A new device for the LHC: first conceptual design studies

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Beam-gas imaging vertex detector: kickoff meeting

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Goal

Ultimately

Perform beam-gas imaging at the LHC to measure the beam position and shape (and also, relative bunch intensities and ghost charge)

- provide precise absolute measurements of the bunch (10^{11} p) shapes per 5 min.

For this purpose we need:

- Precise vertexing detector
- Sufficient beam-gas rate

- The "beam-gas imaging" method is used in LHCb to measure the beam parameters and determine the absolute luminosity
  - Reconstruct tracks and beam-gas interaction vertices with the LHCb vertex detector (VELO)
  - References: See Colin's talk

Initially

- Identify optimal setup for performing the measurements
- Examine the possibility to install the detector near the IPMs (use existing pressure bumps)

Outline

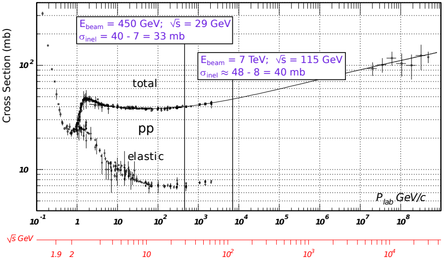
Outline

Beam-gas inelastic rate

Rate of inelastic beam-gas interactions per bunch:

$$R_{\mathrm{inel}} = \int_{z=z_1}^{z=z_2} \rho(z)\ \mathrm{d}z \cdot \sigma_{\mathrm{pA}}(E) \cdot N \cdot f_{\mathrm{rev}}$$

- $\rho(z)$ – gas density
- Inelastic proton-nucleus cross-section $\sigma_{\mathrm{pA}}(E) = \sigma_{\mathrm{pp}}(E) \cdot \mathrm{A}^{2/3}$. A is the nucleus mass number. In the case of ^{20}Neon we have:
  - $\sigma_{\mathrm{pNe}}(450\ \mathrm{GeV}) = 33 * 20^{2/3} = 243$ mb
  - $\sigma_{\mathrm{pNe}}(7\ \mathrm{TeV}) = 40 * 20^{2/3} = 295$ mb
- N – number of protons per bunch
- f_{rev} – bunch revolution frequency, 11.245 kHz



Beam-gas inelastic rate (2)

Rate of inelastic beam-gas interactions per bunch:

$$R_{\rm inel} = \int_{z=z_1}^{z=z_2} \rho(z)\ {\rm d}z \cdot \sigma_{\rm pA}(E) \cdot N \cdot f_{\rm rev}$$

$$p\,V = n\,k_B\,T \;\Rightarrow\; \rho = \frac{n}{V} = \frac{\mathbf{p}\ [\mathrm{Pa}]}{\mathbf{k_B}\ \left[\frac{\mathrm{J}}{\mathrm{K}} = \frac{\mathrm{N\cdot m}}{\mathrm{K}} = \frac{\mathrm{Pa\cdot m^3}}{\mathrm{K}}\right]\ \mathbf{T}\ [\mathrm{K}]}$$

- For $T = 293$ K: $\rho = 2.5\times10^{20}\ p(\text{in Pa})\ \frac{\text{molec}}{\text{m}^3} = 2.5\times10^{16}\ p(\text{in mbar})\ \frac{\text{molec}}{\text{cm}^3}$
- Assuming $\rho(z)$ constant in $\Delta z = z2 - z1$:

$$R_{\rm inel}(\text{in Hz}) = 2.5\times10^{16}\ p(\text{in mbar})\ \Delta z(\text{in cm})\ \sigma_{\rm pA}(\text{in cm}^2)\ N\ f_{\rm rev}(\text{in Hz})$$

$\Delta z = 100$ cm
$\sigma_{\rm pA} = 243$ mb
$N = 10^{11}$ p/bunch
$f_{\rm rev} = 11245$ Hz
$p = 10^{-7}$ mbar

$\Rightarrow R_{\rm inel} = 68$ Hz

Time needed for certain statistical precision on σ_{beam}

- The vertex resolution will be sufficiently good only for events with at least N_{Tr} reconstructed tracks. The fraction of these events, f_{good}, depends on:
  - the geometrical distributions (η) of the beam-gas interaction products
  - the detector geometry

$$N_{\text{good}} = f_{\text{good}}\, R_{\text{inel}}\, \Delta t$$

- In MC simulations of b1-H interactions at 7 TeV and for a detector covering $3 < \eta < 5$ and $-50 < z_{vtx} < 50$ cm, we see:
  - $f_{\text{good}}(N_{\text{Tr}} \geq 5) = 0.43$
  - $f_{\text{good}}(N_{\text{Tr}} \geq 10) = 0.15$
  - expect larger values for heavier targets!
- N_{good} determines the *statistical error* of the measured beam width σ_{beam}:
  $$\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} = \frac{1}{\sqrt{2\, N_{\text{good}}}}$$
- Time needed for performing a beam-width measurement with a certain statistical precision
  - Simplified, single-Gaussian fit (no vertex resolution)
  - $R_{\text{inel}} = 68$ Hz

stat error	f_{good}	N_{good}	$\Delta t[s]$
1%	0.15	5000	490
3%	0.15	556	55
1%	0.43	5000	171
3%	0.43	556	19

Requirement on the precision of the detector

- When measuring the beam shape, it is important to know the detector resolution of the primary vertex (PV) position
- In the simple case of a beam with a Gaussian shape in each transverse coordinate: $\sigma_{\rm raw}^2 = \sigma_{\rm beam}^2 + \sigma_{\rm res}^2 \Rightarrow \frac{\delta\sigma_{\rm beam}}{\sigma_{\rm beam}} = \frac{\sigma_{\rm res}^2}{\sigma_{\rm beam}^2} \cdot \frac{\delta\sigma_{\rm res}}{\sigma_{\rm res}}$
  - The relative uncertainty of the beam width $\delta\sigma_{\rm beam}/\sigma_{\rm beam}$ is determined by the relative uncertainty of the vertex resolution $\delta\sigma_{\rm res}/\sigma_{\rm res}$, and is scaled down by $(\sigma_{\rm res}/\sigma_{\rm beam})^2$
- From our experience with VELO (see Colin's talk), we know that:
  - A 10% relative uncertainty of the vertex resolution is not hard to achieve, 5% is more challenging
  - The PV resolution can change with time – e.g. it is sensitive to detector position and alignment of its components

We aim at PV resolution which is substantially smaller than the beam size (e.g. $\sigma_{\rm beam}/\sigma_{\rm res} = 3$) in order to minimize the effect of the uncertainty of the PV resolution $\delta\sigma_{\rm res}$

Requirement on the precision of the detector (2)

- The best place to install the vertexing detector is where the ratio between the beam-pipe radius and the beam width, $R_{\rm pipe}/\sigma_{\rm beam}$ is smallest
  - small $R_{\rm pipe}$: get closer to the beam – smaller sensors of the vertexing detector
  - large $\sigma_{\rm beam}$: can afford lower vertexing precision $\sigma_{\rm res}$
- Should be ready to make measurements at 0.45 to 7 TeV
  - Higher energy ⇒ smaller beam: $\sigma = \sqrt{\beta\varepsilon}$; $\varepsilon_n = \beta_r\gamma_r\varepsilon \Rightarrow \sigma = \sqrt{\frac{\beta\varepsilon_n}{\beta_r\gamma_r}}$

Example: $\beta = 100$ m; $\varepsilon_n = 2\ \mu$m

- $\sigma_{x,y} = 646\ \mu$m $(0.45$ TeV$)$
- $\sigma_{x,y} = 164\ \mu$m $(7$ TeV$)$

⇒ would need PV resolution $\sigma_{\rm res}$ of about 164/3 $\approx 55\ \mu$m

- Knowing the vertex resolution to 10% would result in about 1% relative systematic error on $\sigma_{\rm beam}$
- The measurement duration, which determines the statistical uncertainty of $\sigma_{\rm beam}$, should be chosen accordingly.

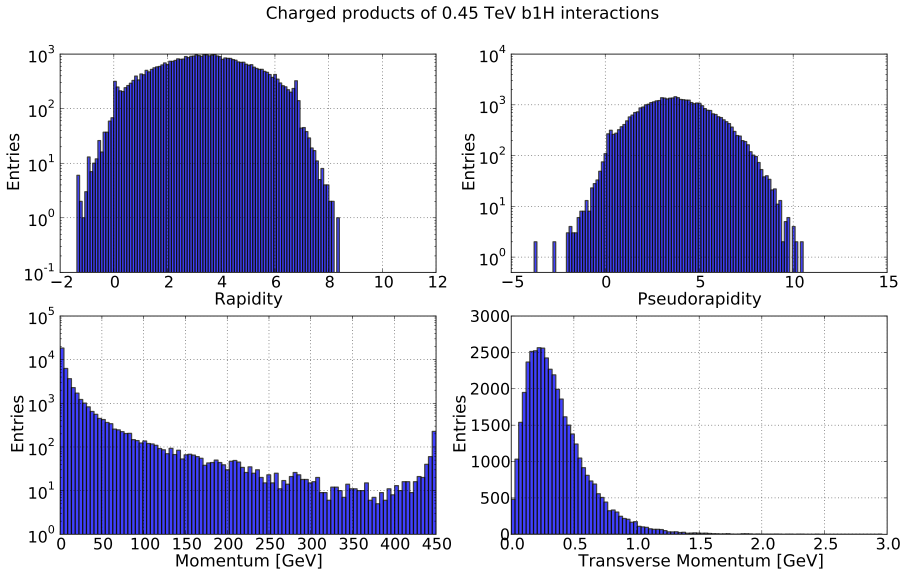
Outline

Beam-gas simulations

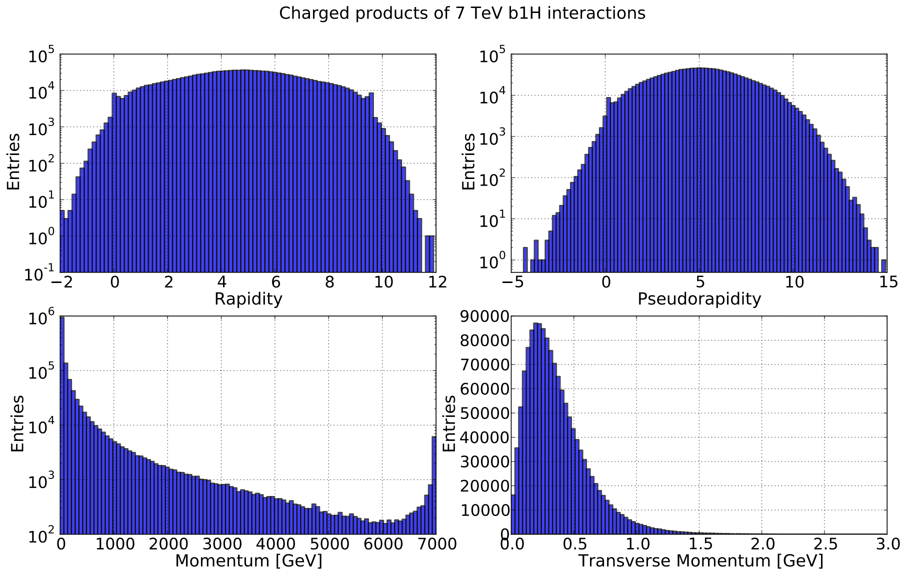
- Beam-gas interactions generated with the LHCb software framework. Use beam1-Hydrogen interactions at 0.45 and 7 TeV to:
  - **study the distributions of the charged products of the beam-gas interactions**
  - **provide input tracks to a simple toy MC detector**
- Variables of interest:
  - rapidity: $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$
  - pseudorapidity: $\eta = -\ln \left[\tan(\theta/2) \right]$, where θ is the polar angle of the particle
  - transverse momentum p_T, which is used to evaluate the multiple scattering when traversing material
- Work ongoing to generate beam-gas interactions with heavier targets
  - Expect significant difference in the charged particle multiplicity and the pseudorapidity distribution
    - Heavier targets produce more charged particles
    - Heavier target – lower boost of the center of mass – lower η
- Currently used MC samples:

Sample ID	Beam energy [TeV]	Gas target	MC Generator
1	0.45	H	PYTHIA
2	7.0	H	PYTHIA

0.45 TeV, Hydrogen, PYTHIA

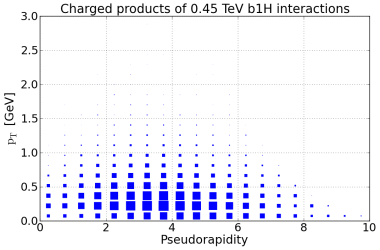


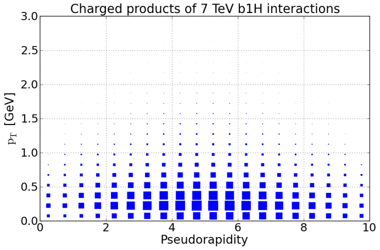
7 TeV, Hydrogen, PYTHIA



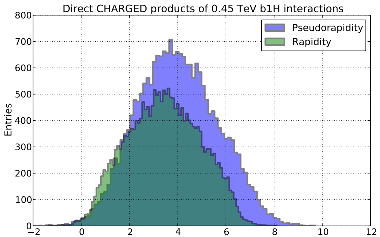
Distributions of 0.45 TeV and 7 TeV samples

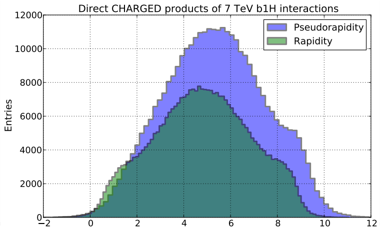
- **Transverse Momentum vs Pseudorapidity**
  – p_T determines the multiple scattering. $< p_T > \approx 400$ MeV for all E and η





- **Rapidity and Pseudorapidity**
  – verify that η and y are similar. Use the formula $y \rightarrow y - tanh^{-1}\beta$ to confirm the observed rapidity shift at 0.45 TeV and 7 TeV

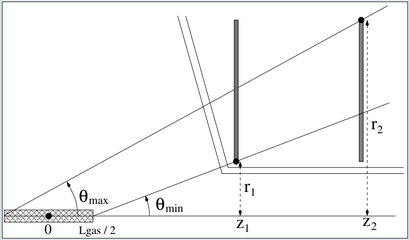


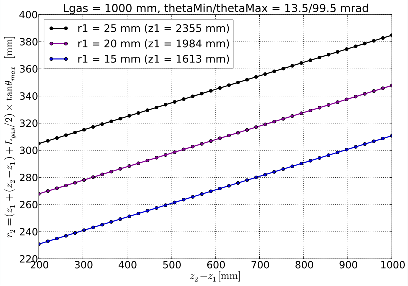


Outline

Layout and η coverage

- Determine the position and the size of the sensors, needed to cover certain η range and certain target length





Fixed parameters (example study):

- $\mathrm{L_{gas}} = 1000$ mm
- $\eta_{\mathrm{max}} = 5 \Rightarrow \theta_{\mathrm{min}} = 13.5$ mrad
- $\eta_{\mathrm{min}} = 3 \Rightarrow \theta_{\mathrm{max}} = 99.5$ mrad
- Consider $r_1 = 15$, 20 and 25 mm

Derived parameters:

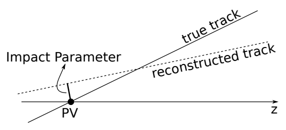
- $z_1 = \frac{\mathrm{L_{gas}}}{2} + \frac{r_1}{\tan\theta_{\mathrm{min}}}$
- Determine the outer radius of the last station, r_2, which corresponds to certain z_2 (or, equivalently, to certain $(z_2 - z_1)$):
$$r_2 = \left(z_2 + \frac{\mathrm{L_{gas}}}{2}\right) \tan\theta_{\mathrm{max}}$$

E.g., for $r_1 = 20$ mm and $z_2 - z_1 = 1000$ mm we need stations covering r up to 350 mm

Multiple scattering and detector resolution

The impact parameter (IP) resolution, σ_{IP}, is determined by:

- σ_{MS} – IP induced by multiple scattering (MS)
- σ_{extrap} – IP induced by detector hit resolution



$$\sigma_{\mathrm{IP}}^2 = \sigma_{\mathrm{MS}}^2 + \sigma_{\mathrm{extrap}}^2$$

In each transverse coordinate:

$$\sigma_{\mathrm{MS}} = r_1 \frac{13.6\ \mathrm{MeV}}{p_T} \sqrt{\frac{x}{X_0}} \left(1 + 0.038\ \log \frac{x}{X_0}\right) \approx r_1 \frac{13.6\ \mathrm{MeV}}{p_T} \sqrt{\frac{x}{X_0}}$$

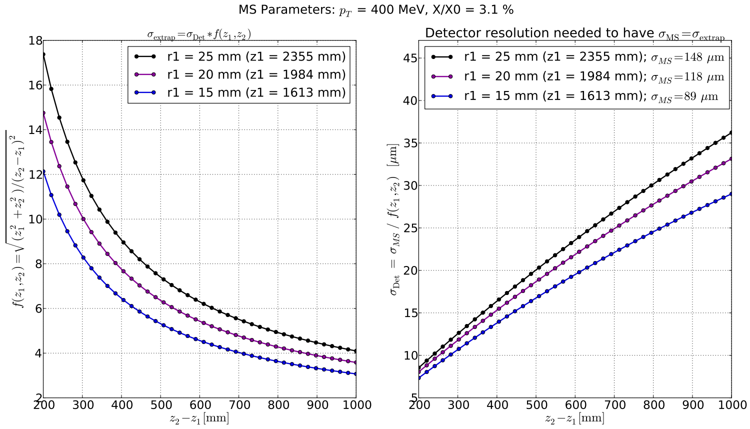
Example parameters used to estimate σ_{MS}:

- $r_1 =$ 15, 20, or 25 mm
- average $p_T \approx 400$ MeV (from the beam-gas simulation)
- $x/X_0 = 3.1\%$, which includes 0.5mm Al wall, 2*0.5mm Si sensors, 70um copper wakefield suppressor at 20° wrt beam axis

$$\sigma_{\mathrm{extrap}} = \sqrt{\frac{z_2^2\, \sigma_1^2 + z_1^2\, \sigma_2^2}{(z_2 - z_1)^2} \cos^2\theta}$$

Using z_1 and z_2 from the previous slide we estimate what hit resolution $\sigma_{\mathrm{Det}} = \sigma_1 = \sigma_2$ is needed in order to have $\sigma_{\mathrm{MS}} = \sigma_{\mathrm{extrap}}$

Multiple scattering and detector resolution (2)



- Note that the different curves correspond to different overall $\sigma_{\rm IP}$
- The requirements on the hit resolution are high; in the conditions of this example study, expect $\sigma_{\rm extrap}$ to dominate
- Taking as an example an LHCb IT/TT sensors with $\sigma_{\rm hit} \approx 200./\sqrt{12} = 58$ μm, we get $\sigma_{\rm IP} \approx 250$ μm
  - $\sigma_{\rm res} \approx \sigma_{\rm IP}/\sqrt{N_{\rm Tr}}$. For $N_{\rm Tr}$ =10 expect $\sigma_{\rm res} \approx 75$ μm

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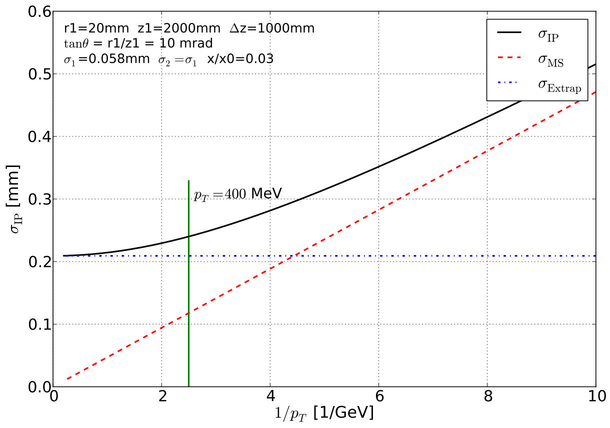

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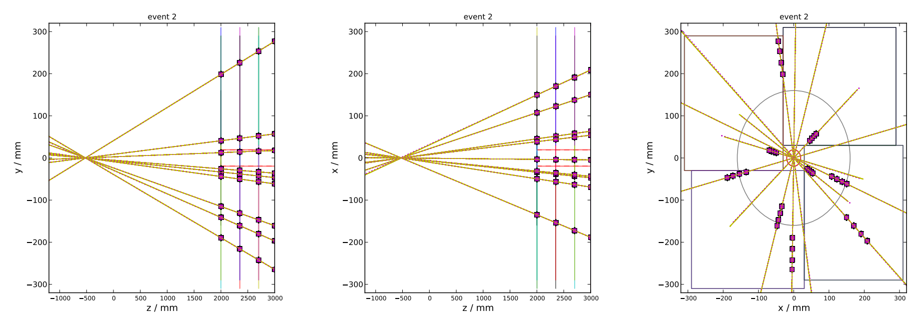
Toy MC detector

Massi developed a toy MC detector for simple detector design studies

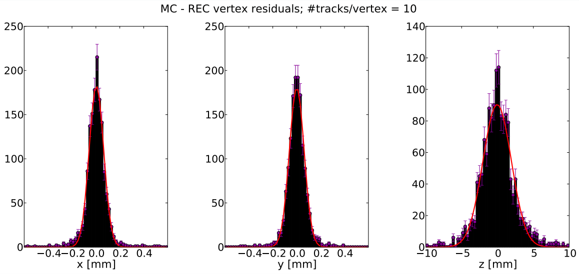
- Define the position, size and radiation length of detector components (sensitive or not)
- Read tracks from beam-gas interactions simulated with the LHCb software framework
- Propagate the tracks through the detector and mark the intersection points (measurements)
- Perform track fit taking into account the detector hit resolution
- Extrapolate the reconstructed track to z_{vtx} and determine the IP and its error



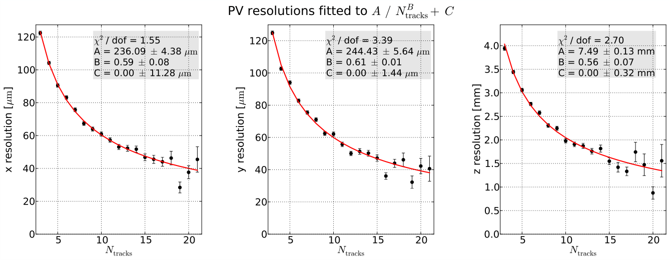
Event display of the toy MC detector. Four x-y measuring planes with size about 30×30 cm, positioned between $z = 2000$ mm and $z = 3000$ mm

Toy MC detector (2)

- With this tool we can check quantities like acceptance and $\sigma_{\rm IP}$ for different detector configurations
- We can feed-in the fitted tracks to a vertex-fitting routine and determine the PV resolution by comparing the positions of the reconstructed and the true MC vertices



Note: these vertex resolutions were obtained with a detector configuration different from what I used as an example so far

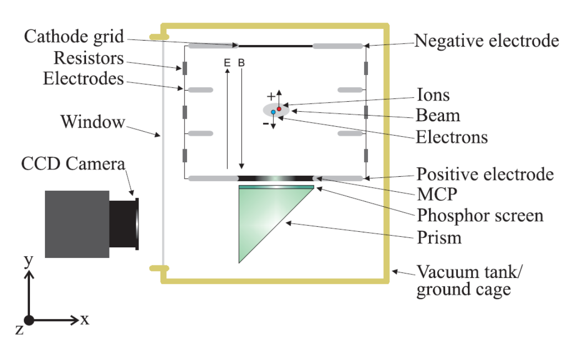


Outline

IPM

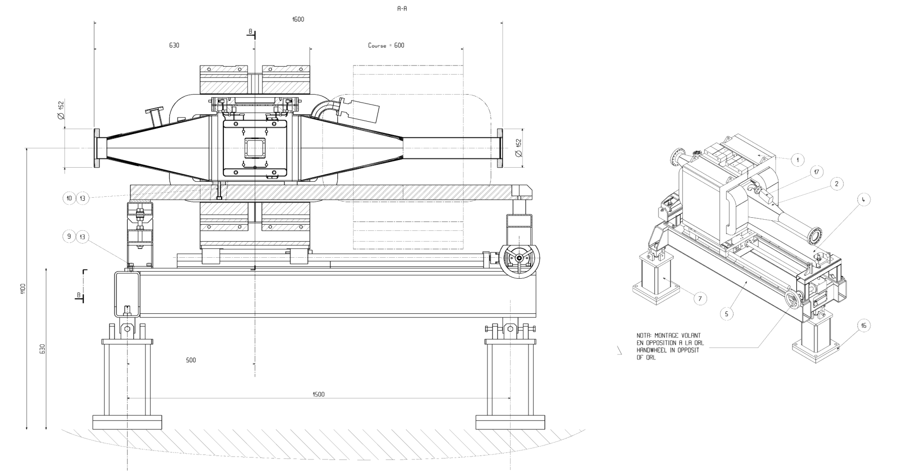
- IPM measures $\mathrm{e}^-/\mathrm{ion}$ pairs produced in the medium by the beam
  - [H. Refsum, CERN-THESIS-2004-022]
- The injected gas pressure is $\leq 10^{-8}$ mbar
  - The SMOG gas injection system (Ne) of LHCb provides $\sim 10^{-7}$ mbar

IPM Layout



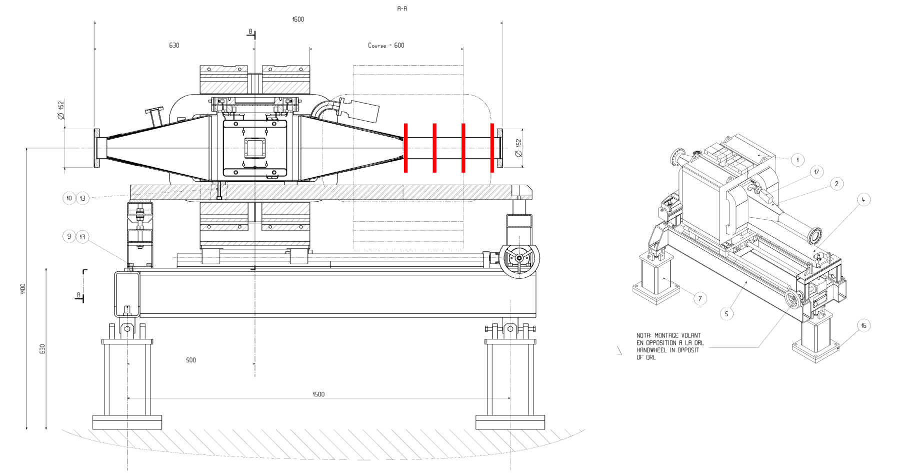
IPM Vacuum chamber layout (LHCBGIV_0001)

IPM drawings from CDD/EDMS



Examine the possibility to install a vertexing detectors around the horizontal beam-pipe (right arm of the chamber).

IPM drawings from CDD/EDMS



Examine the possibility to install a vertexing detectors around the horizontal beam-pipe (right arm of the chamber).

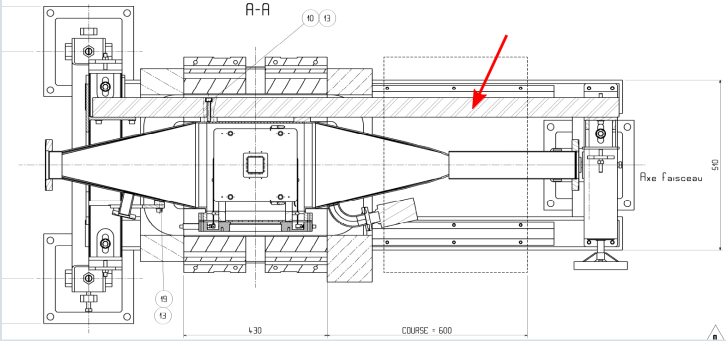
Horizontal vs Vertical IPM

Horizontal IPMs have a horizontal (supporting?) bar, which may be a restriction for the installation of the vertexing detector.

Therefore, Vertical IPMs are better.

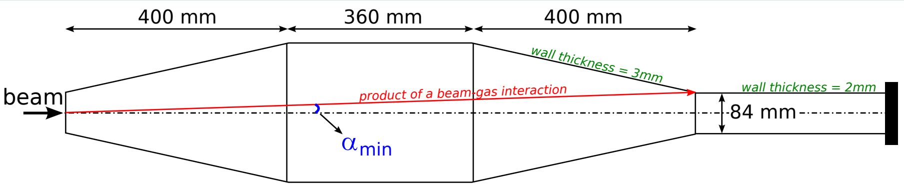
Assumption: the vacuum chambers are identical in the H and V cases.

LHCBGIH_0001



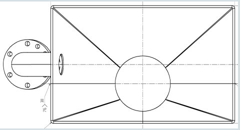
Traversed material of the vacuum chamber

Simplified layout of the vacuum chamber



- When the polar angle of the products of a beam-gas interaction are smaller than $\boldsymbol{\alpha_{min} = \alpha_{min}(z_{vertex})}$, then the particles will exit the vacuum chamber through the horizontal beam-pipe, instead of through the inclined walls.
  - Consequently, the *passage* is through smaller angle, and the traversed material is greater
- I consider that we cannot go further downstream than the indicated point, as we go out of the pressure bump (?)

- The four walls of the inclined part of the vacuum chamber have different angle with respect to the beam axis:
  - two walls have 12.4° = 216 mrad ←
  - one wall has 9.6° = 168 mrad
  - one wall has 2.0° = 35 mrad
- The material of the chamber is stainless steel: X0 = 17.6 mm



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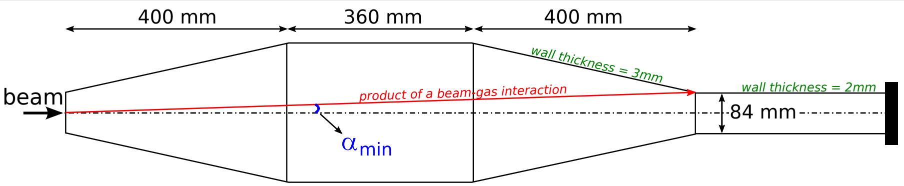
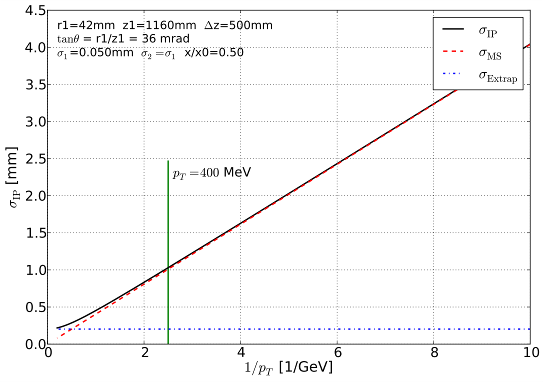


- When crossing a wall with width d, which is inclined by an angle ψ wrt the z-axis, the actual traversed material length is $l = d/sin(\psi)$.
  - The particle polar angle must be added to the angle ψ
- If a particle with $\eta = 4$ traverses the horizontal beam pipe, the material length is $l = 2/\sin(0.037) = 54$ mm (about 3 radiation lengths), which is huge
- The minimal polar angle needed in order not to cross the horizontal beam-pipe is $\arctan(42/1160) = 36$ mrad, or $\eta = 4$
  - In this case we can consider a detector covering $2 < \eta < 4$, or $270 > \theta > 36$ mrad. The corresponding size of the last detector plane is $r_2 = (z_1 + \Delta z)\tan\theta = 458$ mm
- The material length traversed by a particle with polar angle θ
  - $\theta = 36$ mrad $\Rightarrow l = 12.0$ mm, or 68% of X0
  - $\theta = 270$ mrad $\Rightarrow l = 6.4$ mm, or 36% of X0
- We use an average X0 of 50% and the geometrical properties of the setup to determine σ_{IP}

IP resolution with a vertex detector next to the IPMs



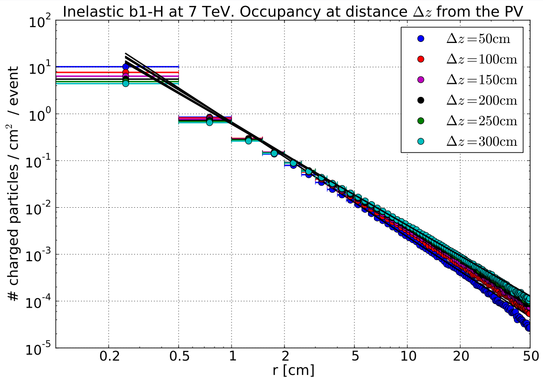
- A less precise detector will do as well, but we cannot get rid of the MS term
- In comparison to the example detector setup discussed earlier:
  - We can cover $2 < \eta < 4$, instead of the preferred $3 < \eta < 5$
  - $\sigma_{\rm extrap}$ is similar in both cases, about $200~\mu$m
  - $\sigma_{\rm MS}$ is about 1 mm for $p_T = 400$ MeV, vs 0.12 mm
- For $N_{\rm Tr}$ =10/20 expect $\sigma_{\rm res} \approx 326/231~\mu$m, which is a few times larger than our goal

Conclusions

- The installation of the considered vertex detector near the existing IPM setup is not possible:
  - The large amount of material of the vacuum chamber leads to PV resolution which is a few times above the requirement
- Tools are being developed and used to determine the optimal layout of the vertexing detector
- A full LHCb MC simulation of the detector is foreseen once a reasonable detector layout is identified

Particle flux and strip occupancy

- Use the simulated b1H interactions to determine the flux of charged particles per cm^2 per event as a function of the distance to the beam pipe



- Integrate the fitted curves and determine the occupancy of a most-inner strip oriented along the x-axis, with size $x : y = 30$ cm $: \ 250\ \mu$m
- The observed occupancy is roughly between 1 and 2% for a strip located at y=25 to 15 mm