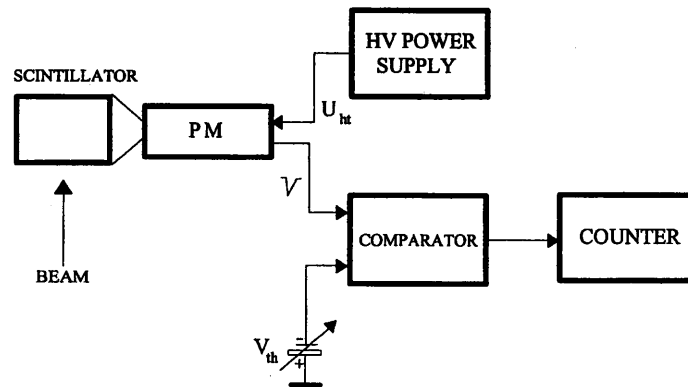


Figure 1: Principle of beam-loss measurements with a scintillator associated to a photomultiplier (PM).
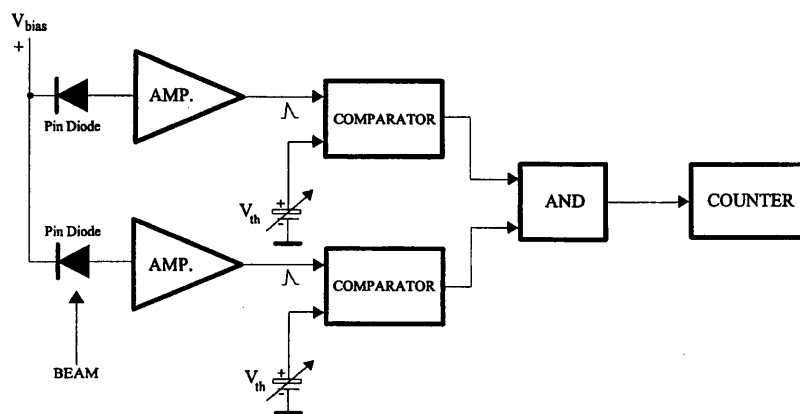


Figure 2: Principle of beam-loss measurements with PIN diodes used in coincidence.
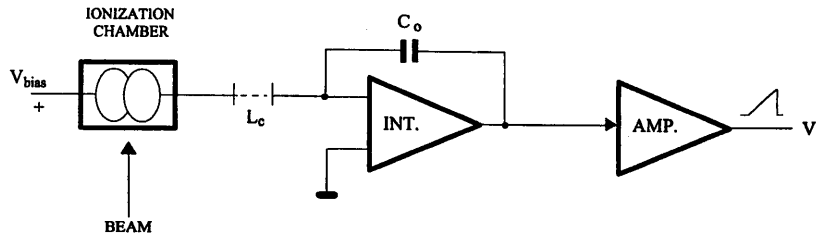
Figure 3: Principle of beam-loss measurements with an ionization chamber.

# 3 LABORATORY TESTS

For the laboratory tests we used a radioactive source SR90. The $\beta$ particle source has a beam diameter of the order of 2 mm so that the detector surfaces are much larger than the source cross-section. The source was placed about 6 mm away from the scintillator and/or the PIN diode surface. The overall electronics operates in counting mode.

## 3.1 Measurements with the scintillator of 100 cm$^2$ area

The output signal frequency is registered as a function of the PM high-voltage $U_{ht}$ and for various threshold voltages $V_{th}$ (Fig. 4). Without source the measured noise is negligible when the PM high voltage is less than 1400 V. The plateau appears clearly (Fig. 4) when the PM high voltage is 1300 V.
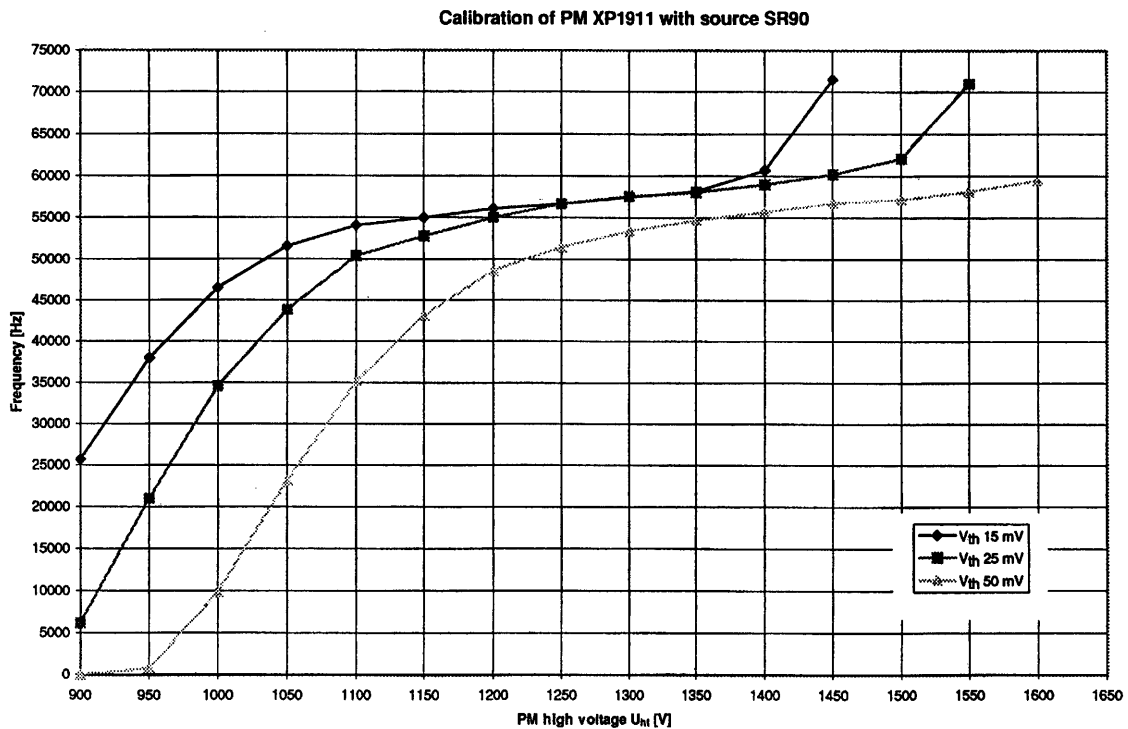


Figure 4: Laboratory measurements: Scintillator irradiated by a SR90 source placed 6 mm away. Vertical axis: PM output frequency [Hz]; Horizontal axis: PM high-voltage $U_{th}$ [V]. The parameter is the comparator threshold voltage $V_{th}$ [mV].

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## 3.2 Measurements with the PIN diode(s)

We did five type of measurements reported in Fig. 5.

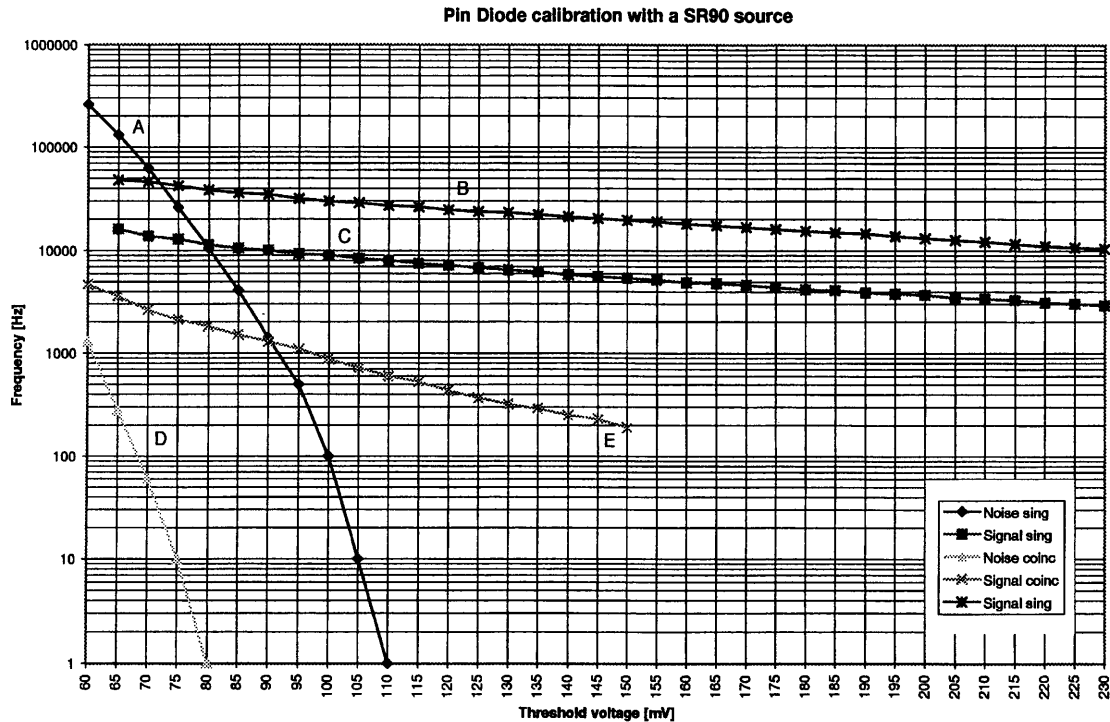**Pin Diode calibration with a SR90 source**



Figure 5: Laboratory measurements: PIN diode(s) irradiated by a SR90 source.

Vertical axis: Diode(s) output frequency [Hz];

Horizontal axis: Comparator threshold voltage $V_{th}$ [mV].

Curve A: Noise frequency (i.e. without radioactive source) of one diode;

Curve B: Signal frequency (i.e. with source)–noise frequency of a single diode when the source is placed in front of the diode active surface;

Curve C: Signal frequency–noise frequency of a single diode when the source is placed in front of the diode substrate;

Curve D: Noise frequency of two diodes placed face to face and in coincidence;

Curve E: Signal frequency–noise frequency measured in D. The two diodes are placed face to face and in coincidence.

*Tests with a single chip.*

a) Measurement of the noise. One sees that the measured 'noise frequency' decreases from 250 kHz to 1 Hz when the threshold voltage is increased from 60 mV to 110 mV.

b) Measurement of the output pulse frequency, after subtraction of the 'noise frequency' obtained from a), with the source placed 6 mm in front of the diode active area. One sees that the effective frequency, induced by the source alone, is reduced by a factor 5 when increasing $V_{th}$ from 60 to 230 mV.

c) Same measurements as for b) but now the source is placed 6 mm away from the chip substrate (consisting of 0.5 mm thick ceramic) supporting the active area. This was aimed at checking for linearity. Indeed curves b) and c) appear to be almost parallel.

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*Tests with two chips placed face to face and in coincidence.*

d) As for a): Noise measurements. The noise is suppressed for $V_{th} \geq 80$ mV.

e) As for b): The signal frequency is reduced by a factor 25 when $V_{th}$ increases from 60 to 150 mV.

## 3.3 Conclusions on the laboratory tests

From Fig. 4, for $U_{ht} = 1300$ V, $V_{th} = 25$ mV, the pulses coming out of the PM have a frequency of 57.5 kHz.

From Fig. 5 when using a single diode, and for $V_{th} = 90$ mV, we measured a frequency of 35.5 kHz (1.5 kHz noise) while the frequency reduces to 1.5 kHz when two PIN diodes are put in coincidence (no measured noise).

We may therefore consider that the scintillator and the PIN diode detector used in single mode have about the same sensitivity. This seems to be coherent since we used a point source and also because we operate in pulsed mode. It must be stressed that the PIN diode 'natural noise' is far from being negligible since from a) we measured a decrease of $\Delta f$ [kHz]$/\Delta V_{th}$ [mV] $\cong 2$.

# 4 TESTS WITH ION BEAMS

## 4.1 Ion beam parameters

We made measurements in LSS1, with lead Pb$^{82+}$ ions, at the time of the second injection into the SPS. The 5.13 GeV/nucleon injected beam consisted of 20 bunches having each a duration of 20 ns. At injection the time interval between the bunches is 100 ns. The total number of injected particles lies between $2.5 \times 10^8$ and $6 \times 10^8$. According to the machine experts, immediately after injection they proceed with the capture. About 1% of the beam is not captured and therefore lost.

For each detector the elementary counting time is equal to two SPS revolution periods (or 46 $\mu$s).

## 4.2 Detector set-up

The large ($10 \times 10$ cm$^2$) scintillator, with its associated photomultiplier, and the ionization chamber were placed on either side of the vacuum chamber (Fig. 6). On both detectors we placed a PIN diode (or two diodes for the purpose of coincidence measurements) so as to be prepared to proceed with comparative measurements.

## 4.3 Measurements

We made measurements with and without beam. The measurements without beam were aimed at estimating the 'noise' induced by the remanent radioactivity.

### 4.3.1 Noise measurements

In the absence of a circulating ion beam we measured the frequency of the pulses delivered by the PM and the PIN diodes and also the ionization monitor output voltage rate. These signals are induced by the natural radioactivity that exists at the location of our detectors and are labelled as SPS noise. Our measurements are as follows (Table 1):

<div align="center">

**Table 1**

</div>

| Case | Type of detector | Laboratory measurement [Hz] | SPS measurement [Hz] | 'SPS' noise [Hz] | Remarks |
|---|---|---|---|---|---|
| 1 | Scintillator alone | 200 | 23 753 | 23 553 | $U_{ht} = 1.3$ kV, $V_{th} = 30$ mV |
| 2 | One diode placed on the scintillator | 3750 | 3934 | 184 | $V_{th} = 85$ mV |
| 3 | Two diodes in coincidence placed on the scintillator | 1 | 2–3 | 1–2 | $V_{th} \cong 84$ mV |
| 4 | One diode placed on the ionization chamber | 6520 | 7008 | 488 | $V_{th} = 83$ mV |
| 5 | Two diodes in coincidence placed on the ionization chamber | 1 | 2–3 | 1–2 | $V_{th} \cong 84$ mV |
| 6 | Ionization chamber alone | $\cong 0$ mV/s | 302 mV/s | 302 mV/s | $C_o = 5$ nF, $G = 64$ |



S: Scintillator          100 cm$^2$
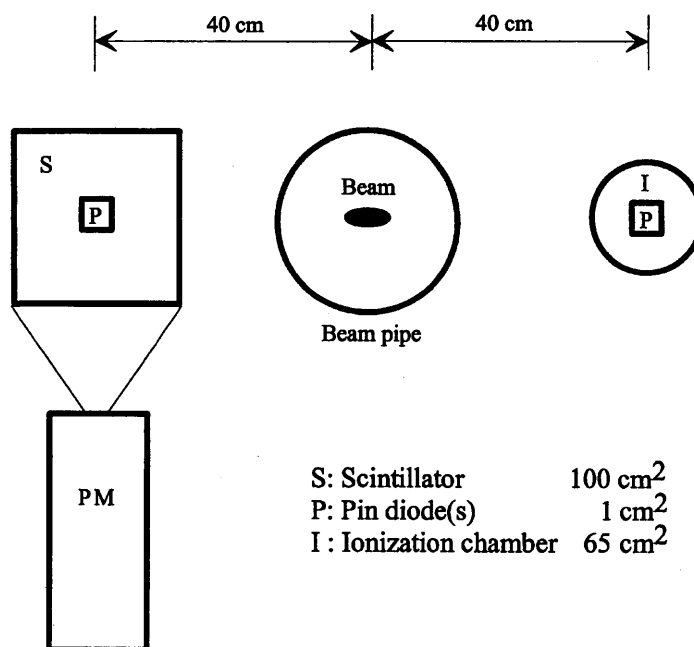P: Pin diode(s)           1 cm$^2$
I : Ionization chamber   65 cm$^2$

Figure 6: Principle of the set-up for comparative measurements within: the scintillator, the PIN diode(s) and the ionization chamber monitors, in the SPS machine.

For a single PIN diode one can notice that, owing to the relatively small active surface, its detection efficiency is much smaller than that of the PM. This has been checked by replacing the nominally 100 cm$^2$ scintillator by a 1 cm$^2$ one. On the other hand, it must be stressed that the PIN diode natural noise (column: Laboratory measurement) is relatively large such that a small variation of $V_{th}$ induces a large variation of the measured frequency (Section 3.3).

From measurements made with the ionization chamber one deduces that the remanent dose is equivalent to: $(10^5 \times 0.302 \times 5 \times 10^{-9})/64 = 2.36 \times 10^{-6}$ Gy/s.

### 4.3.2 Measurements with lost particles

In order to reduce the influence of the noise, without penalizing the experiment, we made our measurements during a time interval of 10 ms immediately after injection. The influence of the 'noise' given in Section 4.3.1 (Table 1 column 'SPS measurement') must therefore be divided by 100. An example of the observed signal delivered by the scintillator is shown in Fig. 7a and that measured simultaneously from the PIN diode is represented by Fig. 7b (diode on the scintillator) and Fig. 7c (diode on the ionization chamber). It appears that most of the losses occur in less than 10 ms after injection. The horizontal dotted line corresponds to the remanent losses induced by the previous batch.

From Fig. 7a one can see that the scintillator provides significant results to an operator. It is worth recalling that the number on the vertical axis represents the number of pulses counted during each 46 $\mu$s time interval.

On the other hand, from Figs. 7b and 7c one observes that the PIN diode itself gives less accurate results since the maximum number of counts, every 46 $\mu$s, is less than the number of injected bunches passing by the detector.

Among all the measurements, made with the scintillator and a single PIN diode, the following total number of counts is quite representative of our measurements (Table 2):

**Table 2**

|  | Case 1 [counts] | Case 2 [counts] | Case 4 [counts] | Case 6 [mV] |
|---|---|---|---|---|
| Signal + Noise | 3289 | 91.0 | 133 | 1123 |
| Noise | 237 | 39.1 | 70 | 3 |
| Signal | 3052 | 52 | 63 | 1120 |

From the above table we can estimate that the ratio: $R$ = number of pulses counted from the scintillator/number of pulses counted from the PIN diode is about 50. This is a factor 2 smaller than the ratio between the active surfaces of these detectors. However, it must be kept in mind that the 'noise' subtracted from the number of pulses registered from the diode is relatively large.

From the ionization output voltage (case 6) one deduces that about $8.75 \times 10^{-6}$ Gy were lost at the level of the detectors.

Two representative measurements made with two PIN diodes (placed on both the scintillator and the ionization chamber) used in coincidence are as follows (Table 3):
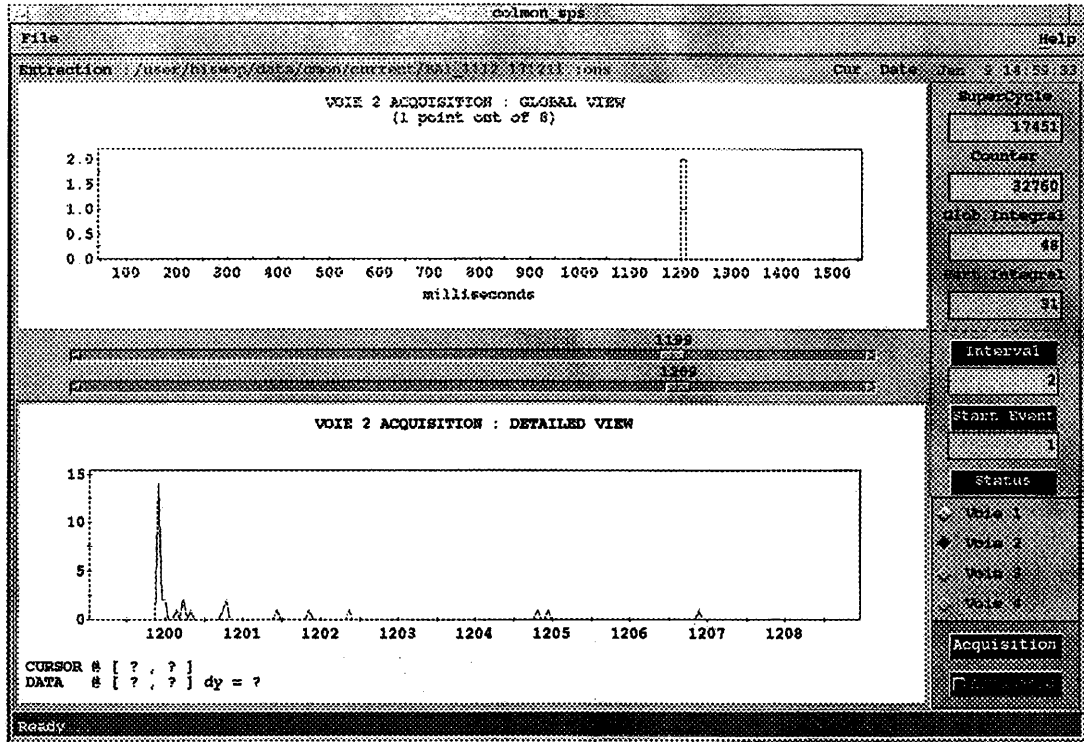
**Table 3**

|  | Case 1 [counts] | Case 3 [counts] | Case 5 [counts] |
|---|---|---|---|
| Signal | 7347 | 38.5 | 30.5 |
| Signal | 4324 | 32.0 | 24.0 |

As a result of the coincidence technique the noise influence is rather small but now the ratio $R$ lies between 150 to 200. Also, since the number of pulses measured by the diode is small, statistical errors should be taken into consideration.
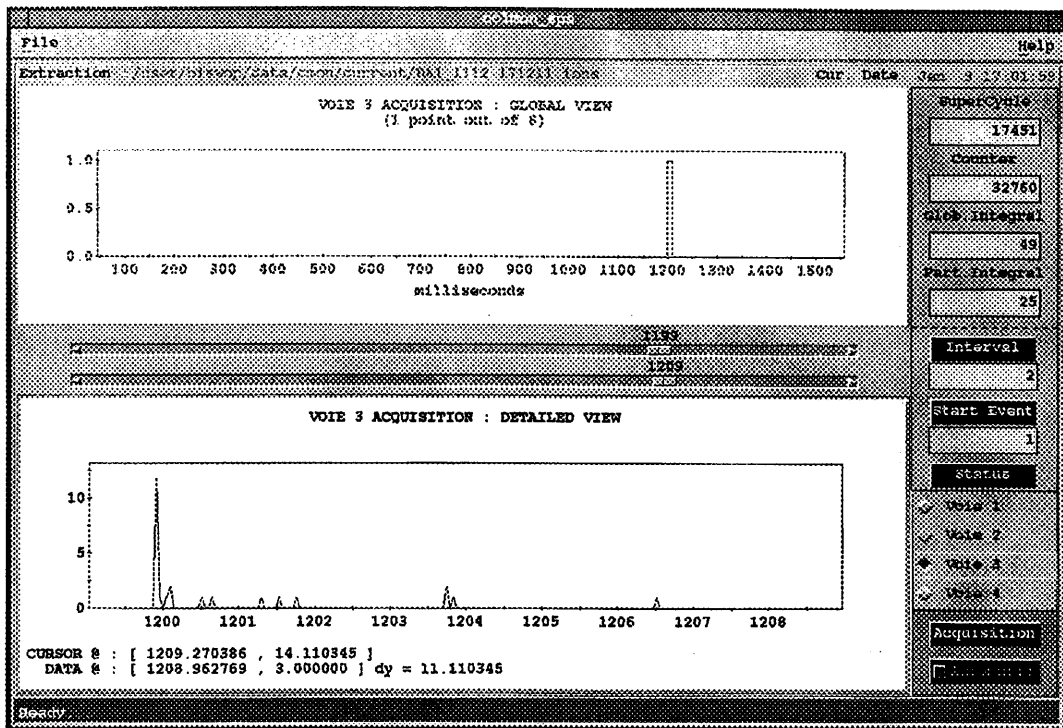
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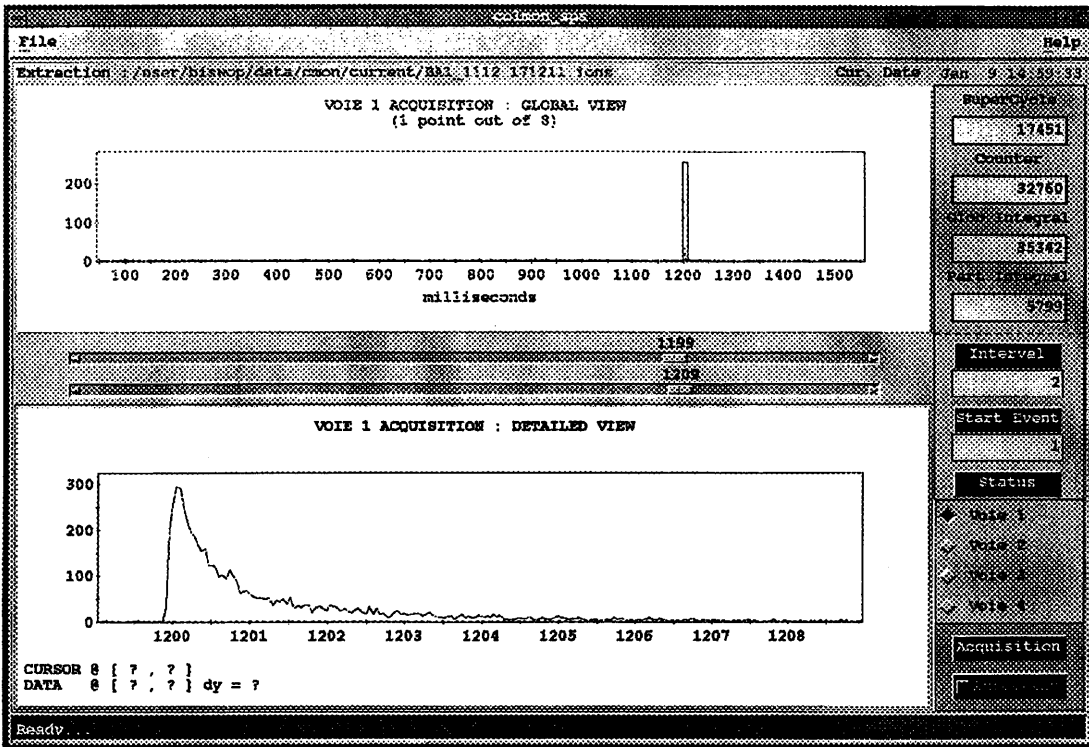
a)



b)

c)

Figure 7: Detector responses to ion beam losses. We consider only the detailed view. Vertical axis frequency [Counts/46 $\mu$s], horizontal axis time [ms]: a) Scintillator response [Voie 1]; b) PIN diode layed on the scintillator [Voie 2]; c) PIN diode layed on the ionization chamber [Voie 3].

## 4.4  Conclusions of measurements made with ion-beam losses

In counting mode the scintillator is a factor 100 more sensitive to the lost beam particles than the PIN diode. This is about the same as the ratio between the surfaces. The loss rate distribution is well observed when using a scintillator. This is not the case for the PIN diode owing to the relative lack of sensitivity of this type of detector.

The ionization chamber gives as expected good and useful results since the resolution is 1 mV, so that one can measure a loss reduced by a factor 1000. This level of loss could not be measured by the PM in counting mode.

## 5  CONCLUSIONS

Scintillators used in counting mode give, in the present case, valuable results. The adequate sensitivity results from the relatively large surface (or volume) of concern. In order to reduce the variability of the measurements as a result of the uncertainty in the spatial distribution of the loss, one could use instead a long scintillator rod. It would also be worth while to use this detector in proportional or integrating mode instead of counting mode.

Ionization chambers are, as expected, quite sensitive. Along the same lines as above one could foresee instead the use of a coaxial cable [3].

In both cases the question raised by the need for distributed high voltage for the polarization of these devices is no longer of concern. Indeed industrial chips provide a way to convert the low voltage, already necessary for the low-level electronics, into high voltages.

# References

[1] K. Wittenburg, Preservation of beam-loss-induced quenches, beam lifetime and beam-loss measurements with the HERAp beam loss-monitor system, Nucl. Instrum. Methods Phys. Res. **A345** (1994) 226–229.

[2] J. Bosser, L. Burnod, G. Ferioli and J.B. Jeanneret, Preliminary measurements of beam-loss detectors foreseen for LHC, PS/BD Note 92–04, SL Note 92–67 (BI).

[3] Test of ion chamber to be used as local beam loss detector in the superconducting magnets to be installed in I-8, ISR Performance Report, ISR-OP/L.Vos/ah, May 1980.