LHCb note 2001-093, Outer Tracker

Outer Tracker occupancies and detector optimisation

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Abstract

The occupancies for all stations in the LHCb outer tracker are presented for various detector and beam-pipe designs

Contents

1 Introduction

In a recent note [1] the outer tracker occupancies are presented for a detailed GEANT implementation (labelled *new*). In this note we present the outer tracker occupancies for a less detailed GEANT implementations of tracking detectors (labelled *old*). The detector simulation and response of these simulation was described in detail in [2]. The program is rather flexible and can be used to simulate various different detector set-ups. The reference situation of the occupancies is the geometry of inner and outer tracker as described in the TP, where each inner tracker station has a horizontal size of 60 cm and vertical size of 40 cm. The station positions of the reference setup are summarised in table 1.

In this note study the outer tracker occupancy for:

- different versions of the beam-pipe
- dependence of station position in the magnet
- dependence on detector thicknesses
- different inner tracker detector sizes

Input to the simulations are generic B-decay events generated with the PYTHIA and tracked through the GEANT based SICBMC version v233r1, with as default database version v229r1. The differences in the geometries used are obtained by modifications with respect to this database.

Differences between the *old* and *new* programs are summarised in [1]. In that note the occupancy difference between the two programs have been calculated and can be used to scale the *old* occupancies to the *new* ones, trying to take into account the proper treatment of geometry and digitizations (e.g. the time-of-flight of long-living, curling tracks). The occupancies presented in this note (except where explicitly mentioned otherwise) are then scaled such that they correspond to our best estimate for realistic occupancy including pile-up and bunch spill-over at a given luminosity. It should be kept in mind that this approach leads to a significant uncertainty on the absolute value of the predicted detector occupancy. We estimate it to be ≈20%. However, in comparing the *relative occupancies* between different experimental set-ups, these modelling uncertainties cancel to a large extend.

In the first part of this note we calculate the occupancies for three cases:

station number	2	3	4	5	6	7	8	9	10	11
z-position	217	330	480	620	700	790	840	890	940	1160

Table 1: Station z-positions as used in the “default” simulation setup

- the average occupancy in a whole tracking station
- the average occupancy in the area *above or below* the inner tracker: the *top* sector
- the average occupancy in the area *adjacent* to the inner tracker: the *side* sector

The definition of the *top* and *side* sectors is illustrated in fig 1.

In section 6 different inner tracker sizes are studied, however the overall active surface in each case is a rectangle. In section 7 a different inner tracker geometry is introduced.

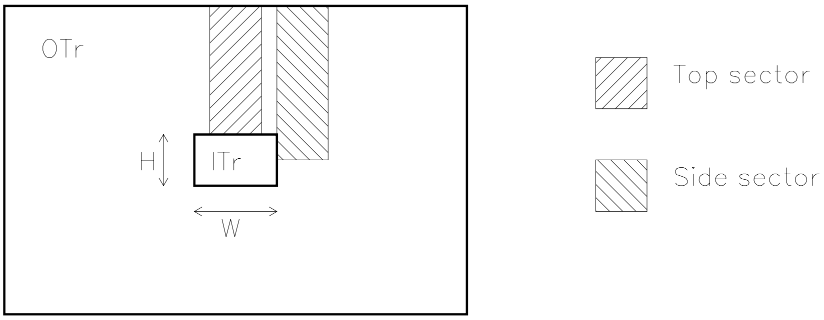


Figure 1: Definition of the "top" and "side" sectors. The dimensions W and H indicate the *Width* and *Height* of the inner tracker, with default sizes W=60 cm and H=40 cm.

2 Occupancy with baseline set-up

The occupancies calculated in the simulations obviously depend directly on the final state multiplicities predicted by PYTHIA, as well as on the generation of secondaries as simulated with GEANT. In figure 2 the average multiplicity is presented for the baseline set-up of tracking, but comparing the default tuning parameters of the PYTHIA and GEANT programs to modified ones. For this study dedicated PYTHIA and GEANT simulations have been done. The comparisons serve as an indication of the possible systematic underestimation of occupancy with our default simulations.

In the dedicated PYTHIA run the "P_t-cut" flag in the multiple interaction model has been set to 1.96 GeV (compared to 3.47 GeV in the standard run, an estimated 3 σ change). These runs show an increased occupancy of approximately 20%, almost independent of station number. This difference is taken into account as an overall estimate of the reliability of the simulations to which we assign a systematic error of 20%. No correction or safety factor for the PYTHIA systematics are implemented.

In the dedicated GEANT run the tracking cut-off values have been reduced from 1 MeV to 100 keV. It is observed that the occupancies increase by 10 to 15 % due to this. In a second dedicated GEANT run explicit generation of delta rays is switched on, leading to an increased occupancy of 10%.

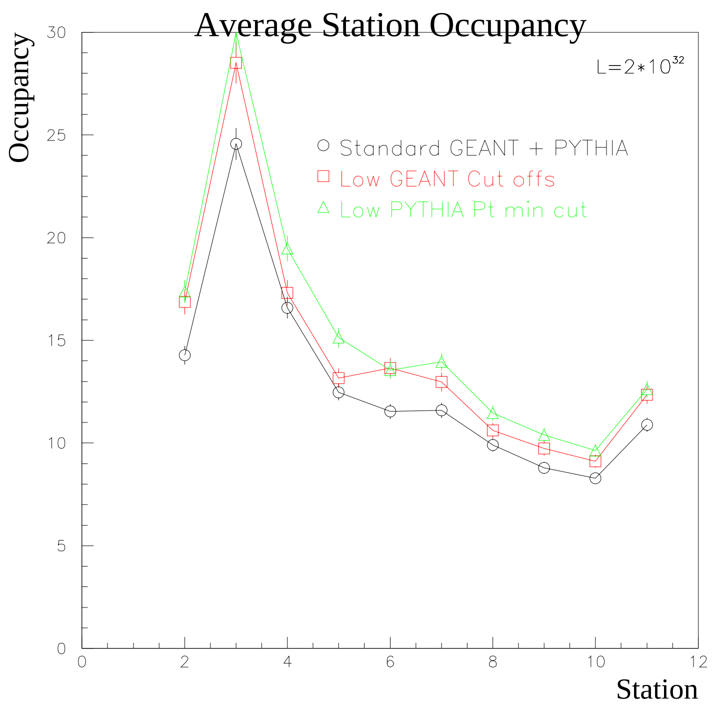


Figure 2: Systematic effects due to PYTHIA and GEANT simulation

A second source of uncertainty is the amount of cross-talk generated between the straw tube cells of the outer tracker. This cross talk is not taken into account in the simulations presented here. Based on test-beam results [4] we take a correction of 10% into account for cross-talk.

In summary, we scale the occupancies obtained in our standard simulations by a factor 1.36 (see also [1]) and assign an overall systematic error of 20%. In all occupancy results in this note, the correction factor of 1.36 has been applied.

The occupancy results are calculated corresponding to running at two different luminosities:

- *low* luminosity : $\mathcal{L} = 2 \times 10^{32}\ cm^{-2}s^{-1}$
- *high* luminosity: $\mathcal{L} = 5 \times 10^{32}\ cm^{-2}s^{-1}$

The baseline detector layout simulated in these studies assumes a radiation thickness of 2% X_0 per station and an Aluminium-Beryllium beam-pipe. The outer tracker occupancies for this set-up are shown in fig 3. These numbers can be compared to those obtained in [1] and are summarised in table 2 [1].

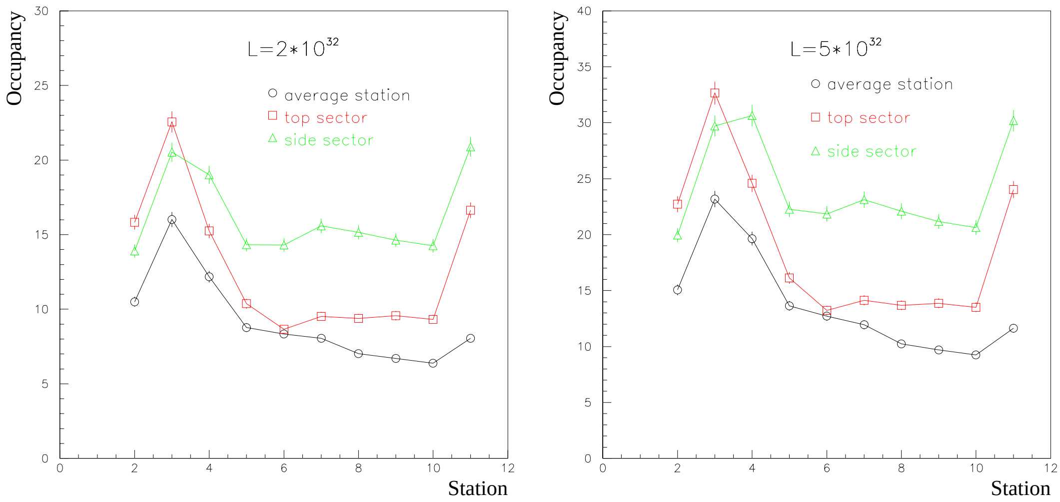


Figure 3: Station occupancy for default tracking detector set-up. Left: low luminosity. Right: high luminosity

The results show that the magnet stations have in general higher occupancy than the downstream region, mainly due to low momentum curling electrons (see the discussion in [1]).

In the downstream stations the hottest areas are the *side* areas. The *top* area is relative quiet. In the magnet stations both the *top* and *side* areas have high occupancy.

In [1] the average occupancies for low luminosity mode are claimed to be at the limit of being acceptable. The results here show that the occupancies in limited detector area's are considerably higher.

[1] As of recently T11 is no longer present in the LHCb spectrometer. The occupancy of T11 is calculated here, but no conclusions from these numbers will be drawn

	Average	Top Sector	Side Sector
	Low Lumi		
Magnet stations (T2 - T4)	10 - 15 %	15 - 22 %	14 - 20 %
Downstream stations (T5 - T10)	6 - 8 %	9 - 10 %	14 - 15 %
	High Lumi		
Magnet stations (T2 - T4)	15 - 23 %	23 - 33 %	20 - 30 %
Downstream stations (T5 - T10)	9 - 12 %	14 - 15 %	22 - 24 %

Table 2: summary of occupancies of default setup

We have adopted the following strategy in order to optimise the tracking detector layout. For a luminosity of $\mathcal{L} = 2 \times 10^{32} cm^{-2} s^{-1}$:

- In the main (non-magnetic) part of the spectrometer the average occupancy in the hottest sectors of the outer tracker should be less then 10%.
- For limited areas in the magnet tracker maximum occupancies up to 15% are tolerated.

3 Beam-pipe

At the time of the TP a naive simulation of the beam-pipe was implemented in the Monte-Carlo. With more realistic designs it has become clear that the number of secondaries generated in the experiment depends strongly on the shape and weight of the beam-pipe, and on the presence of flanges or bellows. This has been studied in detail in [5] using the FLUKA99 simulation program. Here we study the SICBMC/GEANT occupancies for seven different beam-pipe designs. It should be stressed that some of the designs studied are mechanically highly unfeasable while others are rather realistic. These aim of the studies is to understand the amount and sources of secondaries in the experiment. The simulated beam-pipe studies include:

- An Aluminium beam-pipe with stainless steel flanges (design 4.0).
- A beam-pipe consisting of purely Aluminium, including the flanges (design 4.1).
- An Aluminium beam-pipe with Al flanges with a Beryllium 25 mrad cone (design 4.2).
- A Beryllium-Aluminium alloy beam-pipe without flanges (design 7.0).

- A Beryllium-Aluminium alloy beam-pipe with aluminium flanges (design 7.1).
- A beam-pipe consisting of purely Beryllium, including the flanges.
- A setup with a beam-pipe made of Air, i.e. no beam-pipe.

The plots in fig 4 show the occupancy for these simulations. Plot 4B shows the relative average occupancies for the various pipes normalised to the case of no pipe.

The following observations can be made:

- Replacing the stainless steel sections by Aluminium leads to a large reduction on the occupancy.
- Adding a Beryllium cone for the 25 mrad section helps for station 1 and 2, but improves only marginally the occupancy for the downstream stations.
- The performance of Be-Al alloy pipe is halfway that of a full Be pipe and of a full Al pipe.
- The difference between the ("realistic") Be-Al pipe v7.1 and ("unrealistic") Be-Al pipe v7.0 is rather significant. This indicates that a significant amount of hits originates from bellows and flanges. This is in particularly true for station 6, which is positioned close to the second transition area of the pipe.
- The simulations with a full Beryllium pipe (including Beryllium flanges!) gives the best performance. However, even in this case the pipe is still the most significant source of secondaries, contributing to 25% - 30% of the total outer tracker occupancy.

In comparing the occupancy results in this section with those of the forthcoming sections it should be noted that reduced occupancy here, actually means a reduced hit density per unit detector surface, while in other optimisations (e.g. inner tracker size) a reduced occupancy is obtained by increasing the number of channels per unit detection plane. It is important to realize that for pattern recognition performance a reduction in the number of secondaries is clearly more profitable than an increase in the number of readout channels.

Since the TP the design of the beam-pipe has gone through a large evolution. The improvement of the, now baseline, Be-Al pipe compared to the aluminium pipe with stainless steel flanges, is spectacular. Still, on average the number of hits in the detector originating from particles produced in the beam-pipe almost doubles (on average a factor 1.8) the hit rate from all other sources. This indicates that a continued optimisation to improve (locally)

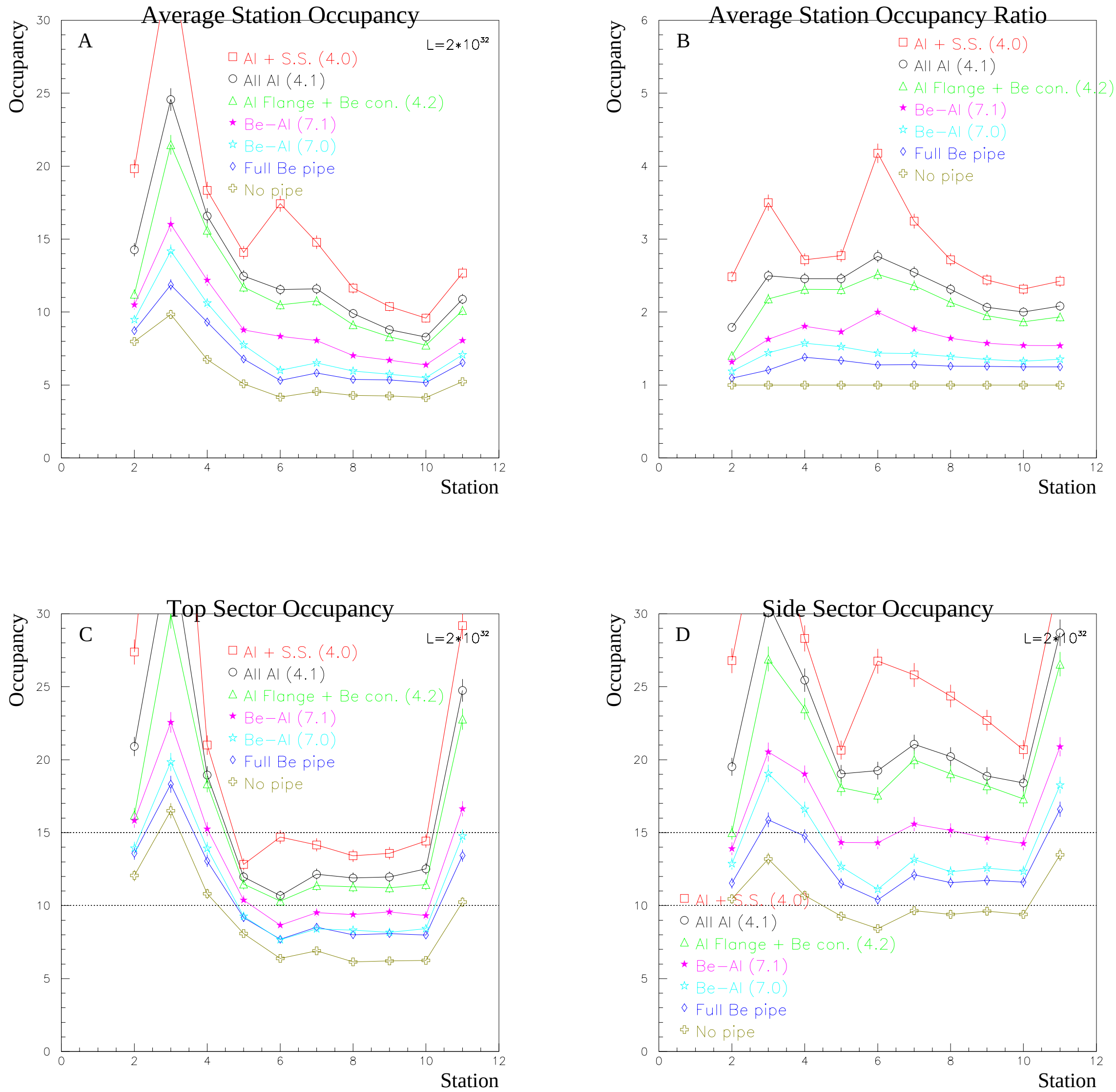


Figure 4: Occupancies based on different beam-pipe assumptions. A: average station occupancy. B: Relative station occupancy normalised on the "no pipe" option. C: top sector occupancy. D: side sector occupancy.

the hit rates could be very profitable. In such a optimisation the positioning of the sensitive planes relative to the flanges and bellows of the beam-pipe are very important.

4 Radiation thickness of the outer tracker

The thickness of the tracking stations (in terms of radiation length X_0) is studied in the plots in figure 5, using the full Aluminium beam-pipe design mentioned above.

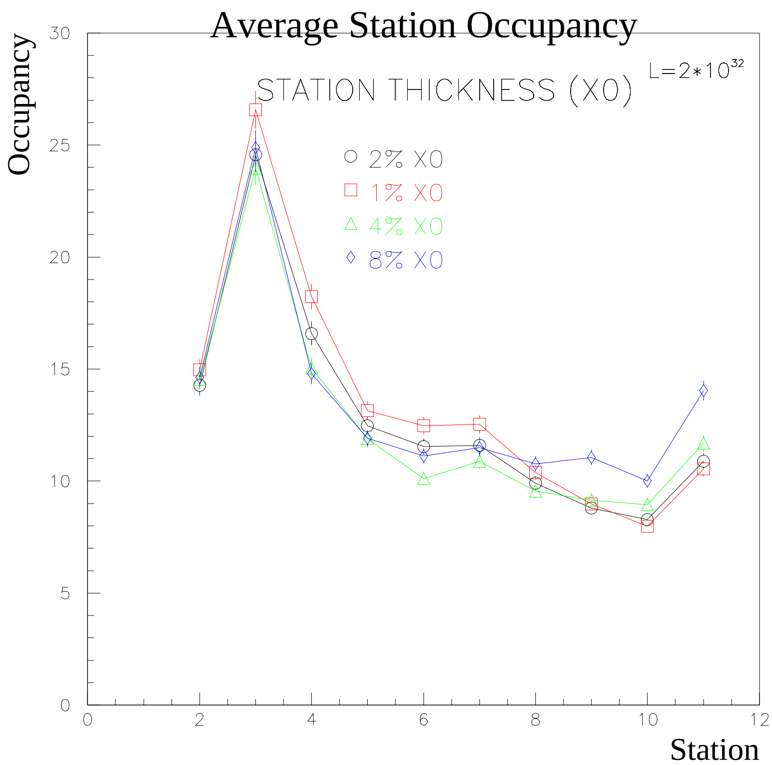


Figure 5: Occupancies for various radiation thicknesses of outer tracker

In TP baseline design stations have a thickness of 2% X_0. The plots in fig 5 show the occupancies for station thicknesses of $1\%X_0$, $2\%X_0$, $4\%X_0$ and $8\%X_0$ respectively. The corresponding thicknesses expressed in interaction lengths are approximately 0.3% λ_I, 0.6% λ_I, 1.2% λ_I and 2.4% λ_I. No large differences in the plots are observed. For the magnet stations the occupancy seems to slightly *higher* for $1\%X_0$ stations, while it increases for $8\%X_0$ stations in the downstream region. The results are interpreted as follows:

- Compared to the number of secondaries generated by the beam-pipe, the additionally secondaries generated by the tracking stations are a small number.
- A large fraction of the hits in the magnet stations are caused by looping electrons [5] often producing many hits per track (i.e. many loops). In the simulations with heavier tracking stations these electrons might be stopped earlier in a sort of shielding effect (see also the discussions in [1] and [5] [2]).
- For 2.4% λ_I (8% X_0) thick stations the additional average interaction rate after traversing 10 tracking stations is approximately 30%. Indeed an occupancy change of that order is observed in the downstream region.

5 Dependence on z − position

To study the occupancy as function of the z-position of the tracking stations we have replaced the standard set-up to a set-up with 11 stations inside the magnet area. The simulated z-positions are listed in table 3. The resulting occupancy as function of the z-position is shown in figure 6.

station number	1	2	3	4	5	6	7	8	9	10	11
z-position (cm)	217	275	330	370	420	480	550	620	660	700	750

Table 3: z-positions of a setup with 11 stations in the magnet

It should be noted that our procedure of "scaling" the detector occupancies with correction factors for the particle time-of-flight and for spill-over can not be applied to these simulations. So the occupancy results cannot not directly be compared by those in fig 3. These results do, however, show that there is a strong dependence of the occupancy on the exact z-position of the tracking stations. This is due to the dependence on the location of structures (flanges, bellows) in the beam-pipe as well as to the magnetic field map. Low momentum particles (mainly electrons) will be generated and follow complicated curling trajectories in the field.

[2] It should be noted that the current note does not address the disadvantages of a setup with thicker tracking stations on the reduced performance on tracking efficiency and resolution.

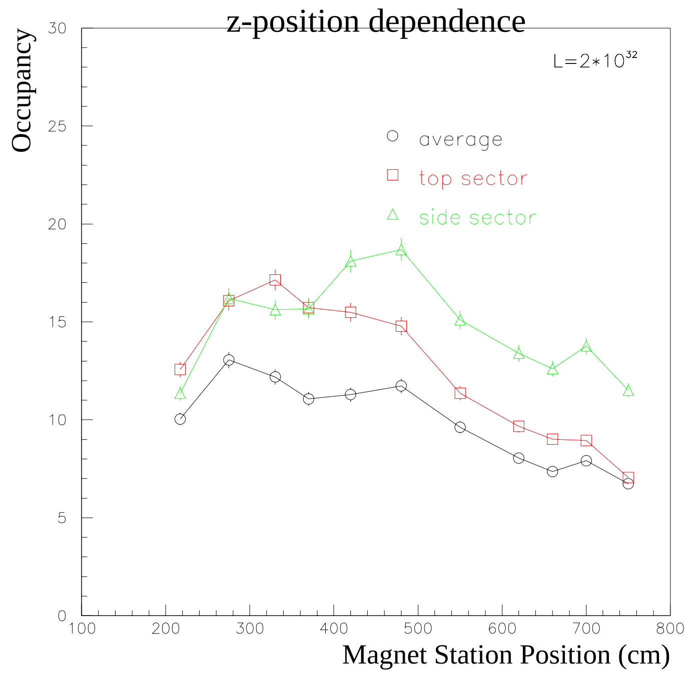


Figure 6: Occupancies for various z–positions in the magnetic region

6 Size of inner tracker

Since the track density decreases with the distance to the beam axis, the outer tracker occupancy varies as function of the dimension of the inner tracker. Figures 7 and 8 show the occupancy for three dimensions of inner tracker detectors: 60x40 cm^2 (the TP-baseline), 80x60 cm^2, and 120x80 cm^2, respectively for low and high luminosity.

From these plots the following observations can be made:

- The "top" sector plots illustrate that a 10cm extension on either side (top and bottom) of the inner tracker leads to a reduction in occupancy by 30%. An extension of 20cm on either side leads to a reduction in occupancy of a factor 2.
- The "side" sector plots illustrate that a 10 cm extension on either side (left and right) of the inner tracker is not very significant.
  An extension of 30cm on either side leads to a reduction in occupancy by 30%.

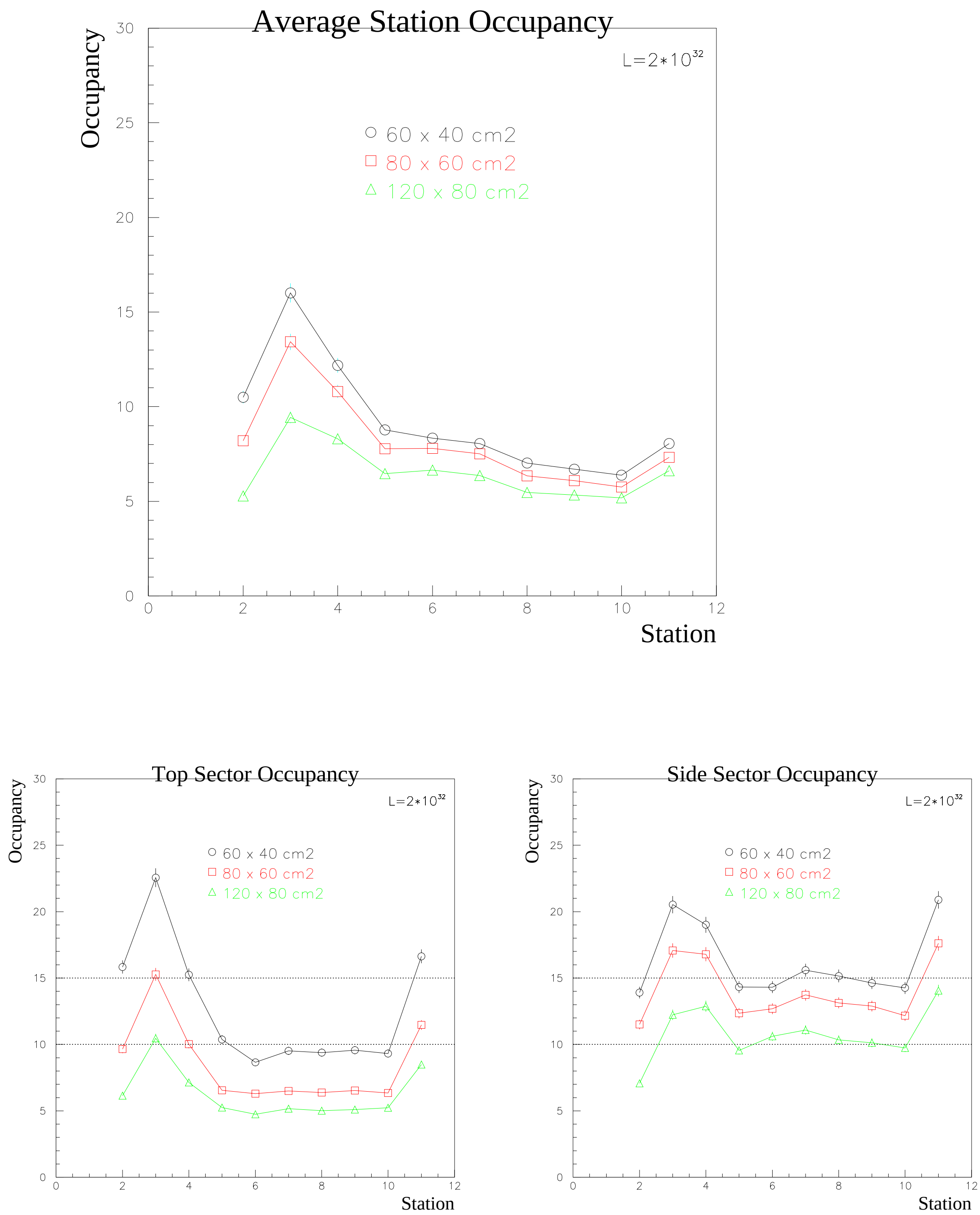


Figure 7: Occupancies based on various inner tracker sizes for nominal luminosity.

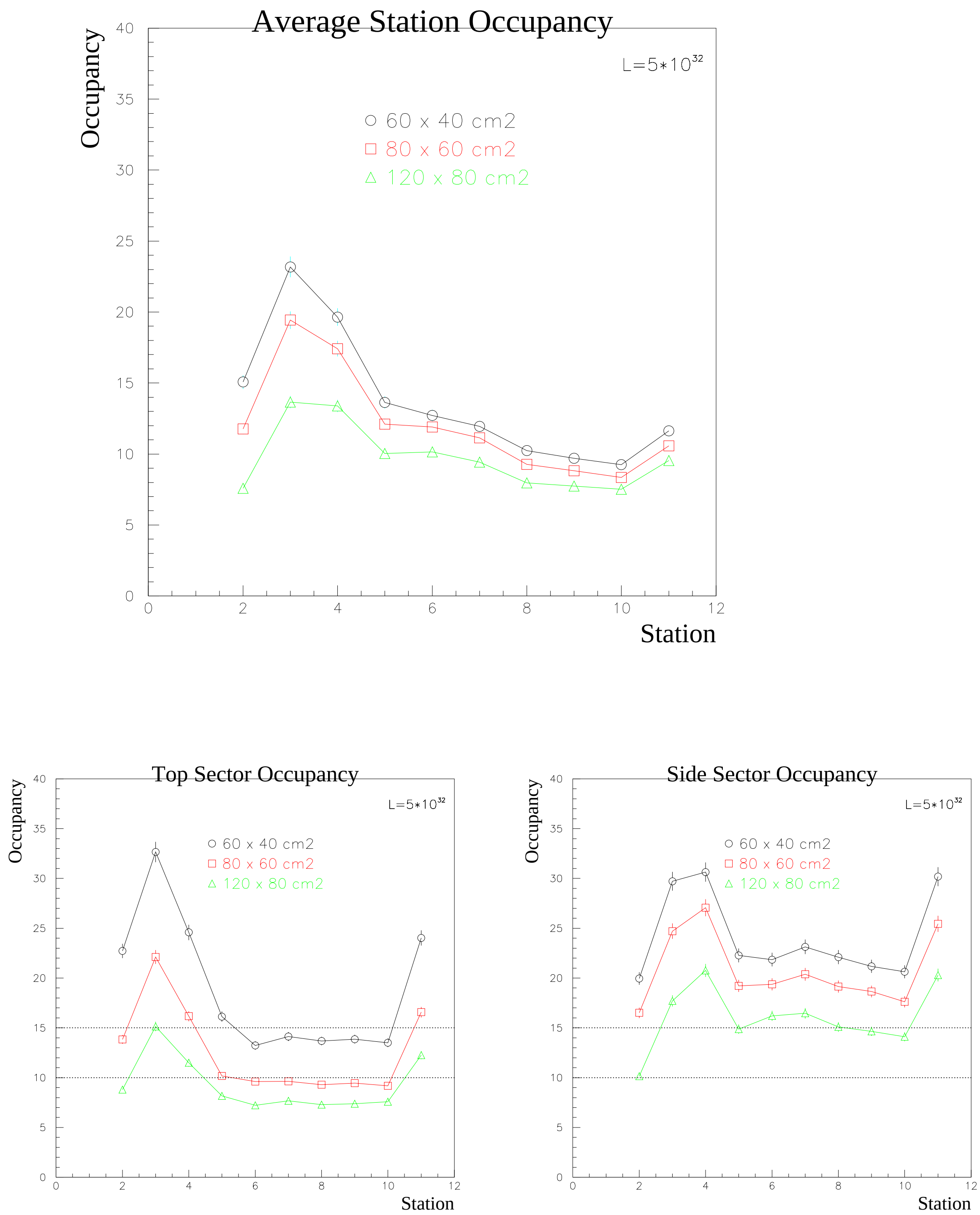


Figure 8: Occupancies based on various inner tracker sizes for high luminosity.

Table 4 summarizes the relative improvement of occupancy for the indicated size increase.

Average Station occupancy:		
Station size:	60x40 → 80x60	80x60 → 120x80
T2	-23%	-35%
T3	-19%	-29%
T4	-16%	-28%
T5-T10	- 9%	-13%
Top Sector occupancy:		
Half height:	20 → 30 cm	30 → 40 cm
T2	-36%	-36%
T3	-34%	-32%
T4	-36%	-29%
T5-T10	-30%	-28%
Side Sector occupancy:		
Half width:	30 → 40 cm	40 → 60 cm
T2	-20%	-37%
T3	-20%	-27%
T4	-16%	-21%
T5-T10	-14%	-23%

Table 4: Reduction in occupancy for various sizes of inner tracker

A possible geometry that would approximately meet the occupancy requirement adopted in secion 2 would be an inner tracker with the following dimensions:

- Station T2, T3, T4: 120 cm width by 60 cm height
- Station T5 - T10: 120 cm width by 40 cm height

As compared to the TP design this implies an increased inner tracker surface by a factor 2.3.

7 Cross geometry of the inner tracker

In order to reduce the total amount of surface covered by the inner tracker, but keeping the same maximum occupancy, an alternative geometry for the inner tracker is considered [6]. The geometry (the "cross" geometry) is sketched in fig 10. Using this geometry for the inner and outer tracker layout, now three potentially high occupancy area's are identified:

- the top sector
- the side sector
- the corner sector

The size of the cross geometry is then optimized to give a maximum outer tracker occupancy of 10% for $\mathcal{L} = 2 \times 10^{32} cm^{-2} s^{-1}$, while at the same time taken allowing only for two different geometries: one for the magnet stations and one for the the seeding stations. The resulting dimensions are:

- for the magnet stations T2, T3, T4:
  $W1 = 50$ cm, $H1 = 20$ cm, $W2 = 140$ cm, $H2 = 60$ cm
- for the downstream stations T5 — T10:
  $W1 = 50$ cm, $H1 = 20$ cm, $W2 = 140$ cm, $H2 = 40$ cm

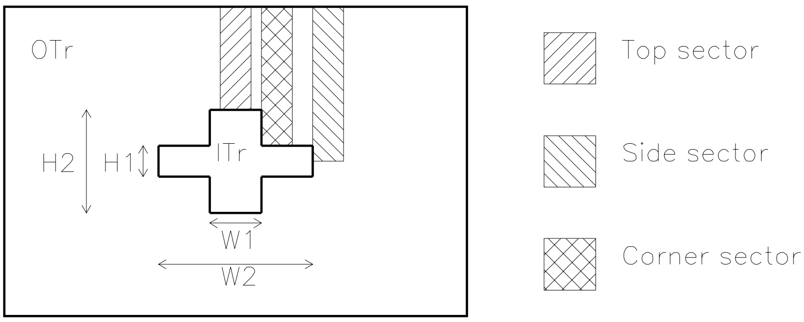
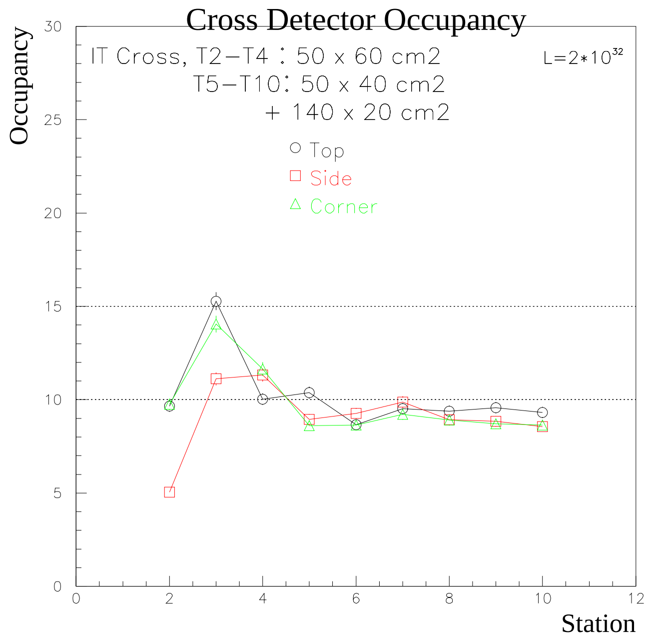


Figure 9: Definition of the "top" and "side" and "cross" sectors

This geometry is subsequently used as input to a technical design of an inner tracker / outer tracker geometry. The resulting size taking into account integral numbers of modules, wafers etc. will be described in a separate note.

The main deviation for a realistic design is a reduced dimension $W2 = 120$ cm. The occupancy plots for this case are also shown in fig 10.

Replacing a rectangular shaped inner tracker of the size 120x0.6 cm^2 (120x0.4 cm^2) for stations T2-T4 (T5-T10) by the cross shaped geometry described here leads to a 33% reduction of the sensitive inner tracker surface, while the maximum outer tracker occupancy remains the same.



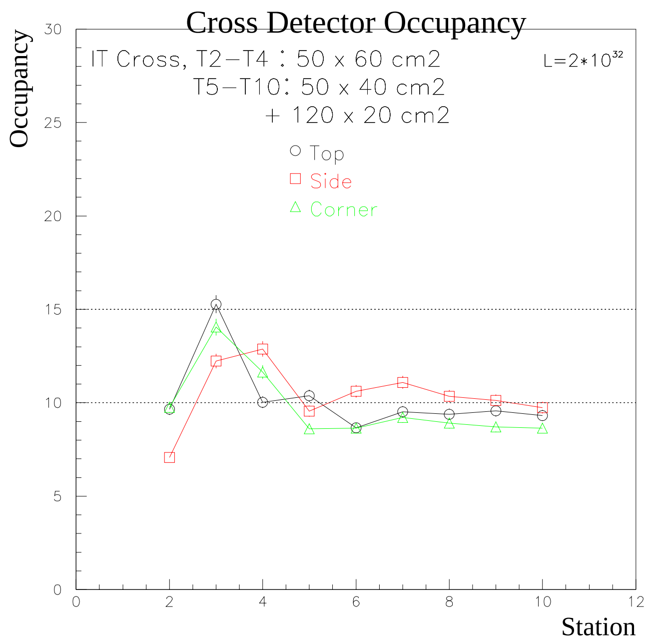


Figure 10: Top: Occupancies for *ideal* cross geometry design, Bottom: Occupancies for *realistic* cross geometry design

References

[1] M.Needham, "Occupancy results with the new outer tracker simulation", LHCb note 2001-085

[2] M. Merk, "Digitizations and Occupancies for Tracking in LHCb", LHCb note 1998-044

[3] O.Steinkamp, "Space Requirements and z Positions for Tracking Stations", LHCb note 2000-108

[4] Testbeam results using an outer tracker prototype detector showed a "digital" cross talk of 5% (i.e. a 5% probability that a hit on a given channel is also seen by one of the neighbouring wires). These results will be described in a forthcoming LHCb note.

[5] L.Shekhtman and G. von Holtey, "FLUKA99 simulations for the optimization of the LHCb vacuum pipe design", LHCb note 2000-104.

[6] T. Nakada, private communication.