Studies on the Super VELO

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Project report by
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Abstract

The Super Velo is the Run 5 upgrade of the VeloPix detector of the LHCb experiment. Its most challenging task is to cope with a luminosity increase of the factor 10. This study examines the potential physics performance of a detector based on the VeloPix design at high luminosity conditions. It is found that an unmodified VeloPix detector shows poor performance when exposed to 10x design luminosity, most gravely high ghost rates of 40 %. When applying basic assumptions about material changes such as cutting the silicon thickness by half and removing the RF Foil, the ghost rate drops by 20 %. When using thin silicon and re-optimizing the tracking algorithm, the ghost rate can even be reduced by 60 %. Applying the additional modification of a pixel area size four times smaller, the ghost rate drops by 88 % and the IP resolution improves. Finally, in a dream scenario with thin silicon, smaller pixels and no RF Foil, big gains in resolution and a ghost rate of less than 4 % can be achieved.

All scripts mentioned in the report plus the result data can be found here:
https://drive.google.com/open?id=0B7ljGkrE-qAgVFgyLWFudFVoZVk

1 Introduction

1.1 The VELO detector

The LHCb experiment is specialized on the high precision measurement of CP violation and rare decays. It is therefore optimized to observe decays of bottom and charm quarks. An important base task for every particle decay measurement is the high accuracy localization of the primary proton-proton vertex and the secondary B-decay vertex. The VELO (abbreviation for **ve**rtex **lo**cator) subdetector of LHCb is designed for exactly this task.

The VELO surrounds the interaction area of the proton-proton collisions of LHCb. It consists of 42 semicircle silicon strip sensors that alternate radial and angular stripes. An exceptional feature of the VELO detector is its small distance from the beam of only 7 mm. The best hit resolution of the VELO is 4 µm [1].

1.2 VELO future upgrade plans

The technology of detector development progresses steadily, making available better detector designs and algorithms every few years. The LHC targets an increase in luminosity which enables to accumulate more data in less time. As one can see in the time line below, the LHCb experiment will see an increase in luminosity by the factor of 4 in Run 3, starting in 2020. In this paper, we define the VELOPIX design luminosity ($= 2 * 10^{33} cm^{-2} s^{-1}$) as 1x luminosity. In order to deal with the higher occupancy rates an upgrade for the VELO will be necessary, the VELOPIX.

The dominant and name-giving change of the detector is the use of pixel silicon sensors. It has approximately 41 million pixels with a feature size of 55 µm squared. A new, rectangular shape also leads to a distance even closer to the primary beam, 5.1 mm. The increased luminosity causes a high occupancy, nevertheless, the track reconstruction speed and precision is increased compared to the VELO [2].

In Run 5, starting around 2030, the LHC will see one more increase of luminosity, this time by a factor of 10. Preliminary simulation studies have shown that the VELOPIX shows high occupancy levels at 10x luminosity. This in turn leads to a small loss in efficiency but worse, to ghost rates of about 40 % in average. This study examines possible effects of technological improvements on the physics performance of the SUPER VELO.

2 Project goals

The goal of this project is to study the potential physics performance of the SUPER VELO. In detail, this includes the conduction of a Monte-Carlo simulation on a VELOPIX-like detector at 10x its design luminosity.

As the performance is expected to show deficits (especially in the area of ghost rates), the main concern of the project is to see which improvements can be achieved by using simple assumptions about technological progress. This includes the availability of thinner silicon sensors as well as smaller pixels. Also, the impact of changing the track reconstruction algorithm is examined.

3 Project realization and results

3.1 Performance of the VeloPix at 10x luminosity

As it is desired to study the performance of a VeloPix-like detector under 10x luminosity conditions, the first step should be the examination of the performance of the unmodified VeloPix. Starting from this reference point the benefits of the modifications applied to the VeloPix can be evaluated.

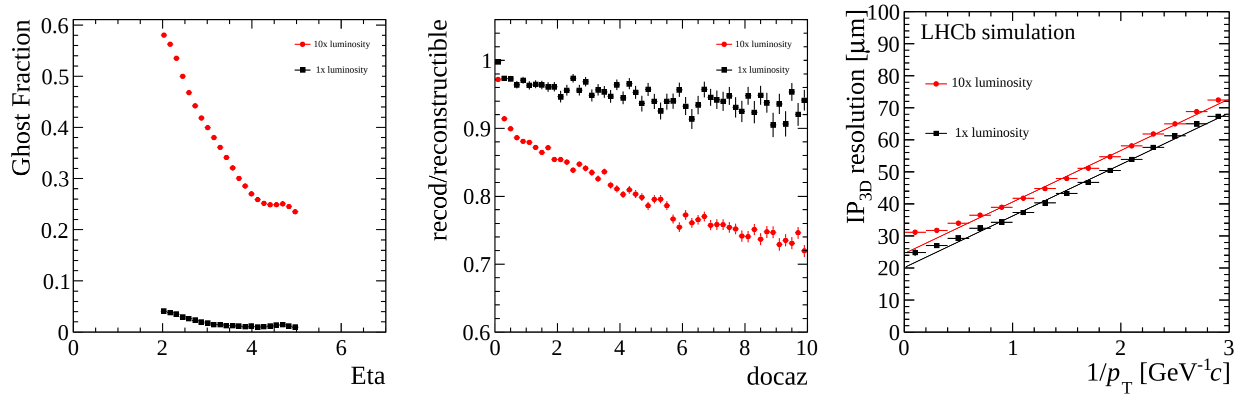
The Monte-Carlo simulation is conducted using established LHCb tools, which include: Gauss[1] for the generation of Monte-Carlo events, randomly generated particle decay events that simulate the branch probabilities of real decays. Boole[2] for the simulation of the detector response to charged and neutral particles as they traverse the active material and the output of the detectors (*digitization*). Brunel[3] for the reconstruction of the particle tracks from the detector digits and their comparison to the 'true' Monte-Carlo particles.

The aforementioned tools are used with a special set of parameters that enable not only the 10x luminosity condition but also a fast simulation using only relevant detector parts. This excludes most detector parts downstream of the VeloPix, leaving only VeloPix, UT and FT detectors for simulation. This speed up procedure is in particular beneficial when working with high luminosity events that have increased computing demands.

In Figure 1 (left) we see the comparison between the performance of the VeloPix at 1x luminosity and 10x luminosity. The first plot shows the ghost rate as a function of the pseudorapidity η. For explanation of the two new terms: The pseudorapidity η describes the angle of a decay particle relative to the beam axis (for LHCb, only values between $2 < \eta < 5$ are relevant). The ghost rate: Monte-Carlo simulation always features information about what 'truly' happens and what the reconstruction algorithm thinks that happens. The ghost rate is the number of reconstructed particle tracks that do not correspond to a real particle divided by the number of all reconstructed particle tracks (see also Section 4.3.1 of the Velo Upgrade TDR [2]). As one can see, the ghost rate is low at 1x luminosity (total integrated value: 1.6 %, see Table 1). At 10x luminosity, on the other hand, the ghost rates rise up to 60 %, leading to a total integrated value of 39 %. That means that almost 40 % of the reconstructed particles are fake and do not correspond to a real track, an undesirable result.

[1]Documentation of Gauss project: http://lhcb-release-area.web.cern.ch/LHCb-release-area/DOC/gauss/
[2]Documentation of Boole project: http://lhcb-release-area.web.cern.ch/LHCb-release-area/DOC/boole/
[3]Documentation of Brunel project: http://lhcb-release-area.web.cern.ch/LHCb-release-area/DOC/brunel/

Figure 1: Comparison of 1x and 10x luminosity. One can see an increase in ghost rates (left), a drop in efficiency (middle) and a loss in resolution (right).



In Figure 1 (middle), we see the efficiency as a function of the parameter DOCAz. DOCAz is the particle's absolute distance of closest approach to the beam line, which is closely related to the lifetime of the decay particle. The efficiency is defined as the number of correctly reconstructed particle tracks divided by the number of all reconstructible tracks (all charged particles that crossed at least three sensors). Again, there is a huge gap in performance between 1x luminosity and 10x luminosity: We see high values over 90 % at 1x luminosity while at 10x luminosity plummets down to 70 %. The Impact Parameter (IP) is the distance of closest approach between a particle and the production vertex. Again, it is closely related to lifetime, and hence it must be precisely measured. The resolution of this parameter is shown in Figure 1 (right) as a function of the inverse transverse momentum. At low momentum (high $1/p_T$) the resolution is dominated by material-induced scattering; at high momentum the resolution is limited by the spatial resolution of individual position measurements. In our case, we see a small degradation at high luminosity.

Table 1: Total integrated values for unmodified VeloPix at 1x vs. 10x luminosity

	1x luminosity	10x luminosity
Ghost rate	1.6 %	40 %
Efficiency	99 %	96 %
Clone rate	3.5 %	3.2 %

3.2 VeloPix with thin silicon

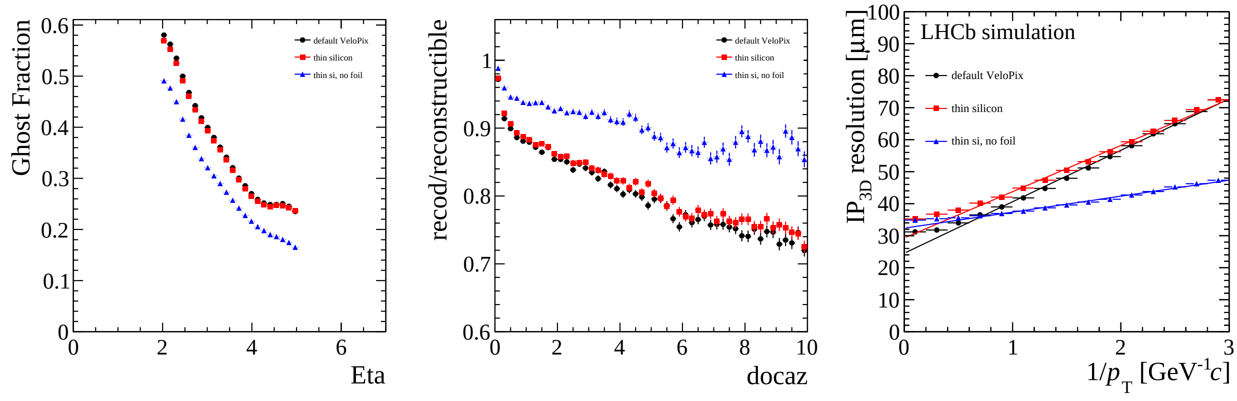
The high ghost rates that occur when using the VeloPix at Super Velo conditions make it necessary to change something in the detector geometry or feature size. Luckily, as the high luminosity conditions start only in Run 5 in 2030, there is enough time for technological progress in the detector construction. The first assumption in this study is a silicon sensor thickness of only 100 µm for the Super Velo (VeloPix thickness: 200 µm). All the other feature sizes are the same, including the chip thickness. A second assumption is the removal of the RF Foil, a small piece of aluminium that separates the primary LHC vacuum from the secondary LHCb vacuum. Just like the silicon of the sensor it is a material barrier and thus causes scattering and a loss in performance of the detector.

A summary of the technical steps to implement the necessary changes for the simulation can be found in the Appendix, Section 7.1.1.

The LHCb tool Panoramix can be used to visualize the detector. This helps in particular to see the difference between a default detector and one with a removed RF Foil.

In Figure 2 and Table 2, we see the results of the two assumptions separately compared to the default VeloPix. We can see that the ghost rates improve over all values of pseudorapidity, an effect dominated by the removal of the RF Foil. Overall, we see a relative

Figure 2: Comparison of the default VeloPix (black), the thin silicon modification (red) and the combination of thin silicon and the removal of the RF foil (blue) at 10x luminosity. One can see that all improvements in ghost rates (left), efficiency (middle) and IP 3D resolution (right) are dominated by the removal of the RF foil.



drop of the total ghost rate of 20 %, with respect to the unmodified detector. The efficiency values for high DOCAz improve significantly when removing the RF FOIL, but as most values are obtained for low DOCAz values, the total efficiency increases only slightly. Nevertheless, the fraction of particles lost to tracking inefficiencies is halved from 4 % to 2 %. In the resolution plot one can see a small drop in resolution of high transverse momentum as the thin silicon modification is applied. When removing the RF FOIL additionally, one can see a huge improvement in resolution for smaller transverse momenta.

Table 2: Total integrated values for VeloPix, thin silicon and thin silicon no foil modification

	def.	ThinSi	ThinSi&NoFoil
Ghost rate	40 %	38 %	32 %
Efficiency	96 %	97 %	98 %
Clone rate	3.2 %	3.3 %	2.7 %

3.3 Optimization of the tracking algorithm

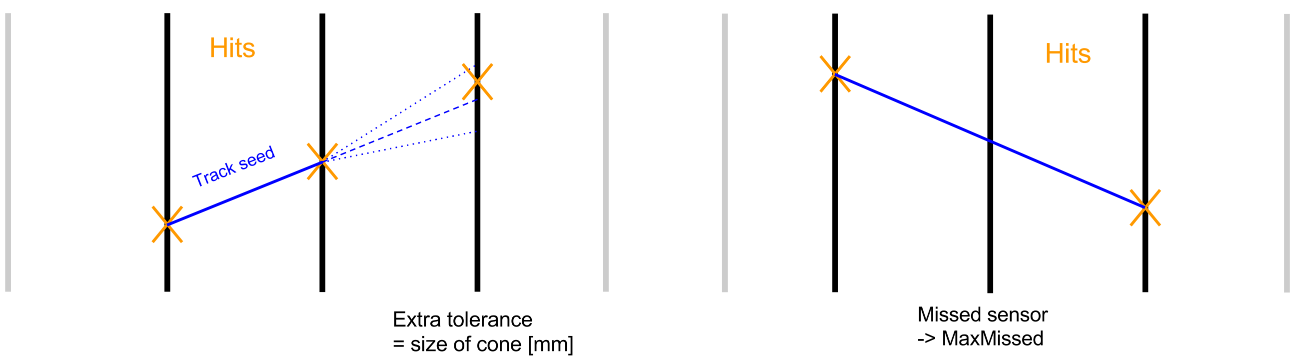
Until this chapter, a track finding algorithm is used that is optimized to give the best results for 1x luminosity and the VELOPIX geometry. This algorithm is now modified to see if the performance can be improved. The setup used in the following is the VELOPIX with thin silicon and the RF FOIL in place.

The changes made to the tracking algorithm are a basic change of the input parameters *ExtraTolerance* =0.6 mm, *MaxMissed* =3 and *MaxChi2Short* =20 that are explained now. Figure 3 shows a simple draft of the tracking algorithm. On the left side, we see that a tracking seed is formed by two hits in two neighboring sensors. The connecting line is then elongated through all sensors. The areas surrounding the points where the extrapolated line meets the sensors is then scanned for hits of the same particle. The size of this search window in mm is given by the *ExtraTolerance* parameter. When a particle leaves not enough energy deposit in a sensor to create a hit signal, we speak of a *missed sensor*. How many of those are allowed in a valid track is defined by the *MaxMissed* parameter. Finally, for particles with only three hits, the *MaxChi2Short* parameter gives a hard cut for a maximum value of χ^2, the sum of the quadratic distances from the hits to the extrapolated line in standard deviations. (The *MaxXSlope*/*MaxYSlope* parameters are also examined but not found to be beneficial.)

A summary of the technical steps to implement the necessary changes for the simulation can be found in the Appendix, Section 7.1.2.

For each set of tracking parameters a new BRUNEL job is necessary. This limits the possible 3D parameter space scan; as a solution each parameter is scanned individually and the optimum of them is combined, however, it is possible, that this is not the optimum of the parameter space. The results are shown in Figure 4 and Table 3. One sees very clearly the positive effects of each parameter on the

Figure 3: Visualization of the effect of the tracking parameters



ghost rate that is reduced drastically (60 %) when combining all optimal values. Also, the efficiency rises in the combination, especially due to the *ExtraTolerance* and *MaxMissed* parameters. On the downside, one sees a loss in resolution of up to 10 µm and the *clone rate* increases more than threefold.

Whenever two different reconstructed tracks correspond to the same Monte-Carlo particle, they form a *clone* (the clone rate is the number of clones divided by all reconstructed tracks.) The increase of the clone rate in the results show that as the track finding requirements are tightened, some particle tracks are split into multiple separate 'end-to-end' tracks, even though they correspond to just one single particle trajectory.

To sum up, the ghost rate can be reduced efficiently by removing material near the beam line and by changing the tracking algorithm. However, the reduction of the ghost rate comes with a high price: Many particle tracks are split up and thus remain almost useless. More technological progress will be necessary to achieve better detector performance.

Table 3: Total integrated values for thin silicon VeloPix and the optimised tracking algorithm

	ThinSi	TrackingOpt
Ghost rate	38 %	15 %
Efficiency	97 %	98 %
Clone rate	3.3 %	11 %

3.4 VeloPix with smaller pixels

A possible technological development might be the availability of silicon sensors with smaller pixels. For the following chapter not only a silicon thickness of 100 µm is assumed but also pixels of half the height and width than for VeloPix (27.5 µm squared). This means an increase in the number of pixel by the factor of four. One can expect a resolution increase and a decrease in occupancy that might together reduce the ghost rate and improve the detector performance.

A summary of the technical steps to implement the necessary changes for the simulation can be found in the Appendix, Section 7.1.3.

When studying the results, a first sanity check is a look on the occupancy plots. We see the expected drop in occupancy about a factor of 1/4. A comparison of the results is discussed after optimizing the track finding parameters in the next chapter. However, some general results can be found in Table 4.

Table 4: Total integrated values for unmodified VeloPix, thin silicon and thin silicon small pixels modification (unoptimized track finding)

	def.	ThinSi	ThinSi&SmPix
Ghost rate	40 %	38 %	34 %
Efficiency	96 %	97 %	96 %
Clone rate	3.2 %	3.3 %	2.4 %

Figure 4: Comparison of the ThinSi VeloPix (black), the optimal values for each parameter and their combination (green). One can see improvements in ghost rates (left) and efficiency (middle) but a loss of IP 3D resolution (right).

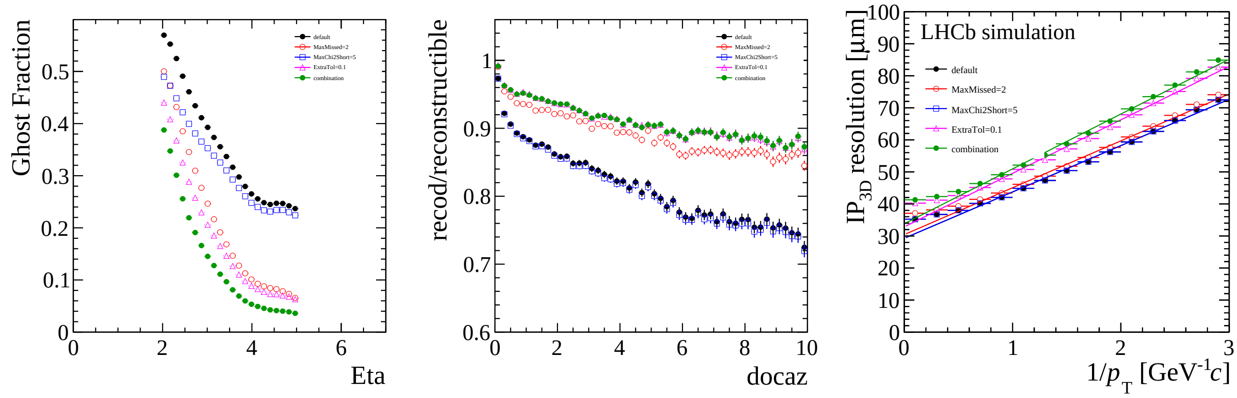
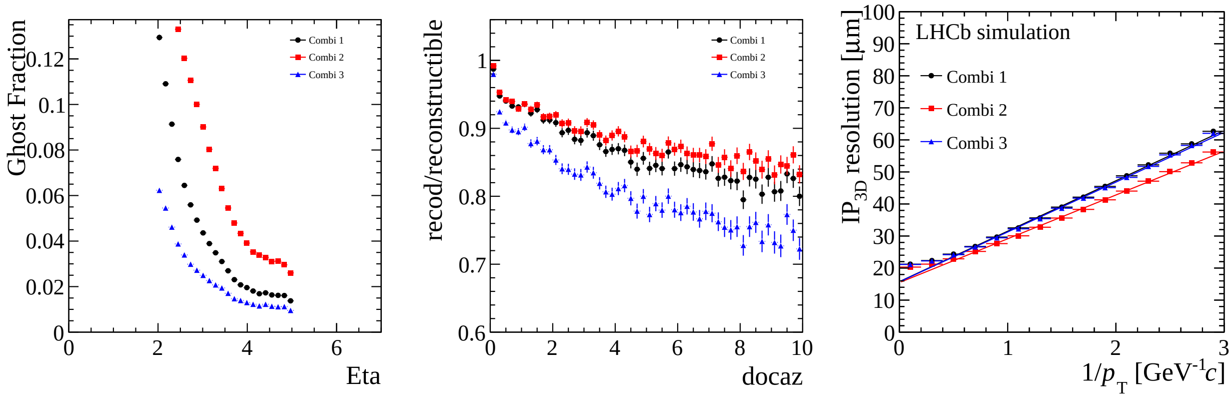


Figure 5: Comparison of the three tracking parameters sets fo VeloPix with small pixels. Each set is a trade-off between high performance in ghost rates (left), efficiency (middle), 3D resolution (right) or clone rates (Table 5).



3.5 Tracking optimization

The same considerations as in 3.3 apply here: The tracking algorithm is optimized for 1x luminosity and a certain detector geometry so a re-optimization of parameters is needed. Again, we scan each parameter *ExtraTolerance*, *MaxMissed* and *MaxChi2Short* (*MaxSlope* again not beneficial) and use then a combination of optimal parameters.

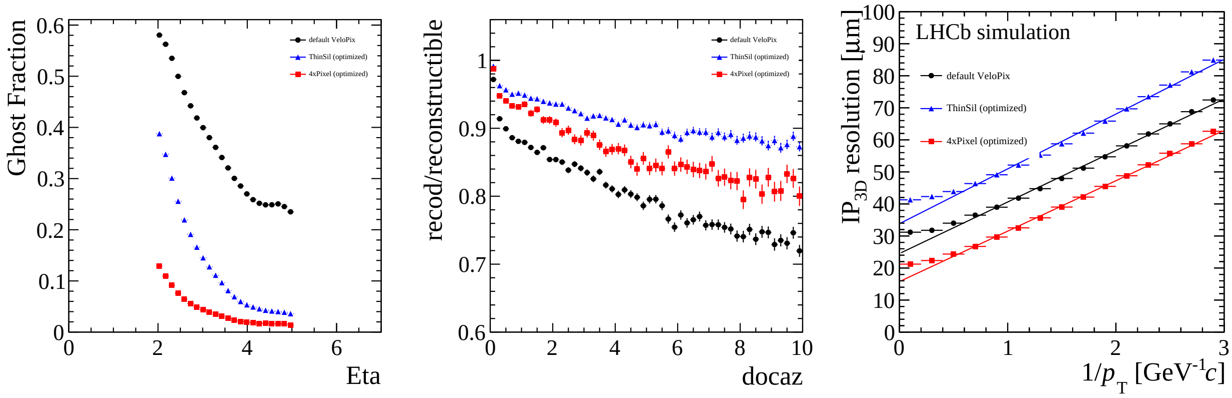
The technical steps to implement optimization are listed in the Appendix, Section 7.1.4.

The results prove that a detector with thin silicon and smaller pixels shows broad improvement in ghost rate, efficiency, clone rate and resolution. In particular, ghost rates as low as 2.5 % can be achieved. Here, three different sets of parameters are presented (Figure 5 and Table 5), each with advantages and disadvantages. The first set shows high efficiency and small ghost rate to the price of a clone rate of about 8 %. The second set has high efficiency, a low clone rate and the best resolution (approximately 10 μm better than the unmodified VeloPix) to the price of a high ghost rate of 8.5 %. The final set features the lowest ghost rate (only 2.5 %) and a low clone rate to the price of 2 % loss in efficiency. Which parameter set is best depends on what is most important for the detector performance. As the goal of this project is a reduction of ghost rate and a high efficiency, we choose Set 1 for a final comparison.

Table 5: Total integrated values for VeloPix with small pixels and three sets of optimized tracking parameters

	4xPixel	Set1	Set2	Set3
Ghost rate	34 %	4.6 %	8.5 %	2.5 %
Efficiency	96 %	98 %	98 %	96 %
Clone rate	2.4 %	8.1 %	3.4 %	6.9 %

Figure 6: Comparison of the unmodified VeloPix and the tracking optimized modifications ThinSilicion and ThinSilicon+SmallPixels. Shown are Ghost rates (left), efficiency (middle) and 3D resolution (right).



3.6 Summary & final results

The goal of this project is to study the potential physics performance of the Super Velo, using a VeloPix-like detector at 10x design luminosity. The unmodified VeloPix shows an integrated ghost rate of 40 %, a result that severely impacts the detector performance.

This makes a technological improvement necessary. As first change the silicon thickness is reduced from 200 to 100 µm. Without any optimization of the tracking algorithm the performance is almost unchanged for thin silicon, but when removing the RF Foil the ghost rate falls by 20 %. With RF Foil in place and tracking parameters optimized, we can reduce the ghost rate by 60 % down to an integrated value of 15 %. Unfortunately, this comes to the price of a high clone rate of 11 %.

Applying the next assumption, we simulate a VeloPix with thin silicon and 4x as many small pixels. Without optimization, the effect is limited, but with optimized tracking parameters we can achieve a ghost rate of only 4.6 % (−88 %) with good efficiency, good clone rates and improved resolution. The final results are summarized in Figure 6 and Table 6.

Table 6: Properties of default vs. optimized thin silicon vs. optimized thin silicon small pixels VeloPix

	def.	ThinSi(opt)	SmPix(opt)
Ghost rate	40 %	15 %	4.6 %
Efficiency	96 %	98 %	98 %
Clone rate	3.2 %	11 %	8.1 %

4 The dream scenario

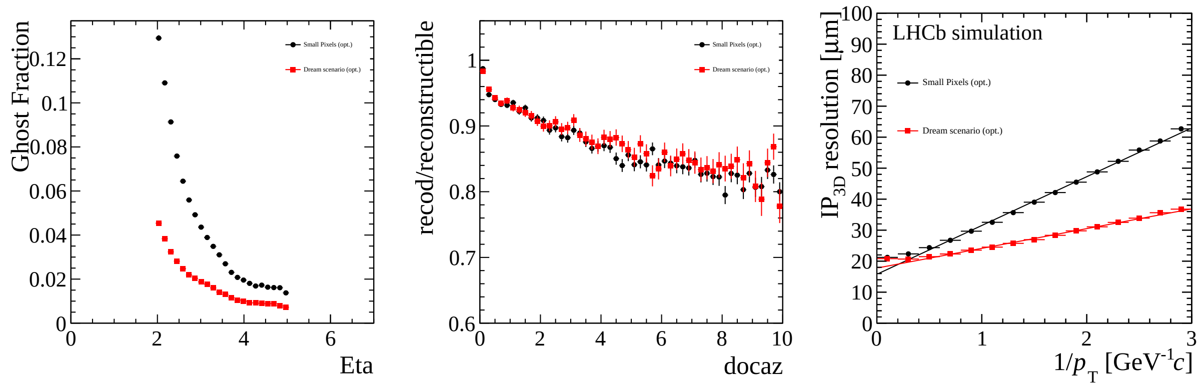
A detector setup to dream of would not only include thinner silicon and smaller pixels, but would also have the RF Foil removed. We combine the steps taken for the smaller pixels and for the removal of the RF Foil in order to see how good we can get (for technical details, see Appendix 7.1.5).

In Table 7 we see the characteristic values for the unoptimized dream detector and two selected sets of optimization parameters. Whereas Set 4 shows the best overall performance, Set 3 has the lowest ghost rate of only 1.9 % but to the price of a high clone rate. Choosing Set 4 as the optimal parameter set for the dream scenario detector, how much performance improvement can we gain with respect to the former detector? The answer to that is in Figure 7. Whereas the efficiency remains almost unchanged, we see another drop in ghost rates and a big gain in IP 3D resolution (over 20 µm for high $1/p_T$). So these are the gains when removing the RF Foil on a detector with thin silicon and small pixels.

Table 7: Total integrated values of Super VELO dream scenario (unoptimized and two sets of tracking optimization parameters)

	unopt.	Set 4	Set 3
Ghost rate	27.9 %	3.4 %	1.9 %
Efficiency	98.5 %	98.5 %	97.6 %
Clone rate	2.1 %	4.4 %	6 %

Figure 7: Comparison of the optimized ThinSilicon+SmallPixels detector to the dream scenario (additional removal of the RF foil), optimized with parameter Set 4. Visible is another drop in ghost rates (left), few change in efficiency (middle) and a big improvement in IP resolution (right).



5 Further research

A few points have not been examined in this study. For example, it might be of interest how an unmodified but tracking optimized VeloPix would perform at 10x luminosity. This would also support the significance of the comparison in Figure 6.

Another path that could be pursued is the further modification of the tracking algorithm. A concrete starting point might be to do the track seeding with three points instead of two (code example *searchByTriplet* found here[4]).

6 References

References

[1] R. Aaij *et al.*, "Performance of the LHCb Vertex Locator", JINST **9** (2014) 09007, doi:10.1088/1748-0221/9/09/P09007, [arXiv:1405.7808 [physics.ins-det]].

[2] R. Aaij *et al.*, "LHCb VELO Upgrade Technical Design Report", CERN/LHCC-2013-021, LHCb-TDR-13.

[4] Omar Awile in Gitlab: https://gitlab.cern.ch/oawile/cl_forward/blob/master/SerialKernel.cpp

7 Appendix

7.1 Technical realizations

7.1.1 Thin silicon and RF foil removal

To implement a detector with a changed geometry it is useful to obtain a local version of the DDDB (*detector description database*). The changes were based on the databases 'dddb-20160304' and 'sim-20150716-vc-mu100'. The parameter to modify the silicon thickness is *SiThick* found in the file 'UVP/Parameters/Ladders.xml'. A thickness of 100 µm is chosen here. To remove the RF FOIL the lines referring to 'RFFoilLeft.xml' and 'RFFoilRight.xml' in the file 'UVP/Structures/VPHalves.xml' have to be deleted. Additionally, the *physvol* blocks with the name *pvRightRFFoil* and *pvLeftRFFoil* in 'UVP/Geometry/LogVol/VP.xml' have to be removed. The changes are wrapped in a .db-file. They are called in the GANGA script with the CondDB().addLayer(dbFile="*filename*",dbName="DDDB") method.

7.1.2 Tracking optimization

In the code, the changes are implemented with help of the *prPixelTracking* (notice lower case p) object found in 'Tf/TrackSys/RecoUpgradeTracking.py'. The modifications (i. e. prPixelTracking.MaxMissed=2) have to be implemented directly after its definition. A 'make' of the package is required before the changes apply. This is a bit cumbersome, but unfortunately, a change of the parameter in the Python script that starts the GANGA job was not successful.

7.1.3 Smaller pixels

The road to create a simulation for the VELOPIX with smaller pixels is longer than the one with only thin silicon. First comes the creation of a local DDDB. In 'UVP/Parameters/ActiveArea.xml' one needs to change the parameters *NRows* and *NColumns* to 512 and *PixelSize* and *InterChipPixelSize* to *0.0275*mm*. The last change assumes there are no more long pixels on the sensors in the inter-chip regions.

After that a change in the code concerning the encoding and decoding of the raw bank storage algorithms is necessary, mainly because there are assumptions in the code about the number of pixels. For designing it in a backward compatible way, constants are introduced in 'LHCb/Kernel/LHCbKernel/VPConstants.h'. All magic numbers in the files 'LHCb/VP/VPDAQ/VPSuperPixelBankEncoder.cpp' and 'Rec/Pr/PrPixel/PrPixelHitManager.cpp' are then replaced by references to these constants. The changes make use of spare bits in the 32 bit data types that are used for storing. Apart from that, only the number of pixel rows and columns in 'LHCb/Kernel/LHCbKernel/xml/VPChannelID.xml' needs to be changed. All changes can be found in the GITLAB branch VPFUTUREUPGRADES. A nightly build for the branch exists (mainly because the change of a header file requires a full recompilation).

A full switch between 256x256 and 512x512 pixel can be achieved by only changing the constants in 'VPConstants.h' and 'VPChannelID.xml' and recompiling.

For the simulation the same GAUSS output as for the thin silicon modification can be used. The VPFUTUREUPGRADES version of BOOLE and BRUNEL can be run locally with the following commands (replace 'Fri' by the weekday of the nightly build):

```
lb-dev --nightly-cvmfs --nightly lhcb-VPFutureUpgrades Fri Boole/master
lb-dev --nightly-cvmfs --nightly lhcb-VPFutureUpgrades Fri Brunel/upgradeTracking
./run gaudirun.py ~/skripts/boole-job_local.py | tee boole-log.txt
./run gaudirun.py ~/skripts/brunel-job_local.py | tee brunel-log.txt
```

Local versions of the code can be obtained with the usual git commands ('git lb-use' and 'git lb-checkout') and compiled with a simple 'make'.

7.1.4 Smaller pixels tracking optimization

Like in the previous chapter, a local build is used to run on a local machine. That enables to apply the changes to the *prPixelTracking* object in 'Tf/TrackSys/RecoUpgradeTracking.py' quickly rather than waiting for the next nightly build. To get a reasonable amount of data processed but without the ability to work on the Grid, a simple bash script is used that starts the processing of a reasonable amount of Gauss sub jobs (in our case: 15) in Boole and Brunel on different LXPlus servers.

7.1.5 The dream scenario

For this simulation we use the same script to run parallel jobs on the LXPlus servers. This time, we need to use Gauss input files that use thin silicon and removed RF Foil. Small pixels are not necessary in the Gauss files, but the DDDB with thin silicon, removed foil and small pixels needs to be implemented in both the local Boole and Brunel scripts. Apart from that, everything works the same as in the last setup.

7.2 Relevant files

You can find all scripts that were referred to plus all the result data and additional information here: https://drive.google.com/open?id=0B7ljGkrE-qAgVFgyLWFudFVoZVk