Possibility to measure beam size at Belle II experiment by simulation

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Abstract

A concept was introduced to estimate the beam size and position in the Belle II experiment. The idea is to use interactions between electrons in the beam and residual molecules of gas in the beam pipe. These interactions produce scattered particles, that may be tracked, and by that the beam parameters may be deduced. This project's goal is to estimate whether this technique is feasible, by running a Monte Carlo simulation.

Contents

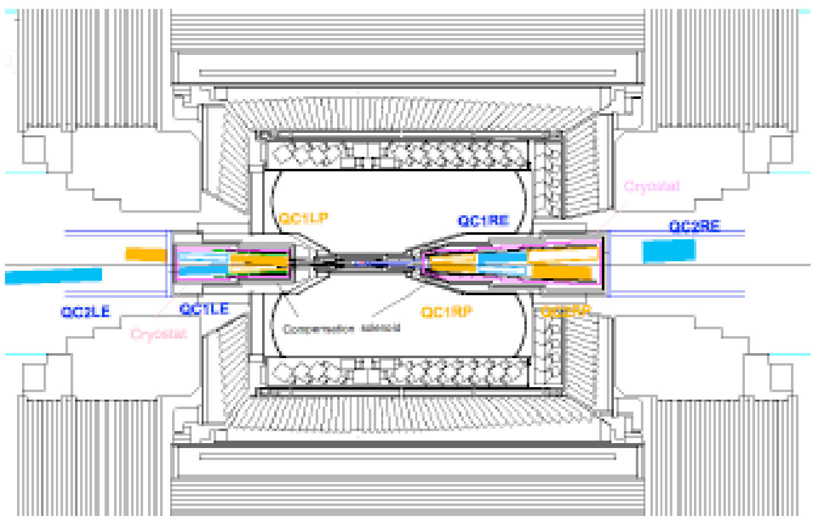
Background and Introduction

Belle II experiment

The Belle II experiment is a particle physics experiment conducted by an international collaboration of physicists and engineers investigating CP-violation effects. It will be conducted at the high energy accelerator superKEKB in Tsukuba, Ibaraki Prefecture, Japan.

Belle II is a sequential experiment to Belle experiment. It will be conducted at the same tunnel. The Super KEKBB factory is an asymmetric-energy e+ e− collider with a design luminosity of $8 \text{ x } 1035 \text{ cm}^{-2} * \text{s}^{-1}$, which is around 50 times as large as the peak luminosity achieved by the KEKB collider , the accelerator used in the Belle experiment.

It is called a B-factory for its large production of B-mesons which provide good conditions to study and measure the CP violation due to its property of decaying into other lighter mesons.



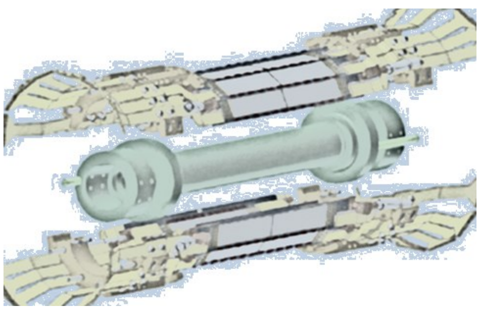
The design of the onion layers detector. The relevant part for this project is the PXD and the SVD that surround the Interaction region.

The detectors

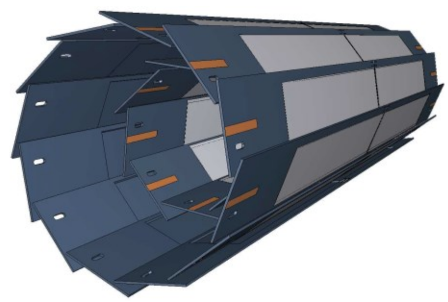
The Belle II detector is a general purpose spectrometer for the next-generation B-factory experiment at KEK. The Belle II detector efficiently collects data of e+-e− collisions made by the SuperKEKB accelerator. The Belle II consists of several sub-detector components.

The part that is most relevant for this project is two layers of pixelated silicon sensors (PXD). The PXD is a barrel-only system consisting of two cylindrical active detector layers coaxial with the beam line. The inner layer is placed as close to the beamline as possible at r = 13mm. The outer layer is at a radius of 22mm. The spatial resolution of the detector is ~10 μ m.

The next component is four layers of double-sided silicon strip sensors (SVD) that measure decay vertex positions of B mesons and other particles. A general name for these six layers is Vertex Detectors (VXD).

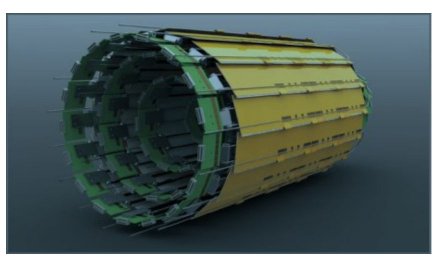


An illustration of the beam pipe around Interaction Region



An illustration of the two layers of PXD that surround the Be part of the beam pipe

A central drift chamber (CDC) that measures trajectories, momenta and dE/dx information of charged particles.
A barrel-shaped array of Time-Of-Propagation (TOP) counters that reconstruct, in spacial and time coordinates, the ring-image of Cherenkov light cones emitted from charged particles passing through quartz radiator bars, another ring-imaging Cherenkov counters with aerogel radiator in the forward end-cap (A-RICH), an electromagnetic calorimeter (ECL) comprised of scintillator crystals located inside a superconducting solenoid coil that provides a 1.5 Tesla magnetic field, and an iron flux-return located outside of the coil which is instrumented to detect K0L mesons and to identify muons (KLM).



The barrel containing the four SVD layers

The concept

Inside the beam pipe the striving is to reach the best possible vacuum. Gas molecules cause unwanted collisions and might cause background, heat and damage to detectors. Interactions with gas also lead to expansion of the beam, which opposes the thoughtful efforts to accelerate and focus the beam, especially around interaction point. There are several pumps that their purpose is to get rid of gas molecules, and keep good vacuum in the system. The best vacuum is maintained around interaction point.

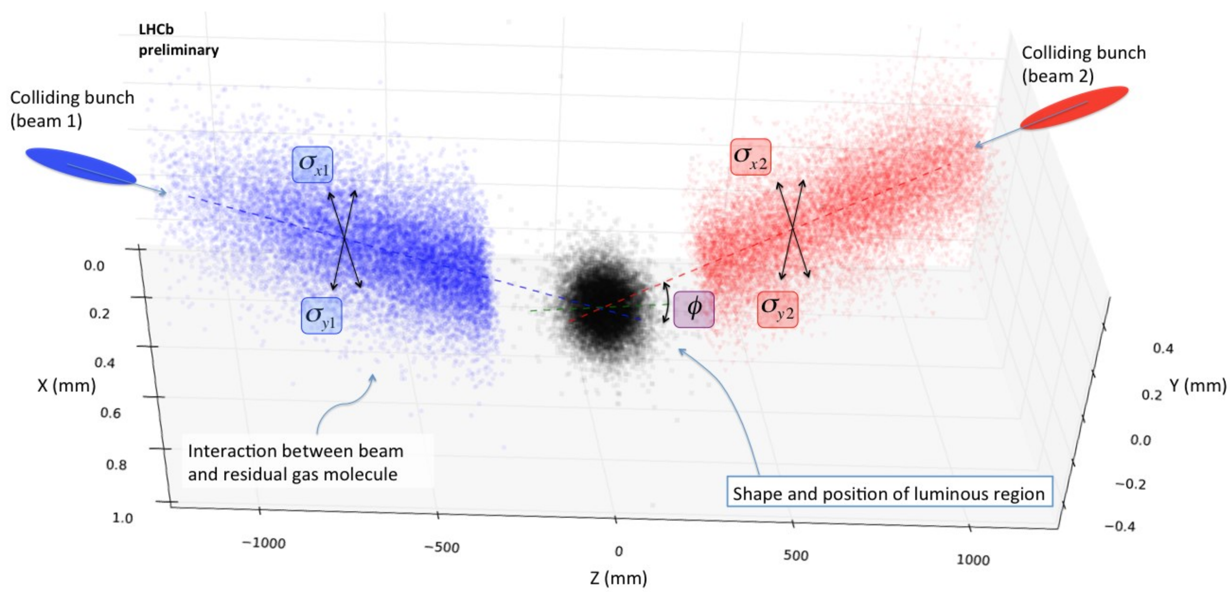
Nevertheless, ideal vacuum cannot be achieved in reality. An idea was suggested to use the residual molecules left , in order to measure the beam size using beam – gas interaction.

When the beam propagates in the beam pipe, the particles collide with air molecules, which they interact with, and get distorted from their original course. By detecting events in the Pixel Detector, the idea is to reconstruct the track of the particles, and estimate where the interaction occurred, and by that getting a picture of the properties of the beam such as position and width.

The assumption is that the particles are distributed Gaussian in the beam, in the main axes in the plane transverse to the direction of propagation. The interesting values are σ_x and σ_y, the standard deviations of the 2 dimensional Gaussian .

This technique was suggested and performed in LHCb collaboration (CERN).

My task for this project is to estimate weather this technique is feasible to perform in BELLE II detector. There are many parameters involved, such as differences in geometry, resolution of the detectors, and type of beam particles. My mission was to get an estimation of the rate of hits in the PXD detector that stem from beam-gas interactions. This is achieved by Monte Carlo simulation.



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This graph is a demonstration of beam-gas & luminous-region imaging. One can see the points that represent the interactions between the two beams with gas molecules. By reconstructing these events one can try to deduce the shape and size of the beam, and especially around the luminous region, (which is around the interaction point).

Simulation

The project is done in an environment that integrates several technologies and languages.
In order to get an estimation of the hits in the PXD, a Monte Carlo simulation was performed.
The system was simulated in Geant4, which was developed in CERN. It is a toolkit for simulation of passage of particles through matter, and it is used in simulations of complex systems. The simulation was done in Geant4 interface inside basf2 frame, which contains the Belle II system's different parts, geometry, materials, and detectors.
The data for the simulation is in XML format files, the source files for the simulation are in C++, and the steering file to initiate the simulation is in Python.
The simulation results were manipulated using Perl scripts. The data was analyzed using ROOT, which is also a product from CERN. The ROOT system provides a set of OO frameworks with all the functionality needed to handle and analyze large amounts of data in a very efficient way. It is in C++ environment.
Some fits and calculations were done in MATLAB.

The method

Of course that in real life the value of the density changes in time and space, and is a little different among the different parts and volumes of the system. For the needs of the simulation we are assuming a constant value which represents the reaction of the system to the gas.

The density of the gas in the system in very low. It is in the order of $10^{-12}\ g/cm^3$. Simulating the actual vacuum in the system to observe the influence of the gas takes a long time and a lot of computation resources. So the method used for this project is simulating bad vacuum. We are assuming that the system in bad vacuum behaves similarly to the system in good vacuum, with interaction rate, and hit rates in the detectors that are proportional to the values in good vacuum with a factor of the ratio between the densities.

$$(*)\ \ \text{Hit Rate in Vacuum} = \text{Hit Rate in Air} * \frac{\mathrm{D_V}}{D_A}$$

Where "Air" denotes the simulated gas, Vacuum denotes the gas of the actual system, $\mathrm{D_V}$ *is the density of the vacuum and* $\mathrm{D_A}$ *is the density of the air.*

To get good estimation for the hits in vacuum, the simulation is performed in different vacuum levels as close as possible to the nominal value of the density of gas in the system. Vacuum is simulated in values of $\frac{1}{10}, \frac{1}{100}, \frac{1}{1000}$ from air in the atmosphere, i.e. 10^{-4}, 10^{-5}, 10^{-6} $\mathrm{g/cm^3}$. With the results from these vacuum values we can check the assumption of linearity in the density, and extrapolate the results to vacuum.

Simulation properties

In the simulation there is only an electron beam. The simulation is of HER (High Energy Ring). Synchrotron radiation is turned off. That is to speed up the simulation, as the photons do not matter for this purpose.

Number of events simulated:

Density (g/cm^3)	Num of generated Events	fraction of a bunch (%)
10^{-4}	$1.017x10^8$	0.02
10^{-5}	$4.399x10^8$	0.07
10^{-6}	$1.018x10^9$	0.16

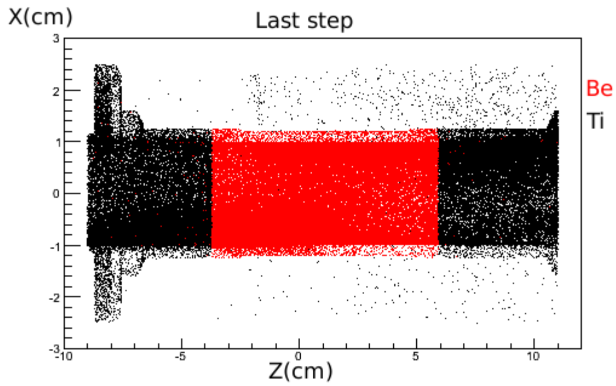
Properties of the accelerator:

Number of bunches	2500
Revolution frequncy (Hz)	10^5
Particles in a bunch	6.5 x10^{10}

Expected bunch size
σx= 7.75 µm
σy= 50.2 nm

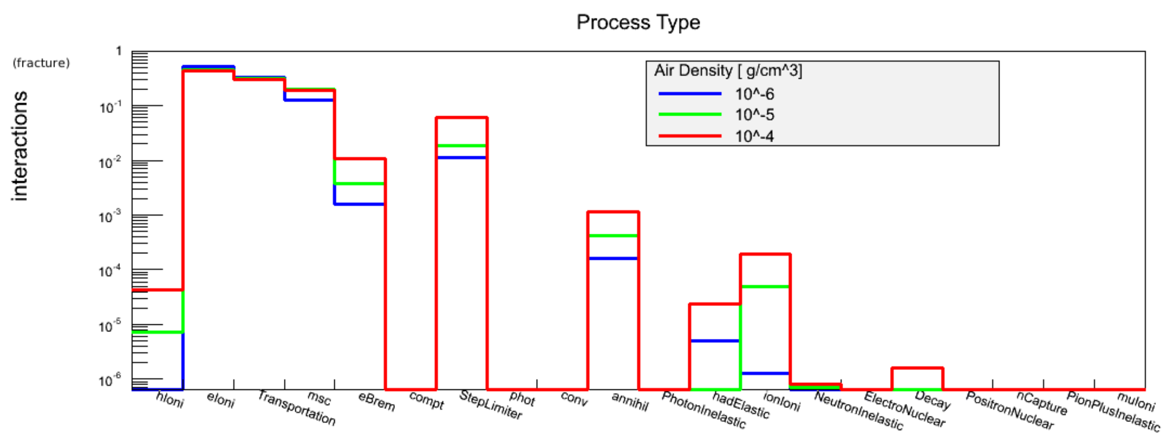
Analysis and results

As mentioned before, simulations were conducted for three values of vacuum. The relevant part of the beam pipe is the Be part, as it contains the IP and the PXD surrounds this part. Counts of hits were taken separately for the Be part, and Ti part.



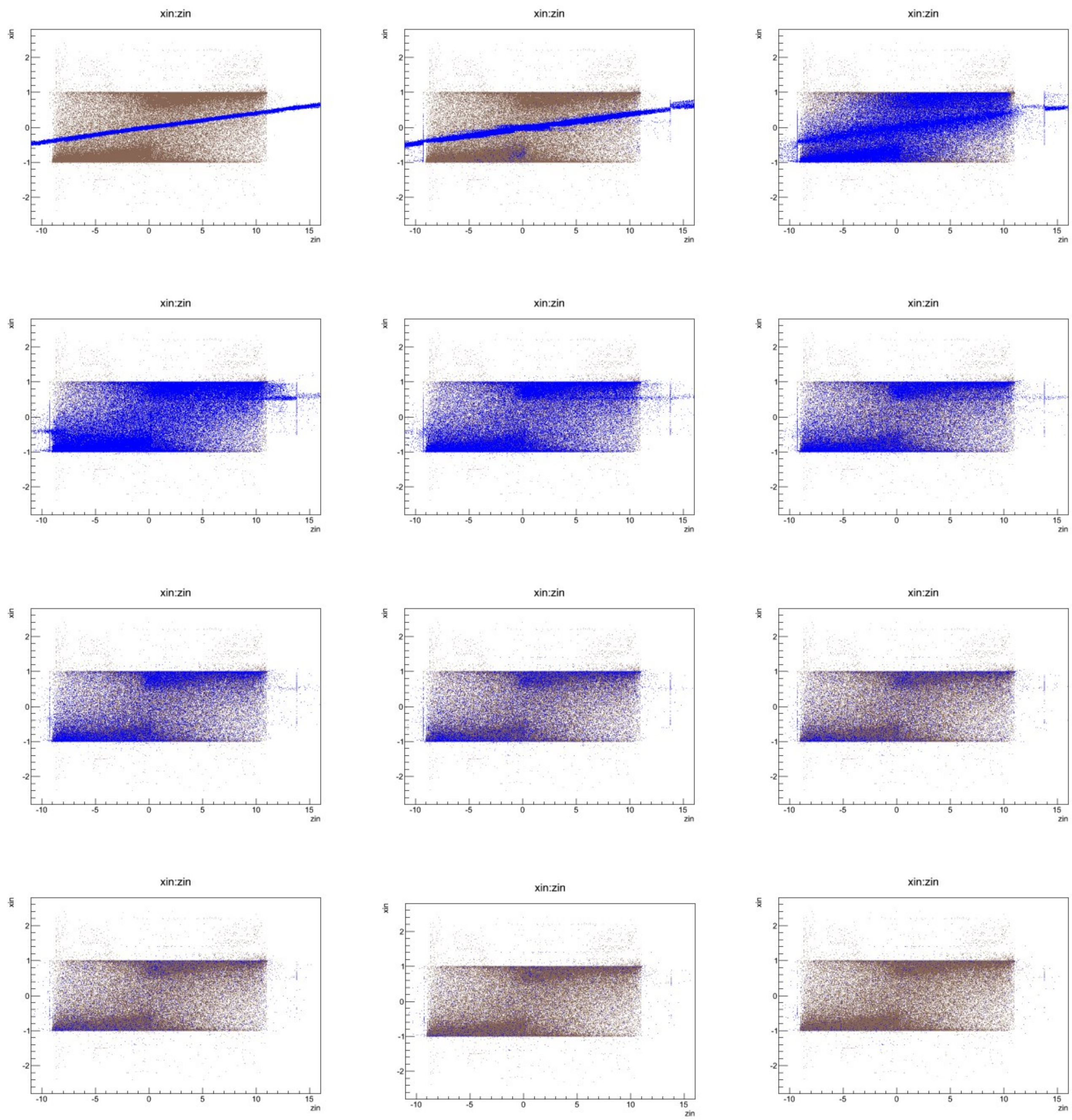
The above graph is a demonstration of the two parts. The marked points are the positions of the last steps. This does not include the detectors layers.

When we observe the first interactions between the beam and the gas we get 100% electron ionization process.



In the histogram above there are the fractions of the processes from all processes that were simulated, the processes that cause interactions with matter from all steps that the particles make.
[For a complete list of the physical processes, see reference number 4]

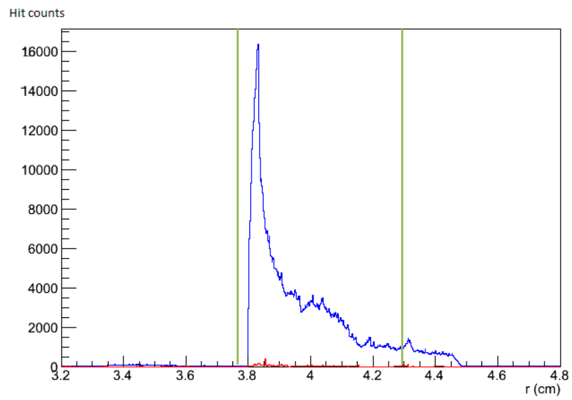
Illustration of beam – gas interaction in bad vacuum



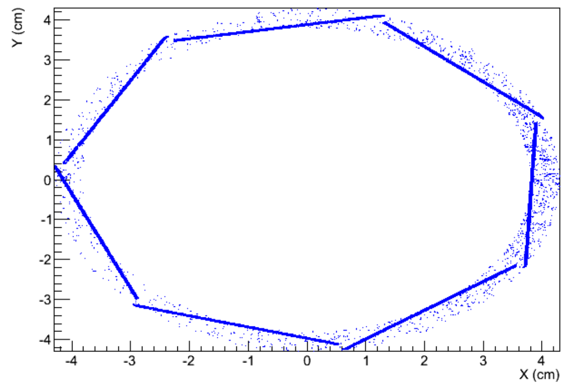
Projection on the XZ plane of a step by step simulation of the beam of electrons interacting with gas molecules in the beam pipe at density of 1e-5 g/cm^3 .
The brown points represent the last step of a charged particle, and the blue points indicate the interaction steps. A new step is introduced when a particle changes the trajectory or goes through a different medium. The first graph (top left) is the first interaction with matter that occurs. This step is almost 100% electron ionization.

Determining the hit count in a VXD layer

To estimate the hit count in a VXD layer, the relevant data is taken, i.e. hits are taken from charged particles only, from the central beam pipe. A ring which contains the layer is taken. The inner and outer radiuses of the ring are chosen according to the r coordinates which include most of the hits.
Then, another count is produced to get rid of the counts of the interactions that occurred between the layers and not on the detector itself. The ring is sandwiched between two rings with the same area as the ring that contains the layer. The count of hits in those two rings is an estimation for the background hits. The hits in the two rings are subtracted from the hits of on the ring of the layer itself.

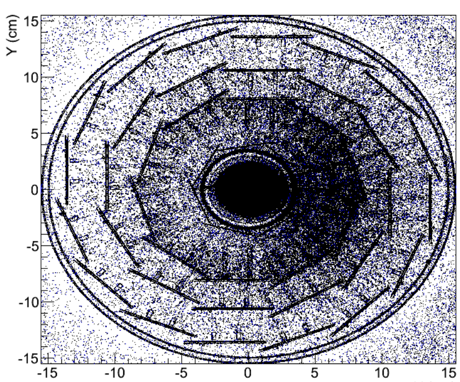


Number of hits in the first SVD layer as a function of r.

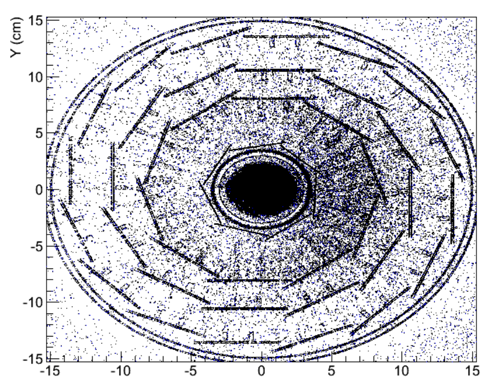


A ring containing the first SVD layer in order to get the hit count

In order to get a clear picture it necessary to not include hits that come from scattering from the flanges at the edge of the central beam pipe. Another cut was taken: -65.5<Z<105 , in order to fix this and reduce the count of hits in between the layers.



All interactions.



Central beam pipe: not including particles scattered from the flanges at the ends

The structure of the four SVD layers is demonstrated in these graphs. The PXD layers cannot be noticed here, they are inside the dark area in the center.

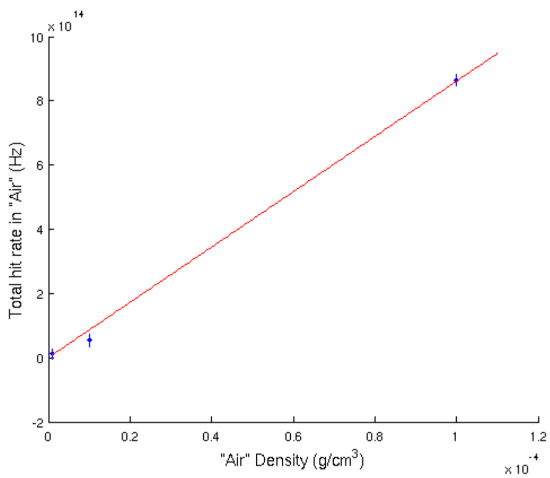
Extrapolating to vacuum

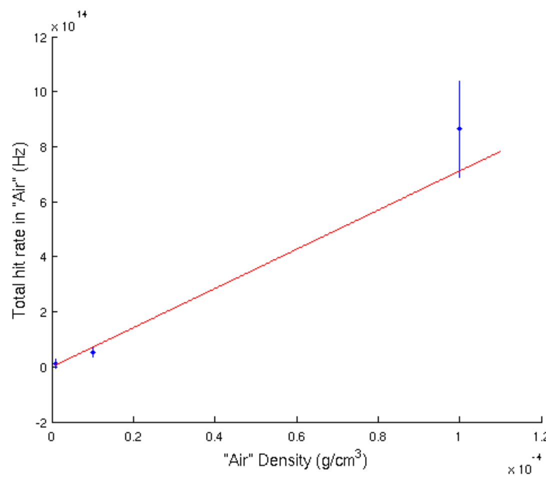
First, each count was normalized from the number of events simulated to the scale of all of the bunches.

$$(**)\ \ \text{Hit Rate in Air} = \text{H} * \text{f} * \frac{\text{P}}{\text{Events}}$$

H – is the hit count from the simulation , f - is the revolution frequency , P-is the total number of particles which consists out of the particles in a bunch times the number of bunches. Events- is the number of generated electrons in the beam.

The three points are supposed to have a linear relation, so a linear fit was applied with minimum χ^2. Hit rate of 0 is forced for density of 0 in order to get physical results , as the wanted point of interest is closer to 0 than to the other densities. When taking in account the error as the statistic deviation of the count, we get a fit which is unprobable. (The left plot) When taking the error of a count as the background count , we get a good fit in terms of linearity.





Linear fits applied to the 2nd PXD layer

By these two variations of the same data , the left plot leaves the point of 10-5 out, while the right plot leaves the 10-4 far from the line. In order to get an estimation, we are just assuming that the effective linear function has a uniform probability distribution to be found between these two lines. From that extract the rate in the vacuum of the system.

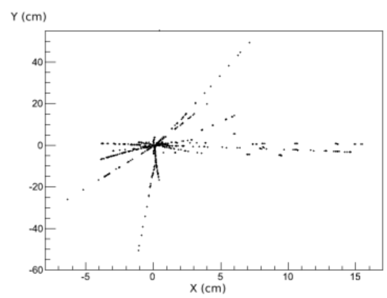
This process was repeated for each layer, for the two parts of the beam. The plots look similar to the ones shown, in all of them the 10-5 point is a little lower. This result was received for different data sets, and different amount of statistics, so it is not a statistic fluctuation, but something between the densities causes the rate to rise faster with the density at higher densities.

Layer	Part of beam pipe	Hit rate	Err	Relative Err (%)
1^{st} PXD (inner) layer	Be	0.6778 GHz	0.01601 GHz	2.4
	Be + Ti	1.081 GHz	0.0635 GHz	5.9
2^{nd} PXD (outer) layer	Be	7.865 MHz	0.4310 MHz	5.5
	Be + Ti	676.4 MHz	42.66 MHz	6.3
1^{st} SVD layer	Be	0.4368 GHz	0.02338 GHz	5.4
	Be + Ti	3.814 GHz	0.3052 GHz	9.6

Estimated rates in the detectors layers

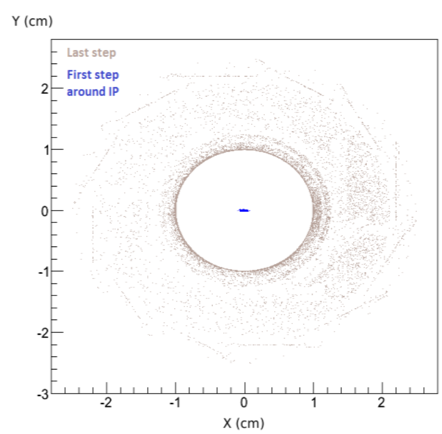
ElectroNuclear scattering

Although most of the processes around the beam (secondary tracks) are single tracks, there were also some Electro – Nuclear interactions, which produce multiple tracks. These tracks may be reconstructed using tracking algorithms, and might assist in estimating beam parameters. As two detections allow crossing them and finding the origin point. The rate of this process is estimated to 4 KHz. Calculated using formula (**) with the hit count of these reactions, and then applying formula (*).



An example of multiple tracks generated at IP

Applying the beam gas interactions technique should yield the bunch width in IP as demonstrated in the following graph.



Projection of hits on XY plane. In gray are the last steps of particles, blue marks the first interactions of the beam with the gas within σz . This demonstrates the bunch at IP. Also the structure of the PXD layers is demonstrated

Conclusion

In this project, a simulation of the experiment was conducted. I used the method of simulating a fraction of the beam, and different value of vacuum than in the system, and extrapolating the results to the nominal values.
The idea of using beam – gas interaction in order to get an estimation of the beam properties is interesting, although the results of the simulation, and the conditions in the detector might affect the effectiveness of this technique.

First, the fact that most of the interactions between the beam and gas molecules are electron ionizations, makes it not so promising. The product of electron ionization is a single track. From a single track the ability to locate the origin point of the event is limited. Although, a technique of estimating closest approach distance can be used in order to receive an idea about the density of the beam in the wide dimension.

Second, the issue of resolution is an important factor. The width of the beam in Y axis is about 50 nm, while the resolution of the PXD is about 10 microns. In that case we cannot expect to be able to say anything about the width of the beam in that axis, only the approximated position within the resolution. In X axis however, the width of the beam is around 7 microns. With the width in the order of the resolution, there is a possibility to say something about the width.

One point which is important to mention, is that the simulation was using the conditions of full nominal bunch current. Measurements of this kind will be performed before physics runs. In that case the bunch current and luminosity will be lower, so all the rates that were estimated and presented in this report will be lower in reality.

In conclusion, due to the results and the parameters of the beam and detectors , such measurement do not seem so promising. Nevertheless, multiple tracks generating events might be a place to continue investigating the option to use the beam gas scattering. Furthermore , when going a little far from IP the beam is wider, due to focusing, and that may allow getting over the resolution obstacle and taking some measurements that allow realistic estimations.

Acknowledgment

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Reference

- Belle II Technical Design Report -
  Edited by: Z. Doleˇzal and S. Uno , High Energy Accelerator Research Organization

- Impact of Beam-Beam Effects on Precision Luminosity Determination at the LHC -
  W. Kozanecki (CEA Saclay), with W. Herr & T. Pieloni (CERN)
  Slides from Beam-beam Workshop, CERN, 20 March 2013

- Geant4
  http://geant4.cern.ch/

- Geant4
  List of physical processes
  http://geant4.cern.ch/support/proc_mod_catalog/processes/

- Geant4
  Physics Reference Manual (Information about the physical processes in G4 simulation)
  http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/PhysicsReferenceManual/fo/PhysicsReferenceManual.pdf

- Belle II
  Belle2.kek.jp

- PXD white book
  edited by Z. Dolezal, C. Kiesling, C. Lacasta & H.-G. Moser

- Physics at Super B Factory
  KEK Report 2009-12