LHCb note 2001-85, Outer Tracker

Occupancy results with the new outer tracker simulation

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May 28, 2001

Abstract

First results on occupancies with the new simulation and digitization code for the outer tracker are presented.

Contents

1 Introduction

One of the most critical parameters for the performance of the outer tracker is the detector occupancy. This is because:

- The outer tracker granularity (5 mm) is quite large.
- The long drift-times in the straw tubes mean that it is foreseen to read out two bunch crossings.
- The electronics is not able to resolve two hits in the same cell within 30 ns resulting in a dead-time.
- Pattern recognition performance is observed to degrade for events with high occupancy.

To give a sense of the scale of the problem Fig. 1 shows a typical simulated $\mathrm{B_d} \rightarrow \pi^+\pi^-$ event in the LHCb detector. As can be seen in addition to the tracks from the primary interaction there are many secondaries generated in the beam-pipe and other parts of the LHCb detector. It can also be seen that some of these low energy secondaries become trapped in the magnetic field and curl giving hits long after the original interaction.

In this note the first results of occupancy studies with the improved simulation and digitization of the outer tracker described in [1] are discussed. In the following section numbers obtained with the old and new simulation are compared. This is then followed by an investigation of the effect of spillover from previous bunch crossings that was not properly taken into account in previous studies.

For the numbers quoted with the old simulation the data were generated with version v234r1 of SICBMC. The Al-Be alloy pipe ('design 7.1') was used throughout. The numbers with the new simulation are with the same version of SICBMC — apart from the new tracking simulation. The following measures of occupancy were calculated:

- Average occupancy per station.
- Hot event fraction, per station where a station is defined as hot if more than 25 % of the wires in that station are hit.

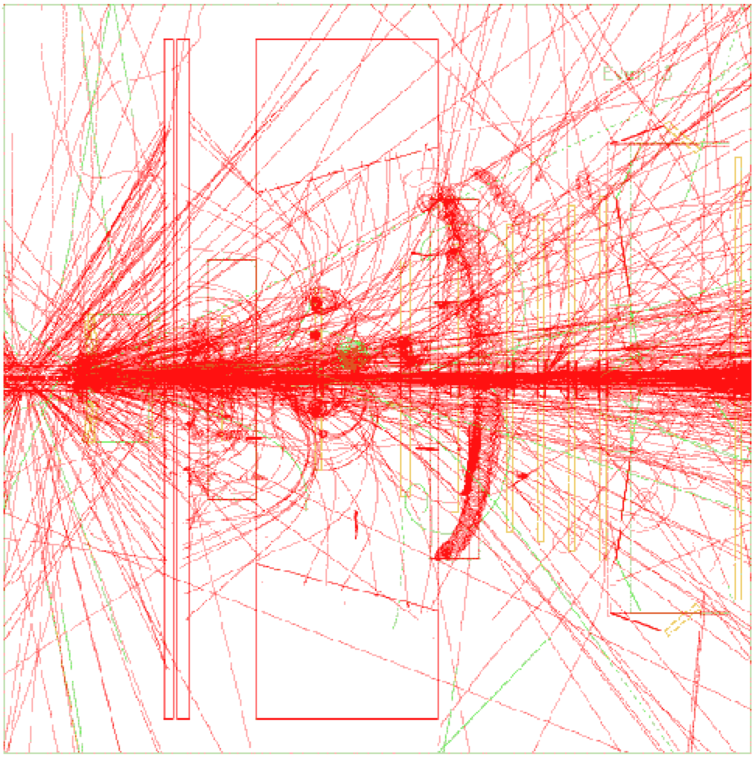

Figure 1: Typical simulated $B_d \rightarrow \pi^+\pi^-$ event in the LHCb detector.

For the average occupancy numbers a scale factor of 1.36 was applied. This comes from:

- Lowering the Geant cut-offs for particle tracking in previous studies [2] was found to increase the occupancy by 12%.
- δ-rays are not explicitly generated by default. Turning δ-rays on was found to increase the occupancy by 10% [2].
- Cross-talk and noise are not yet included in the digitization code. A factor of 10% is applied to account for this.

It has also been observed that changing PYTHIA settings within reason can increase (or decrease) the occupancy by 20% [2]. This should be taken as an additional uncertainty on the occupancy results.

It should be borne in mind when reading this note the occupancies of $\sim 10\%$ are currently considered to be tolerable for the seeding region of T7-T10. For

T2-T6 occupancies up to 15% are allowable.

2 Comparison of results with the new and old simulation

The old tracking simulation that dated from the time of the technical proposal is described in [3]. At that time the tracker was modelled as a series of eleven boxes with each box representing a station. Monte Carlo information known as 'MCTrackingHits' was stored for each box. In the case of the tracker a MCTrackingHit corresponded to entrance and exit points for station along with an associated time-of-flight relative to the time of the primary proton-proton interaction. Only at the digitization stage was the actual layer structure of the stations constructed. This approach was extremely flexible and allowed many geometry changes to be studied without the need to regenerate data. However, it was unrealistic in some respects. For example:

- All the material was distributed in two walls at the station entrance and exit. In reality material will be distributed throughout the station.
- The inner and outer tracker were assumed to be at the same position in z — this will not be the case.
- The modelling of the inner tracker frames and electronics was not realistic.

In the new simulation all these problems are fixed. For both the inner and outer tracker a layer structure has been implemented in the simulation and Monte Carlo information is stored per layer[1]. In addition the inner and outer tracker are now positioned at different z positions [4]. In what follows numbers for the old and new simulation are compared. It should be noted that since the two simulations are inherently quite different this comparison is difficult. Furthermore, some of the cross-checks performed below required the generation of special datasets. It was not practical to generate samples of more than ~ 1000 events for such checks.

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[1] In the case of the outer tracker this corresponds to two staggered planes of straw tubes.

2.1 Particle Fluxes

To understand the effect of the more realistic description of the material in the detector the particle flux was compared in the old and new simulation. The flux in both cases is calculated as follows. An MCTrackingHit is said to be in the outer tracker if:

- The x and y coordinates of the entrance point lie outside the inner tracker hole of 60×40 cm^2.
- The x coordinate lies inside the outer angular acceptance of 300 mrad.
- The y coordinate lies inside the outer angular acceptance of 250 mrad.

This choice of cuts makes the comparison between old and new simulations as reasonable as possible. The number of MCTrackingHits in the outer tracker in a region of z (corresponding to a station in the old simulation and a double layer in the new simulation) is then simply counted and divided by the appropriate area to give the flux. This procedure gives 10 numbers corresponding to stations 2 to 11 in the case of the old simulation. For the new simulation it gives 42 numbers each corresponding to a double layer of straws. In Fig. 2 the particles fluxes found in $\mathrm{B_d} \rightarrow \pi^+\pi^-$ events piled-up to a luminosity of 2×10^{32} cm^{-2}s^{-1} are plotted for the new and old simulation. For clarity in the case of the new simulation only the numbers for the first and last layer are shown. The numbers for the new simulation are generally $\sim 9\%$ higher than the corresponding ones for the old with a statistical error of 3%. This error does not take account of any systematic uncertainty coming from how appropriate it is to compare the two numbers directly. There are several reasons why the particle flux in the new simulation might be expected to be higher than in the old:

- The redistribution of material in the new simulation means that entrance wall of each station is significantly thinner than in the old simulation. This means that very low energy secondary electrons which previously were stopped in the entrance walls can make it into the chambers. For example, in studies with the old simulation reducing the $\mathrm{X_0}$ in the entrance window from 1% to 0.25% causes particle fluxes to increase by $5 - 9\%$ depending on the station.
- The material description of the frames and inactive material of the inner tracker is more realistic in the new simulation compared to the

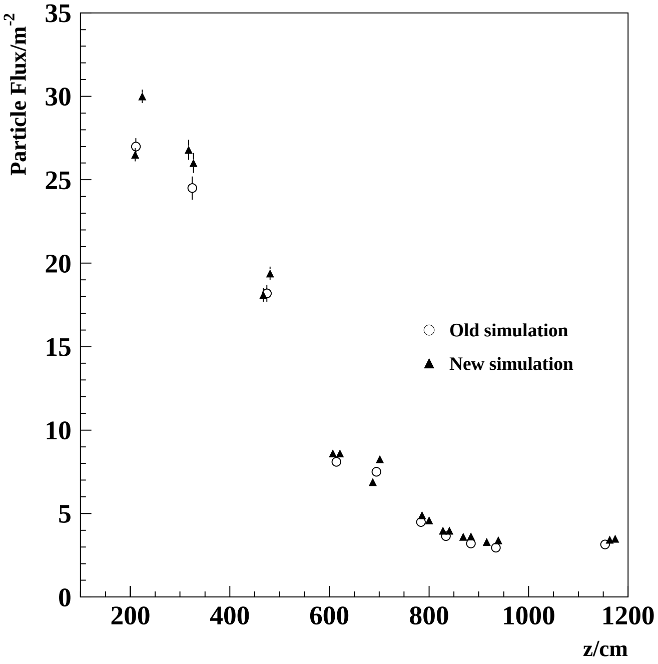

Figure 2: Comparison of particle flux in the outer tracker for the old and new tracking simulation.

old. In particular the treatment of the inner tracker frames was quite simplistic in the old simulation. However, since the inner tracker frames only contribute approximately 3% of the total outer tracker flux in the new simulation any such increase must be small.

- The stations have moved in z. Moving the station positions in the old simulation to those of the new was found to change the particle fluxes by around $\sim 2\%$.

It is also interesting to note that the particle flux changes quite rapidly when comparing the first and last double layer for stations 2,3,4 and 6 in the new simulation. In the case of stations 2,3 and 6 this is due to positioning of the flanges and bellows of the beam-pipe relative to these stations. The difference between the first and last layer of station 4 is due to the effect of curling tracks in the magnet.

2.2 Occupancies

Since the new and old simulation are quite different it was decided that rather than adapting the old FORTRAN software new digitization code would be developed in C++ [1]. The new code has the following advantages:

- Parameterizations of efficiencies and resolutions extracted from test-beam data are used.
- A proper treatment of electronics dead-time and finite readout gate is made.
- The possibility of spillover from bunch crossings before or after the event is foreseen.

For a fair comparison with the old software an infinite dead-time and an infinite readout window were assumed in the new code. In Fig. 3 the average occupancy in $\mathrm{B_d} \rightarrow \pi^+\pi^-$ events piled-up to 2×10^{32} $\mathrm{cm^{-2}s^{-1}}$ is compared in the old and new simulations. As can be seen in stations T8-T11 the occupancy increases by $\sim 20 - 30\%$ in going from the old to the new simulation. For stations T3-T7 the increase is even more dramatic — around 45%. The hot event fraction (Fig. 4) shows a similar pattern. There are more hot events in the new simulation compared to the old. For completeness Fig 5 shows some of the occupancy distributions from which the average occupancy and hot event fraction results were derived.

There are several reasons why the occupancy increases in the new simulation:

- As stated in Section 2.1 the particle flux increases by around $\sim 9\%$ in going from the old to the new simulation.
- The single cell efficiency averaged over the cell has increased from 93% to 97%. In addition the shape of the efficiency parameterization has changed. The shape of the old parameterization effectly made the straws ‘thinner’ in z. This meant the number of straws hit by a very steep track was correspondingly reduced. Running the new digitization software using the old parameterization a decrease in occupancy of 4.5% is found.
- The number of digitizations made per plane was limited to one hundred in the old software. However, since this limit is very rarely broken in the new code this should be a small effect.

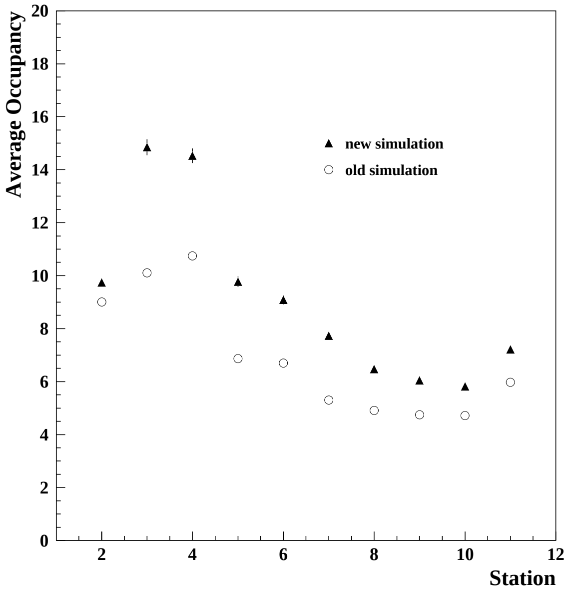

Figure 3: Average occupancies for piled-up B events in the old and new simulations The luminosity in both cases is 2×10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

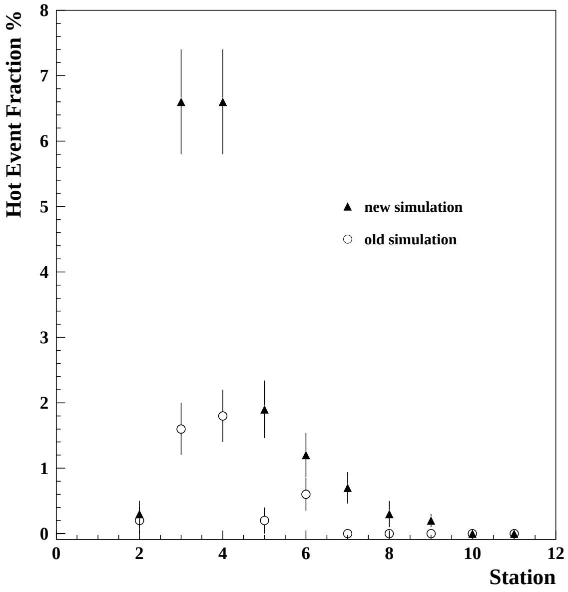

Figure 4: Hot event fractions for piled-up B events in the old and new simulations. The luminosity in both cases is 2×10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

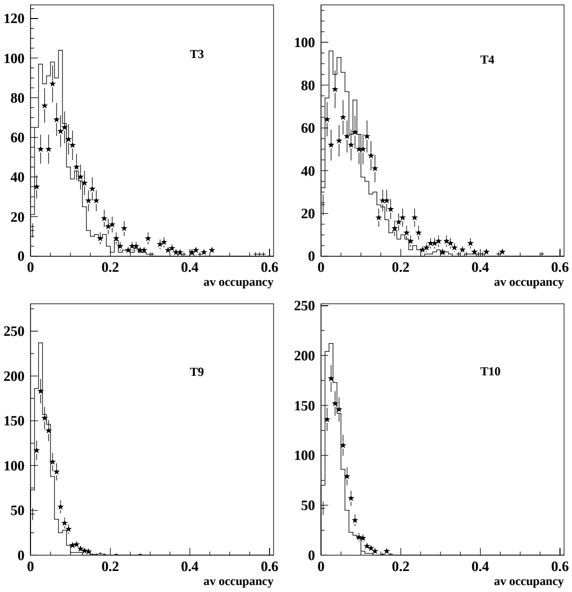

Figure 5: Example occupancy distributions for piled-up B events in the old (solid line) and new (stars) simulations. The correction factor of 1.36 discussed in Section 1 has not been applied to these distributions.

- In the old simulation the detector was divided into eight sectors. Digitization across the sectors was not handled correctly. This should only have a $\sim 1-2\%$ effect on the occupancy.

The first two points explain much of the occupancy increase observed in stations T8-T11 between the old and new simulations. No simple explanation for the remainder of the increase was found. However, it should be noted that it is hard to quantify what the 9% increase in flux translates to in terms of occupancy. The particles gained are likely to be steep secondaries. In this case a 9% increase in flux would lead to a larger increase in occupancy terms. Finally, there also maybe subtle differences in the treatment of steep and curling tracks between the two sets of code that have not yet been uncovered.

One question that might be asked is what is the effect of the reduction in the pitch from 6 mm in the old simulation to 5.25 mm in the new simulation on the occupancy. To first order there is no effect — the increase in number of hit wires is compensated by the increase in the number of wires. However, toy Monte Carlo studies show there can be small changes in the occupancy at the per mille level for very steep tracks that hit more than one wire in a layer. This conclusion was checked in a special run with the old simulation where the pitch was set to 5.25 mm. This gave the same result (though with less statistical precision) as the toy Monte Carlo study. At the level of $\sim 1\%$ changing the pitch has no effect on the occupancy.

3 Spillover Studies

In the past 'bunch spillover' from interactions in the bunches preceding or following the B event were not properly taken into account. This is particularly important in the outer tracker because the long drift-times involved mean that it is necessary to read out a 50 ns window. Instead in the past it was argued that the additional occupancy from spillover could be accounted for by assuming that the effect of spillover from other bunches is the same as that of pile-up in the same bunch. In what follows this claim is checked and the effect of spillover investigated more thoroughly.

Spillover is currently implemented at the digitization level in Brunel [5]. The procedure is shown Fig. 6. First tapes of minimum bias piled-up to the required luminosity are made using Brunel. These are then used as an input stream along with the B signal events (and if required an additional stream for pile-up) to the outer tracker digitization software. The digitization code itself handles the job of applying the appropriate spill time offset to the minimum bias events.

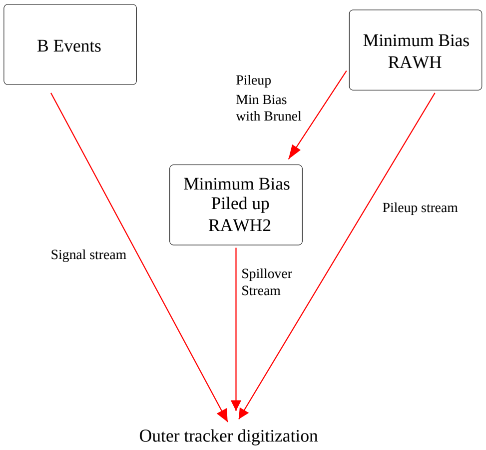

Figure 6: Spillover procedure.

For these studies the digitization code was run in a more realistic manner. An electronic dead-time of 30 ns and a readout gate of 50 ns were assumed. The digitization code was first run with for $\mathrm{B_d} \rightarrow \pi^+\pi^-$ events with spillover at -25 ns and $+25$ ns relative to the B event[2] and occupancy numbers determined. Then step-by step spills were added working back to -200 ns before the event. The luminosity used for these studies was 2×10^{32} $\mathrm{cm^{-2}s^{-1}}$. Fig. 7 shows the average station occupancy versus the number of spills before the event used. For stations outside the magnet the distribution is flat. Inside the magnet, the distribution rises. This is due to low momentum tracks that become trapped in the magnetic field and curl giving hits in the detector for several hundred nanoseconds after an interaction. The problem is worst for station 4 where the magnet field is highest. In this station a significant increase in the occupancy is observed going from 7 to 8 spills before the event. For stations 4,5,6 the distribution was fitted with:

$$Occ(n) = A_\infty - Be^{-Cn} \tag{1}$$

where n is the number of spills before the event considered. The parameter A_∞ then gives a measure of the occupancy if all the spills before the event were taken into account.

The numbers obtained with spillover are compared to those obtained previously with pile-up and no spillover in Fig. 8. For stations T4, T5, T6 the value of A_∞ coming from the fit is taken as the occupancy. For the other stations the value and error quoted are those obtained when a constant is fitted to the distributions in Fig 7. It should be noted that this method has the advantage of reducing statistical fluctuations coming from the spillover procedure as spillover events are used differently in each run.

In Fig. 9 the hot event fraction is compared in both cases. The following can be seen:

- The average occupancy numbers with spillover are significantly lower than those with pile-up for the magnet stations. The effect is most visible in station 4 where the occupancy is reduced by a factor of 30%.
- The number of hot events with spillover is dramatically reduced everywhere — but again especially in the magnet stations.

This can be understood as follows. The results for ‘B+pile-up’ were obtained with no cut on the readout time. Therefore all the hits due to curling tracks

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[2] The B event itself was not piled-up.

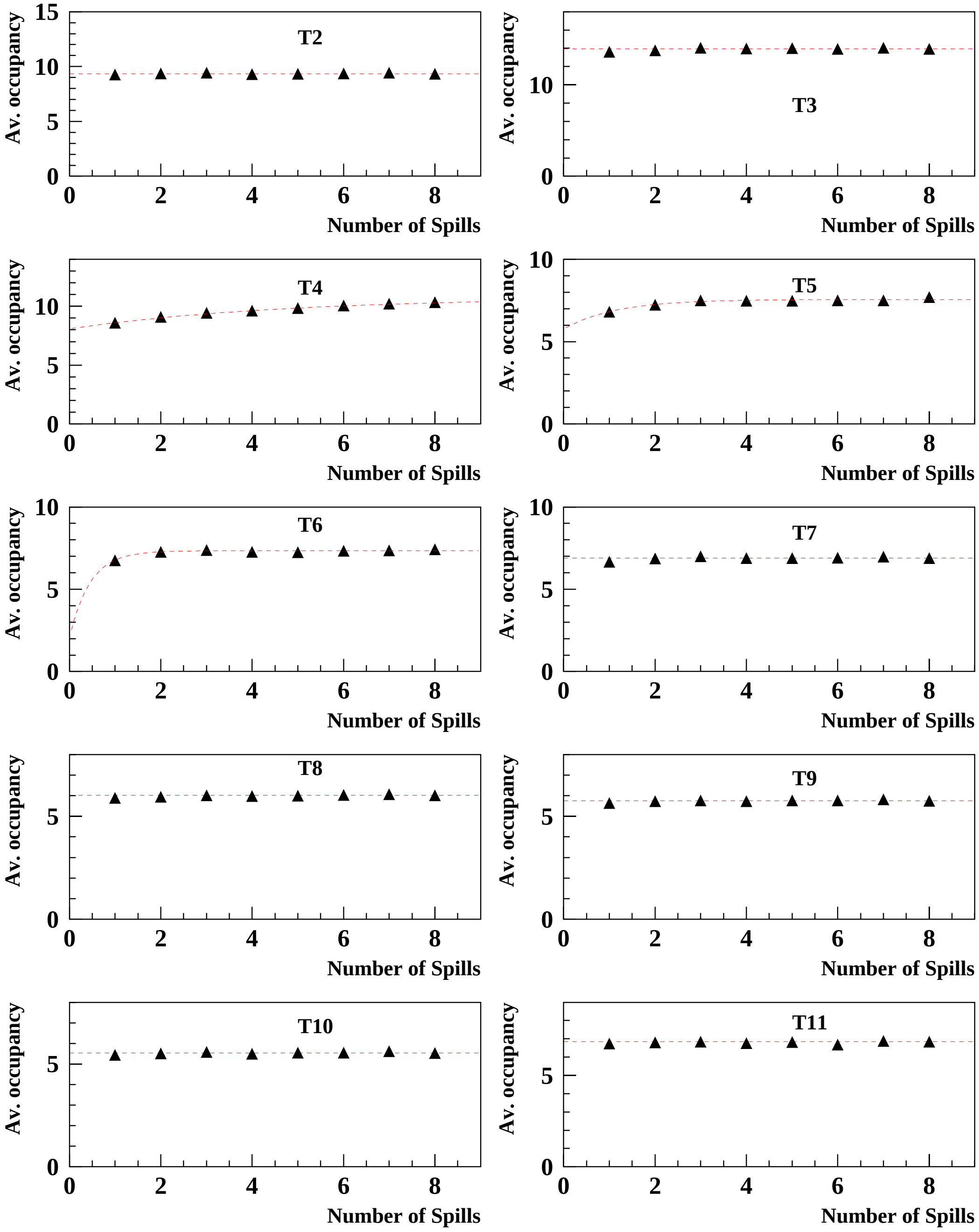

Figure 7: Average occupancy versus number of spill's before the event considered in the outer tracker digitization. The dashed lines are the results of the fits described in the text.

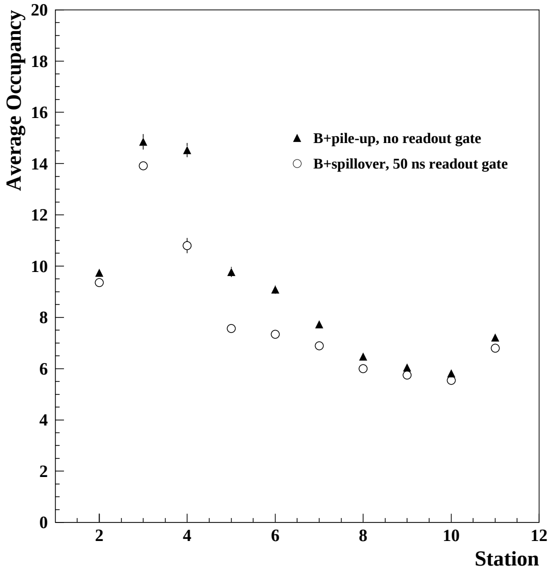

Figure 8: Average occupancy for 'B+spillover, 50ns readout gate' compared to 'B+pile-up, no readout gate'. The luminosity in both cases is 2×10^{32} cm^{-2}s^{-1}.

in the B event out to large times were taken into account in the occupancy calculation. When the readout gate is applied these hits are thrown away. Of course additional hits from minimum bias events from previous spills are gained. However since B events are about a factor five times hotter than minimum bias events (and hence more likely to have curling tracks) the loss outweighs the gain and the average occupancy is reduced. This effect will be largest for the magnet stations which are the ones most effected by long-lived curling particles. A similar argument applies for the observed reduction in the hot event fraction.

4 Spillover and Pile-up

In the Technical Proposal it was assumed that events with multiple pp interactions are rejected by the L0 pile-up veto. At present it is not clear that this will be the case. Therefore in this section numbers are given for single and multiple interactions containing B events at luminosities of 2×10^{32} cm^{-2}s^{-1} and 5×10^{32} cm^{-2}s^{-1}. As in the previous section a dead-time of 30 ns and a readout window of 50 ns were assumed.

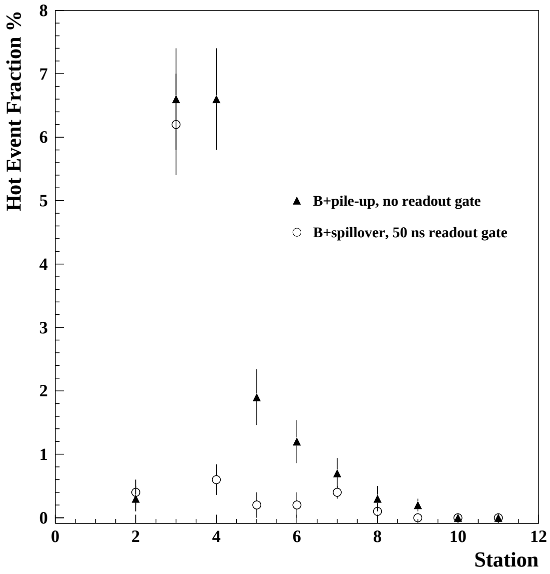

Figure 9: Hot Event Fractions for 'B+spillover, 50 ns readout gate' compared to 'B+pile-up, no readout gate'. The luminosity in both cases is 2×10^{32} cm^{-2}s^{-1}.

The numbers at 2×10^{32} cm^{-2}s^{-1} with pile-up were obtained in the same way as in the previous section. There is insufficient minimum bias available to allow spillover back to times further than -50 ns and pile-up at 5×10^{32} cm^{-2}s^{-1}. In addition, the time taken to carry out the digitization procedure becomes quite significant. Therefore only spillover from the bunches at -50 ns, -25 ns and $+25$ ns was considered. For stations 4,5 and 6 the fit results obtained in Section 4 are are used to give correction factors to account for the fact that only two spills before the event have been considered. This assumes that the only parameter in the fit that changes is A_∞. Comparing the fit results with and without pile-up and 2×10^{32} cm^{-2} this seems to be the case within errors. In addition for stations 5 and 6 the calculated extrapolation factor is small — 4.2% and 1% respectively. In the case of station 4 the extrapolation factor is sizeable, around 19%.

The results are collated in Table 1 and shown graphically in Figs. 10 and 11. At low luminosity the occupancies seem tolerable — though with no safety margin. This is especially true for T3. At high luminosity with pile-up in the B event the average occupancy in almost all stations is larger than the limits set in Section 1. In addition in this note only average occupancies have been considered the areas close to the beam-pipe will be hotter than the average — this will be studied in a forthcoming note.

Station	Spillover 2×10^{32} cm^{-2}s^{-1}	Spillover and pileup 2×10^{32} cm^{-2}s^{-1}	Spillover 5×10^{32} cm^{-2}s^{-1}	Spillover and pileup 5×10^{32} cm^{-2}s^{-1}
2	9.36 ± 0.03	11.14 ± 0.04	11.89 ± 0.19	16.09 ± 0.28
3	13.91 ± 0.04	16.47 ± 0.06	17.86 ± 0.37	23.60 ± 0.44
4	10.8 ± 0.3	12.60 ± 0.3	14.76 ± 0.57	19.21 ± 0.74
5	7.56 ± 0.04	8.90 ± 0.05	10.34 ± 0.18	13.38 ± 0.23
6	7.34 ± 0.03	8.68 ± 0.03	10.07 ± 0.2	13.21 ± 0.26
7	6.89 ± 0.03	8.12 ± 0.03	9.09 ± 0.13	12.16 ± 0.21
8	6.0 ± 0.03	7.11 ± 0.03	6.98 ± 0.12	10.49 ± 0.17
9	5.75 ± 0.02	6.83 ± 0.03	7.43 ± 0.12	10.0 ± 0.16
10	5.54 ± 0.02	6.58 ± 0.02	7.17 ± 0.08	9.64 ± 0.16
11	6.80 ± 0.02	8.12 ± 0.04	8.76 ± 0.1	11.86 ± 0.16

Table 1: Summary of occupancy results with and without pile-up.

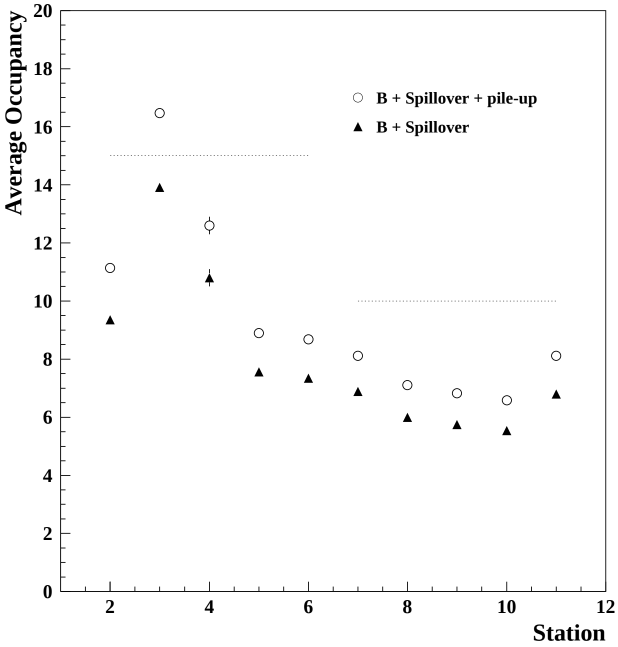

Figure 10: Occupancies at 2×10^{32} cm^{-2}s^{-1} for B events with single interactions (labelled 'B+Spillover') and multiple interactions (labelled 'B+Pile-up+Spillover'). The dashed lines indicate the maximum tolerable occupancy.

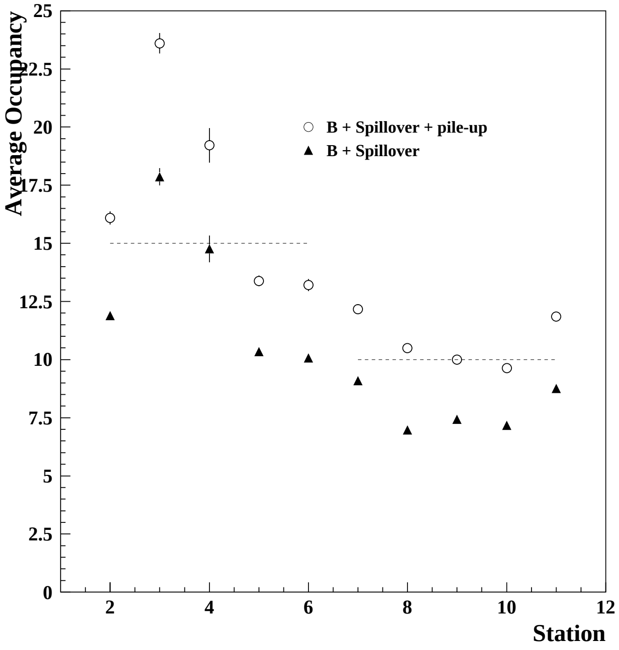

Figure 11: Occupancies at 5×10^{32} cm^{-2}s^{-1} for B events with single interactions (labelled 'B+Spillover') and multiple interactions (labelled 'B+Pile-up+Spillover'). The dashed lines indicate the maximum tolerable occupancy

5 Conclusions

First occupancy results with the new tracking simulation and digitization software have been presented. The new simulation gives results that are significantly higher than the old. Part of the effect has been shown to be due to an increase in the particle flux and the improved parameterization of the single cell efficiency. No obvious cause for the rest of the observed increase was found. It should be stressed that the occupancy is dominated by low energy secondaries that tend to be steep or curling. Such particles can cause many straws in a layer to be hit. This means that the occupancy can be very susceptible to small changes in the detector modelling at both the simulation and digitization level. For example, if only the closest neighbours of a hit wire are considered in the digitization procedure the occupancy decreases by 10%. Given all this it is felt that the outer tracker occupancy is only known with a systematic error of at least 20% coming from the uncertainty in the detector modelling. This is in addition to the 20% uncertainty due to the PYTHIA settings used.

The new simulation has allowed the effect of spillover to be studied. The results show that for all the stations except T4 it is sufficient to consider spillover from -50 ns, -25 ns and +25 ns. For T4 the situation is more complicated. Around 19% of the occupancy is due to spills occurring more than -50 ns before the event. That is to say only considering the spills at -50 ns, -25 ns and +25 ns *under-estimates* the occupancy by 19%. Some parameterization of the digitizations that are lost in this way therefore needs to be implemented.

Occupancy results have been presented for low and high luminosity running. The occupancies at low luminosity seem tolerable but with no safety margin. It is difficult to operate the detector at high luminosity. Since the results can only be trusted to an overall accuracy of 25% it is felt that alternative designs with increased inner tracker size need to be considered. This will form the subject of a future note.

References

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