Beam imaging with vertex reconstruction of beam-gas interactions

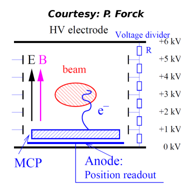
Plamen Hopchev (CERN BE-BI-BL)
Major contributions by C. Barschel and M. Ferro-Luzzi

9th DITANET Topical Workshop on
Non-Invasive Beam Size Measurement for
High Brightness Proton and Heavy Ion Accelerators

16 April 2013

Profile measurements with gas

Process	Products	Measure with
Ionisation	Electrons/ions	MCP / Anode / Phosphor screen + photon detector



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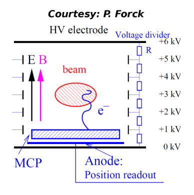

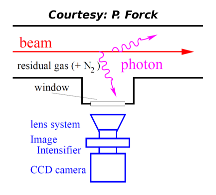

Profile measurements with gas

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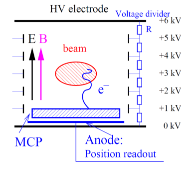
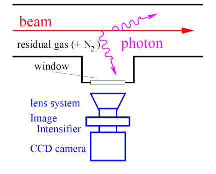
Fluorescence	Photons	Photon detector (CCD camera, PM)
Inelastic collision (QCD)	**Charged particles**	**Tracking detector**



Courtesy: P. Forck



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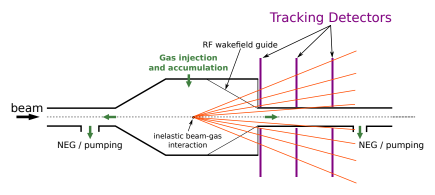


Outline

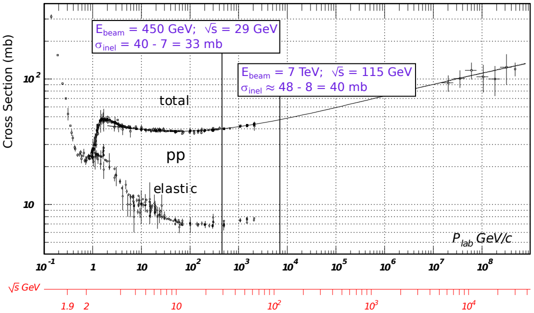
1. Inelastic beam gas interactions
2. LHCb beam gas vertexing results (some highlights)
3. BGV – Beam Gas Vertexing project
   – development of a new monitor for the [HL]LHC

Rate of inelastic interactions

Rate of inelastic beam-gas interactions per bunch:

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

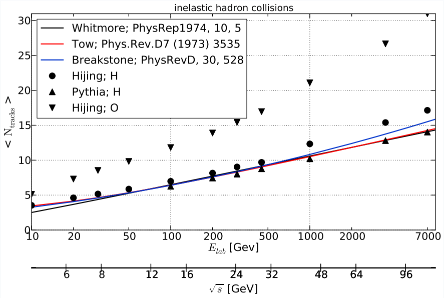
- $\rho(z)$ – gas density
- Inelastic proton-nucleus cross-section
  $\sigma_{\text{pA}}(E) \approx \sigma_{\text{pp}}(E) \cdot \mathrm{A}^{2/3}$
  A – atomic mass
  In the case of $^{20}\mathrm{Ne}$:
  - $\sigma_{\text{pNe}}(450\ \text{GeV}) = 243$ mb
  - $\sigma_{\text{pNe}}(7\ \text{TeV}) = 295$ mb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



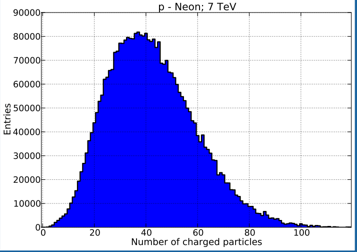
At the LHC, pressure of a few $\times 10^{-8}$ mbar over 1 m is needed to get $R_{\text{inel}} = 50$ Hz

Charged particles multiplicity

- Here, “charged particles” = long-lived charged particles produced in a beam gas interaction
  - The more we detect, the better precision we get on the position of the interaction
- Comparison of the average number of charged particles

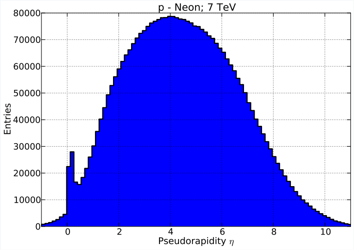


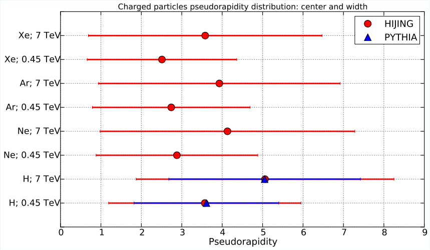
- Distribution of the number of charged particles
- Comparison of simulations with measurements of previous experiments
  - $p - \mathrm{H}$ collisions: reasonable agreement
  - $p - \mathrm{ion}$ collisions: to be made



Angular distribution

- In a beam-gas collision, the products fly in the direction of the incoming projectile
- Use Monte Carlo simulations to study different target gasses
  - HIJING generator for targets heavier than H
  - LHCb computing framework
- Pseudorapidity $\Leftrightarrow$ polar angle ($\eta \Leftrightarrow \theta$): $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$





Different rapidity shift depending on the target gas and the beam energy. The pseudorapidty distributions are relatively broad.

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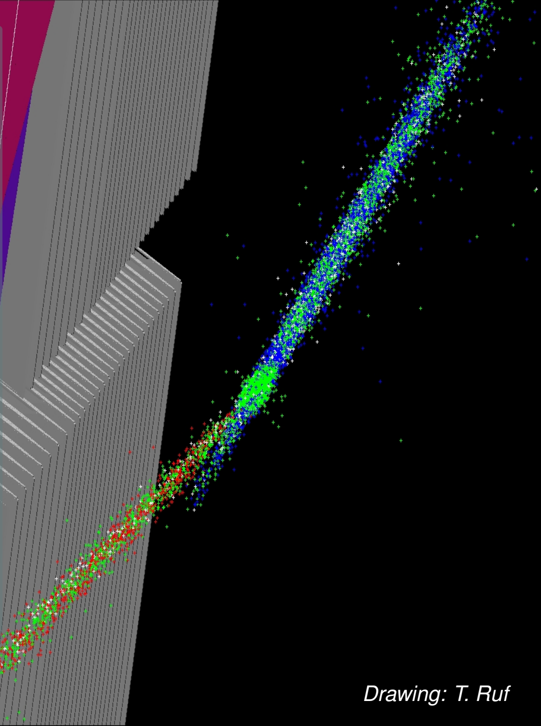
   – development of a new monitor for the [HL]LHC

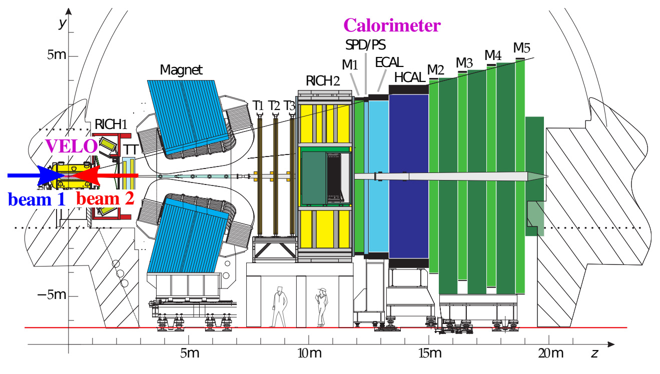
- **Method proposed in 2005**
  [NIM A 553, 3 (2005) 388]
  - **Novel method for absolute luminosity determination**
- **Applied for a first time in LHCb (2009)**
  [arXiv:1008.3105 [hep-ex]]
- **2010 lumi results in agreement with the “van der Meer scan” method (rel. errors $< 5\ \%$)**
  [arXiv:1110.2866v2 [hep-ex]]
- **Will show examples of LHCb beam measurements:**
  - **position**
  - **angle**
  - **width**
  - **relative bunch populations**
  - **ghost charge**



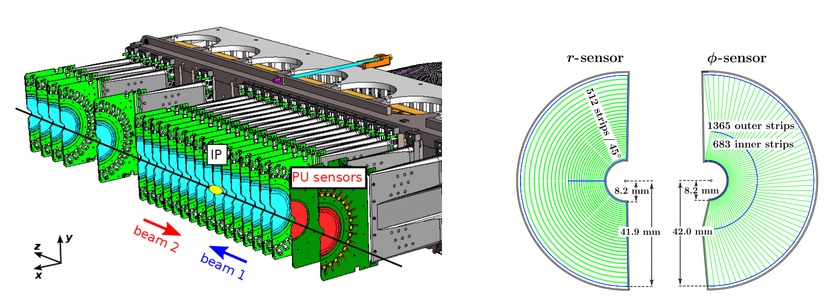
Drawing: T. Ruf

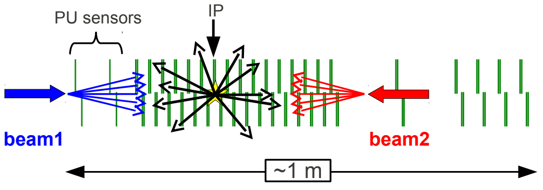
The LHCb detector

- Dedicated to b–physics
- Single arm spectrometer, covers $\eta \in [2,5]$
- Design luminosity: 2×10^{32}cm^{-2} s^{-1} (2 fb^{-1} per year)
  - low probability for multiple interactions per bunch-crossing
- The VErtex LOcator (VELO) is the main system used in the beam-gas measurements



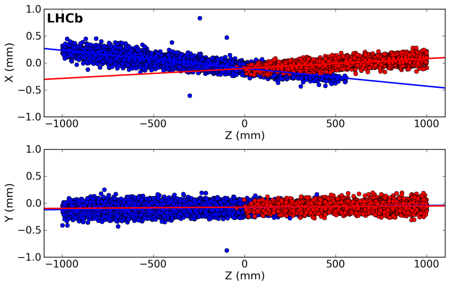
VELO and beam gas interactions

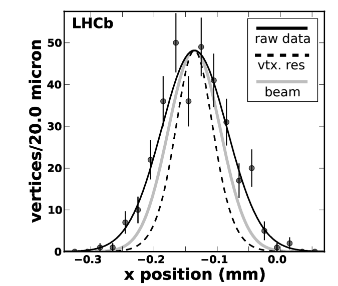




Measurement concept

- Reconstruct the tracks from beam-gas interactions
- Accumulate vertices ⇔ statistical precision
- Fit to a line ⇒ determine position and angle
- Project ⇒ determine width

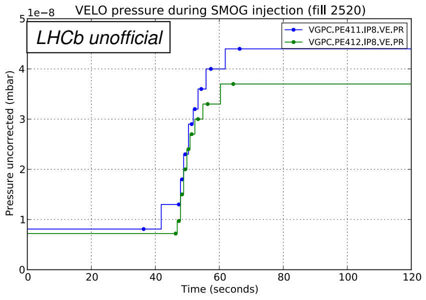


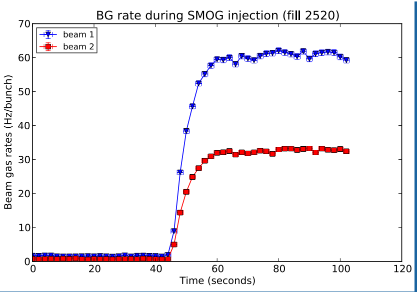


Neon injection system (SMOG)

Figure: C. Barschel Ph.D. thesis, in preparation

- Increase the pressure in the VELO region
  - nominal $\approx 10^{-9}$ mbar
  - with SMOG $\approx 10^{-7}$ mbar
- Beam gas (trigger) rates $\approx 30 - 60$ Hz per 10^{11} p



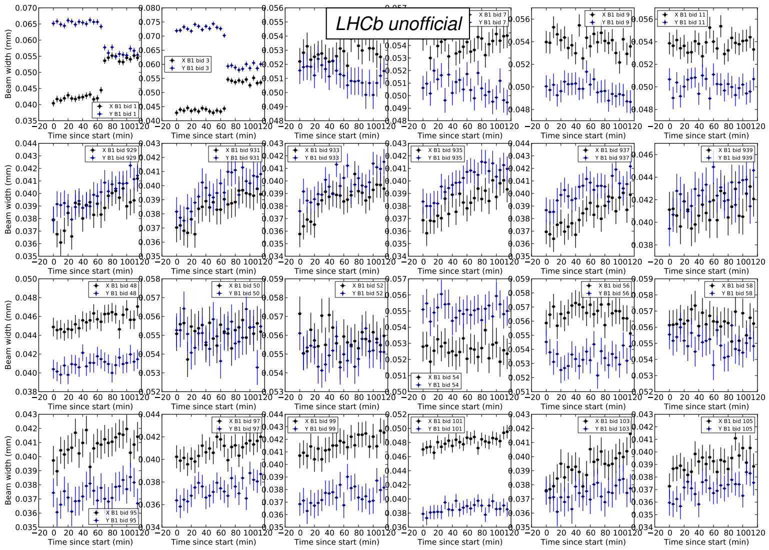


Bunch width evolution

Figure: C. Barschel Ph.D. thesis, in preparation

Fill 3060 (LHC MD), BEAM 1

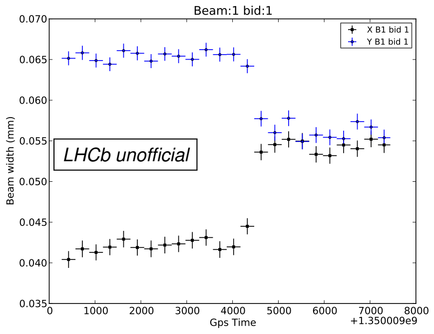
BID ≡ Bunch ID

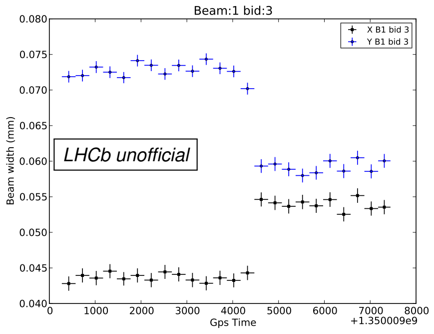


Bunch width evolution

Figures: C. Barschel Ph.D. thesis, in preparation

Fill 3060 (LHC MD), BEAM 1, zoom on BID 1 & 3

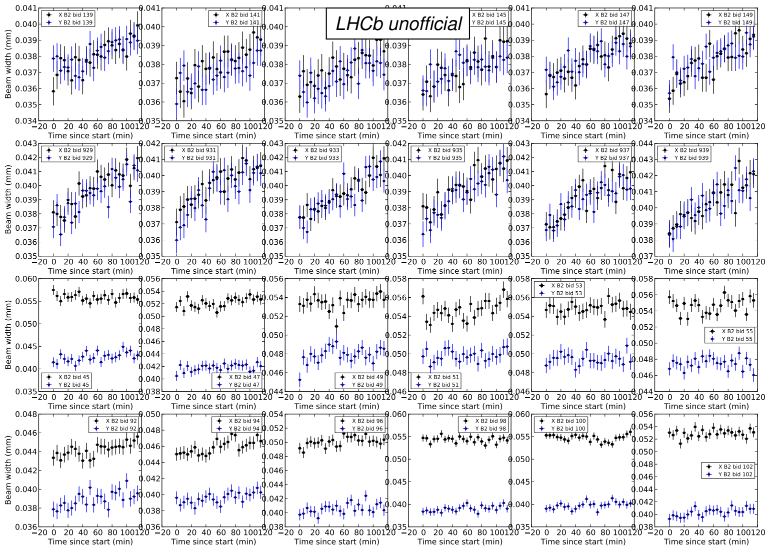




Bunch width evolution

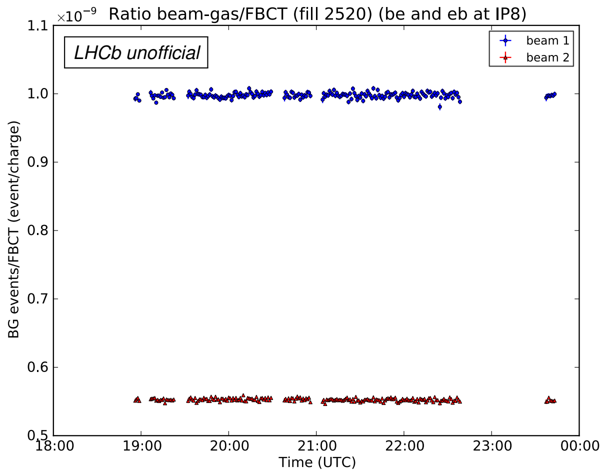
Figure: C. Barschel Ph.D. thesis, in preparation

Fill 3060 (LHC MD), BEAM 2



Relative bunch populations

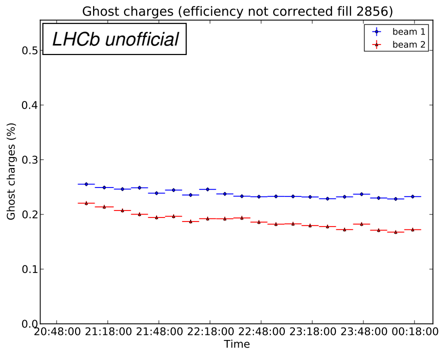
Figure: C. Barschel Ph.D. thesis, in preparation



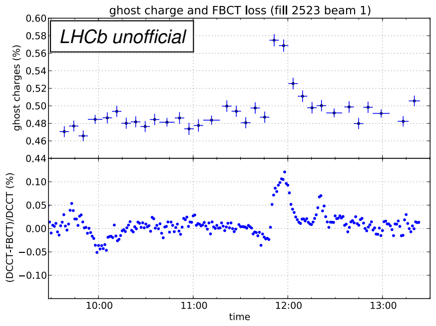
FBCT = Fast Beam Current Transformer (measure individual bunch intensities)

Ghost charge evolution

Figures: C. Barschel Ph.D. thesis, in preparation



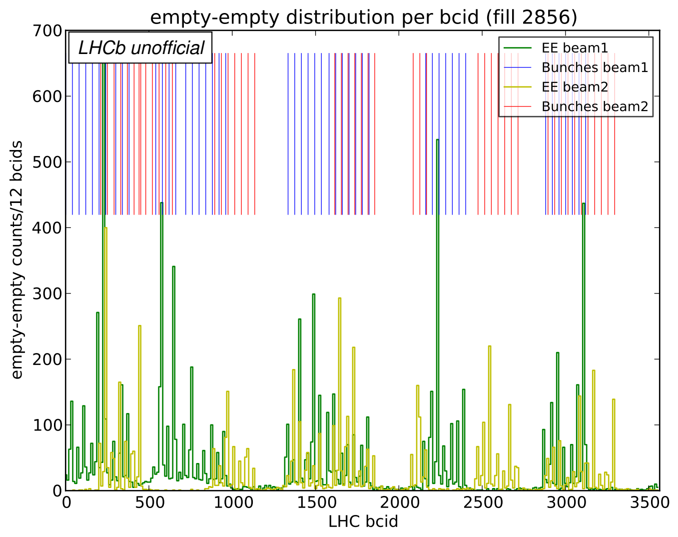
LHCb measurement compared to DCCT–sum(FBCT), fill 2523



DCCT = DC Current Transformer (measure total beam current, precise absolute scale)

Ghost charge vs BID

Figure: C. Barschel Ph.D. thesis, in preparation



Other possible measurements

- Having the 2-d profile of the beam allows more detailed studies to be made
  - Used in more recent LHCb analyses
- Dynamic range for bunch tails: needs more studies
  - Higher gas pressure and a trigger would allow high resolution studies; systematic effects may become important
- An additional timing detector would allow to measure the longitudinal profile

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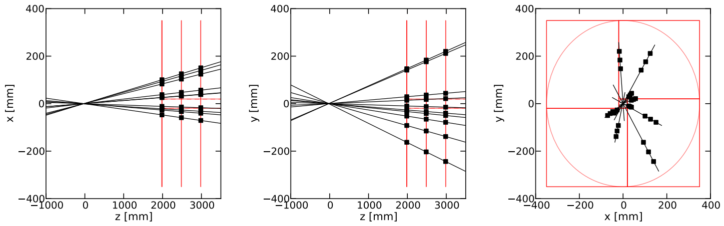
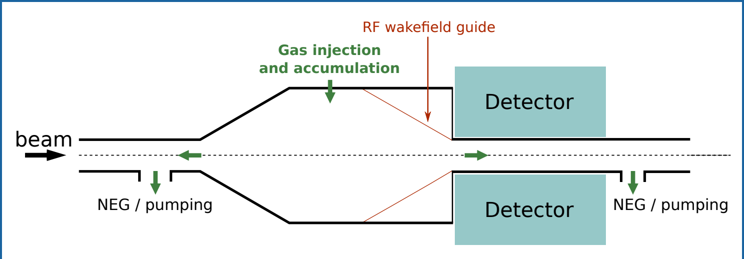


- **Need a dedicated pressure bump**



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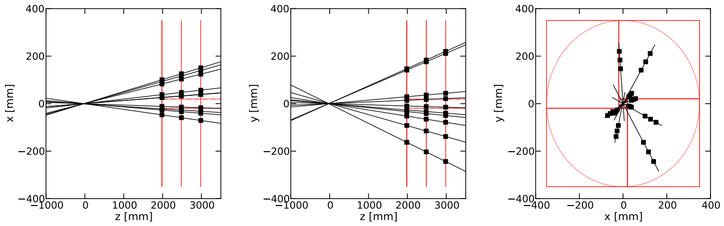

Collaborating with EPFL/ CERN-PH for the design/ construction of detector + read-out

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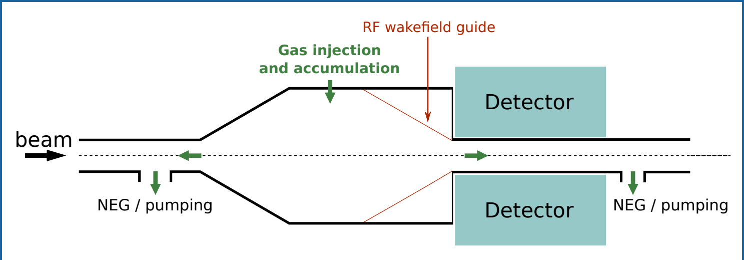
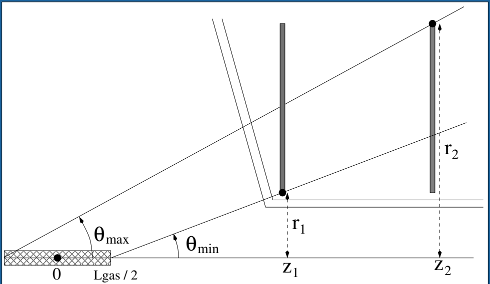


Detector external to the chamber; No movable parts

Pressure bump design in collaboration with TE/VSC

Detector acceptance

- **Determine the position and the size of the sensors, needed to cover certain**
  - **Range of angles $[\theta_{\mathrm{min}}, \theta_{\mathrm{max}}]$**
  - **Target length $\mathrm{L_{gas}}$**

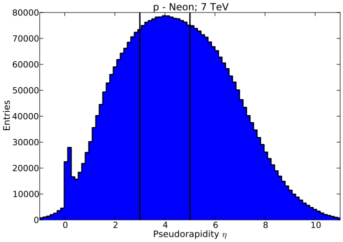


- **Aim at minimal r_1**

Example values used in our study:

- $\mathrm{L_{gas}} = 1000$ mm
- $\theta_{\mathrm{min}} = 14$ mrad ($\eta_{\mathrm{max}} = 5$)
- $\theta_{\mathrm{max}} = 100$ mrad ($\eta_{\mathrm{min}} = 3$)

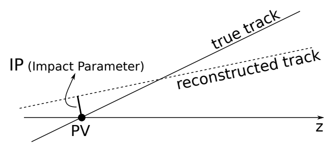
Simulated $\mathrm{p} - \mathrm{Ne}$ collisions



Tracking precision

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



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

$$\sigma_{\mathrm{MS}} \approx r_1 \frac{13.6\ \mathrm{MeV}}{p_T} \sqrt{\frac{x}{X_0}}$$

$$\sigma_{\mathrm{extrap}} \approx \sqrt{\frac{z_1^2 + z_2^2}{(z_2 - z_1)^2}} \cdot \sigma_{\mathrm{hit}}$$

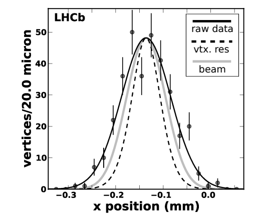
Vertexing precision

- For a beam with Gaussian transverse shape:

$$\sigma^2_{\mathrm{raw}} = \sigma^2_{\mathrm{beam}} + \sigma^2_{\mathrm{vtx.res}}$$

- When $\delta\sigma_{\mathrm{raw}}/\sigma_{\mathrm{raw}} \to 0$:

$$\frac{\delta\sigma_{\mathrm{beam}}}{\sigma_{\mathrm{beam}}} = \frac{\sigma^2_{\mathrm{vtx.res}}}{\sigma^2_{\mathrm{beam}}} \cdot \frac{\delta\sigma_{\mathrm{vtx.res}}}{\sigma_{\mathrm{vtx.res}}}$$



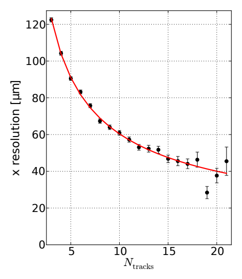
Therefore, it is important to have

- Small $\delta\sigma_{\mathrm{vtx.res}}$ / $\sigma_{\mathrm{vtx.res}}$: aim at 10 % (LHCb experience)
- Small ratio $\sigma^2_{\mathrm{vtx.res}}$ / σ^2_{beam}: aim at 0.2

- If we assume $\sigma_{\mathrm{vtx.res}} = \sigma_{\mathrm{IP}}/\sqrt{N_{\mathrm{Tr}}} \Rightarrow$

$$\frac{\delta\sigma_{\mathrm{beam}}}{\sigma_{\mathrm{beam}}} = \frac{\sigma^2_{\mathrm{vtx.res}}}{\sigma^2_{\mathrm{beam}}} \frac{\delta\sigma_{\mathrm{vtx.res}}}{\sigma_{\mathrm{vtx.res}}} = \frac{1}{N_{\mathrm{Tr}}} \frac{\sigma^2_{\mathrm{IP}}}{\sigma^2_{\mathrm{beam}}} \frac{\delta\sigma_{\mathrm{vtx.res}}}{\sigma_{\mathrm{vtx.res}}}$$

- The vertex resolution depends on the z position too



Accuracy goals

- **Initial estimates of what is achievable, based on current knowledge**
  - Values apply for 0.45 to 7 TeV

Quantity	Accuracy	Time interval	Key factors
Relative bunch width	$5\ \%$	<1 min	vertex resolution stability
Absolute average beam width	$2\ \%$	<1 min	σ_{beam}, σ_{MS}, σ_{extrap} (σ_{hit})

- Of global importance: Rate of "good" events (acceptance, gas type, gas pressure)

❖ **Assuming** $\delta\beta/\beta = 3.5\ \% \Rightarrow \delta\epsilon_{\mathrm{beam}}/\epsilon_{\mathrm{beam}} = 5.3\ \%$

The BGV team

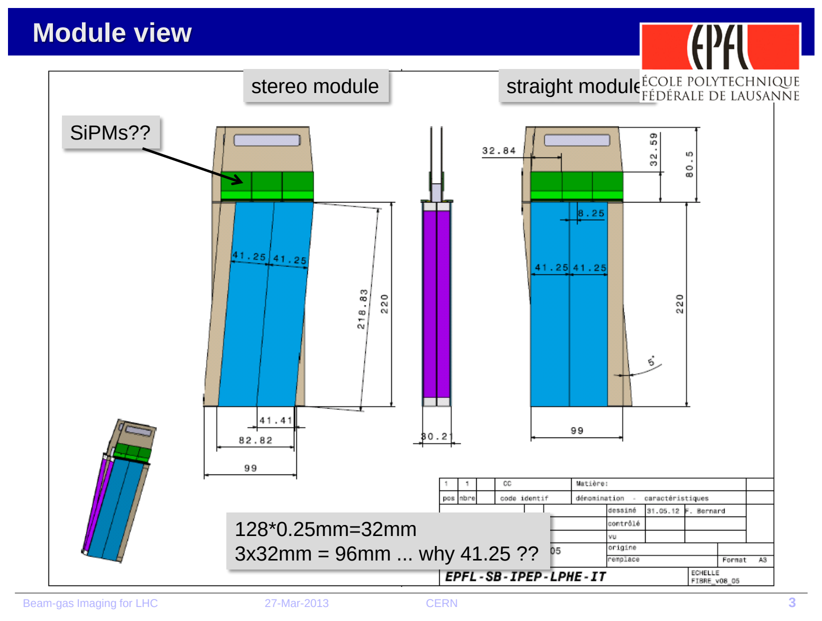
Past and current contributors

BE-BI:	B. Dehning, P. Hopchev, R. Jones, M. Kuhn F. Roncarolo, M. Sapinski, G. Trad, R. Veness
BE-ABP:	M. Giovannozzi
TE-VSC:	V. Baglin, G. Bregliozzi, M. Jimenez
CERN-PH (LHCb):	C. Barschel, M. Ferro-Luzzi, R. Jacobsson, R. Matev, J. Panman
EFPL:	A. Bay, G. Haefeli and other collaborators

EPFL / PH $\Rightarrow$ LHC BGV

- EPFL is developing Scintillating Fibre (SciFi) replacement modules for the LHCb silicon Inner Tracker (LS1)
- LHCb is considering to use long SciFi modules for the Upgrade Tracker (LS2)
- SciFi is a new technology within LHCb $\Rightarrow$ EPFL eager to test modules in real LHC beam conditions
- The installation of a BGV prototype detector for one ring requires considerable equipment and manpower

Slide by M. Ferro-Luzzi – Possible detector module



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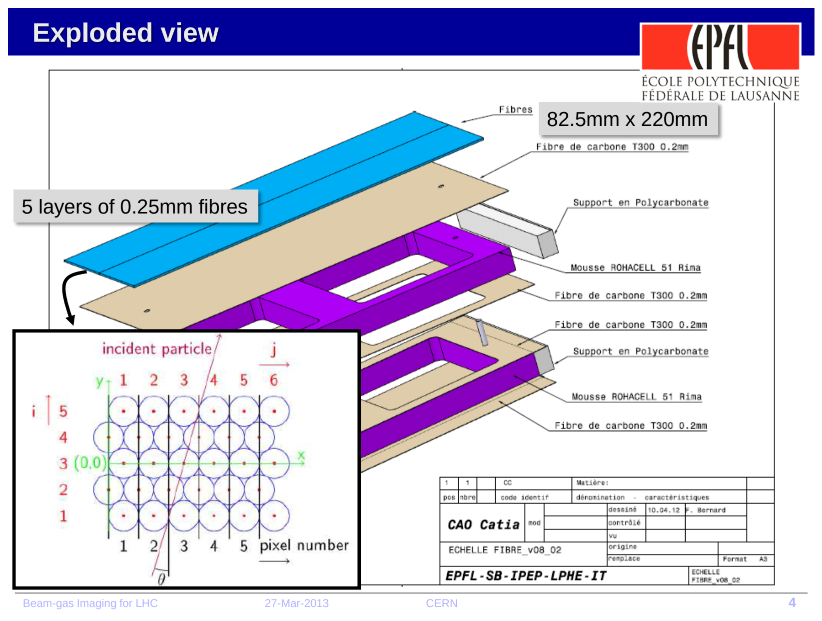
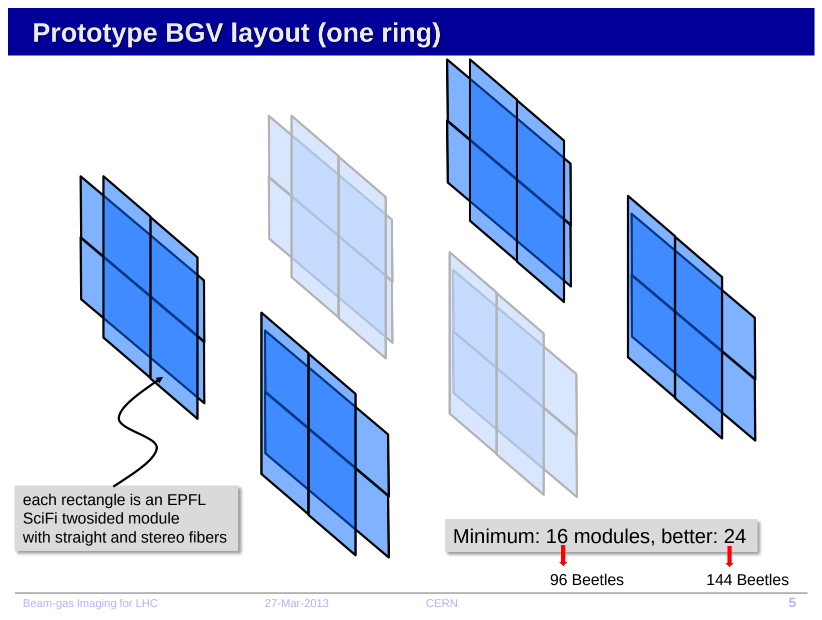


Slide by M. Ferro-Luzzi – Possible detector layout

Prototype BGV layout (one ring)



Status of the BGV project

- **The prototype phase of the BGV project is approved and funded by HL-LHC**
- **The proposal for a prototype installation on one beam at the LHC is supported by LMC**
  - Green light to start negotiating the schedule with the electric and vacuum teams
  - System design and construction in parallel
- **Working towards an installation of a BGV prototype either in LS1 or, as a minimum, in subsequent technical stops**

BGV TWiki: **https://twiki.cern.ch/twiki/bin/view/BGV/WebHome**

Additional Slides

Data rates

important to use a well localized target

Assume

- Achieve a raw beam-gas rate of max 1 MHz => can trigger with a simple activity trigger (scintillator pad)
- R_{L0} = level-0 trigger rate < ~1 MHz
- t_{hlt} = avge time to take HLT decision
- N_{cpu} = nr of CPU cores available in HLT
- e.g. for N_{cpu} ~ 100 we need to achieve $t_{hlt} < N_{cpu} / R_{L0} = 0.1$ ms
  - need to be smart... multi stage approach: (1) request high hit multiplicity, (2) simple projective z-vtx location from cluster info (no tracking), (3) full reconstruction...
    - the higher the purity of the raw rate, the more relaxed the HLt algo

Data rate:

- HLT rate out R_{hlt} = depends on cuts applied, say ~ 1kHz to tape
- Cluster info = say 14 bits for the channel, 3 bits for the interchannel distance
- Event size = ~ 17bits/clus * 10 clus/plane/evt * 6 planes = 1 kbit/evt + overhead!

=> ~0.2 kB/evt * 1 kevt/s = 0.2 MB/s

0.2 MB/s * 10^7 s/yr = 2 TB/yr

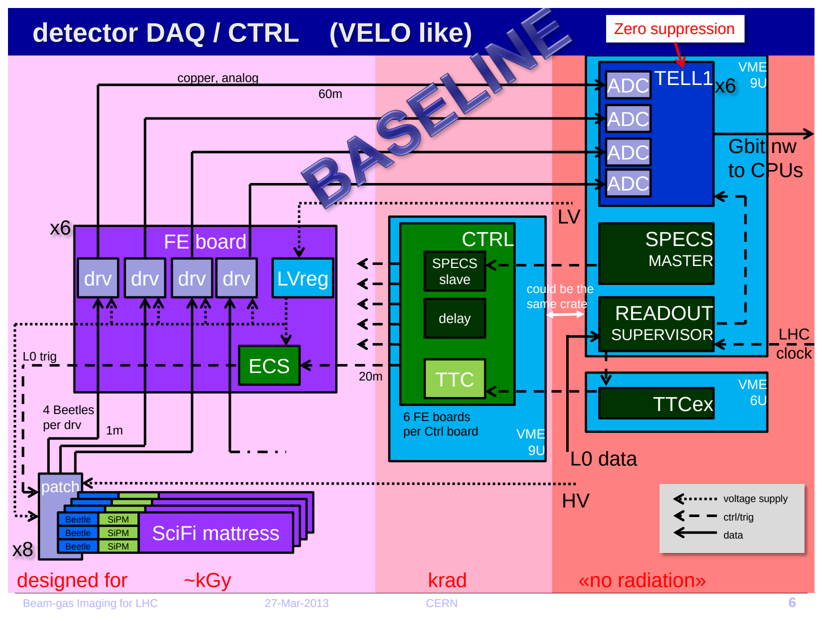
=> think about histos, store only fraction a fraction of the full data

Modules/beetles

- Each module is a «double» mattress with 3 Beetles per side.
- Assume either 16 / 24 modules
  - 96 / 144 Btl
- Considered three possibilities:
  - VELO like readout: 4 Btl/drv, 4 drv/rpt, 4Btl/Arx, 4Arx/Tell1 => 6 / 9 Tell1
  - IT like readout: 3 Btl/dig, 12Btl/Orx, 2Orx/tell1 => 4 / 6 Tell1
  - «Upgrade» readout: 96 Btl into one Tell40, requires new optical intreface boards...
- Retained as baseline: VELO like readout

  Advantages:
  - EPFL/CERN «know-how» of all the front-end and back-end boards
  - Most components readily available
  - Full support available until at least LS2
  - Possibility to recycle LHCb IT in LS2 (very similar to VELO)

Slide by M. Ferro-Luzzi – Possible DAQ/CTRL Scheme



Slide by M. Ferro-Luzzi – Preliminary detector inventory

Value of detector + readout equipment APPROXIMATE

kCHF

Part	quantity	cost/ pc	cost all	provenience
Module (= 2 mattresses)	16	1	16	EPFL
Beetle FE chips (encaps)	96	0.1	10	EPFL
Beetle PCBs	32	0.1	3.2	EPFL
RPT	6	0.8	4.8	EPFL
RPT crate	2	0.6	1.2	EPFL
ECS	6	0.5	3	CERN/PH
LVreg	6	0.5	3	EPFL
Drv	24	0.3	7.2	EPFL
analog cables 60m	24	0.25	6	CERN/PH
TELL1 (+ccpc+gbe)	6	5.1	30.6	EPFL
Arx	24	0.35	8.4	EPFL
CTRL	1		10	CERN/PH
specs slave	1		2	CERN/PH
TTC	1		2	CERN/PH
delay	1		1	CERN/PH
specs master	1		2	CERN/PH
Readout Sup	1		10	CERN/PH
TTCex	1		5	CERN/PH
VME 9u	1		10	CERN/PH
VME 6u	1		5	CERN/PH
LVPS	1		5	CERN/PH
HVPS	1		5	CERN/PH

- fibres:
  0.3m*5*384*32=18km
  6 kCHF
- SiPM: 0.8kCHF*96= 8kCHF

- To be refined
- But the bottom line is that this amounts to something of the order of ....

total ~ 150kCHF

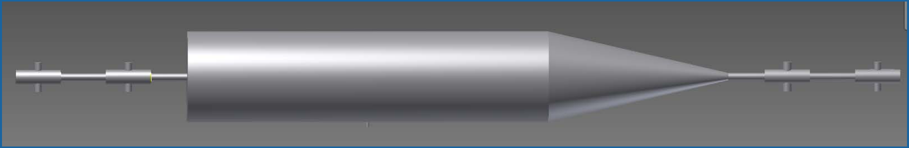
- Yet to be added:
  - L0 detect & trigger
  - HLT/DAQ hardware

Gas target design (1)

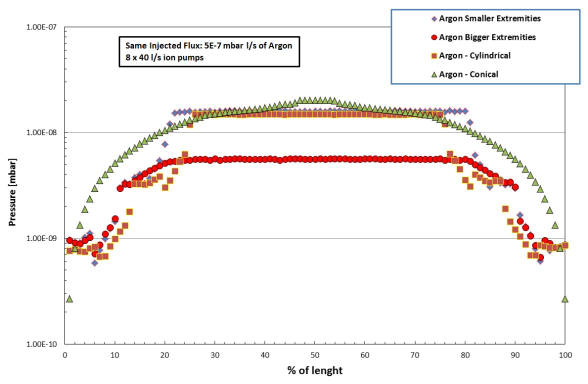
- Densities (averaged over 1m) that would be needed for the BGV to work adequately for some representative gas types
- F_{good} is the fraction of events producing at least 10 tracks in the acceptance of small-size detector

Gas type	A	F_{good}	ρ [10^7 cm^{-3}]	p at 293 K [10^{-9}mbar]
Hydrogen	1	0.002	5800	2300
Neon	20	~0.020#	160	64
CO_2	16*	0.020*	60	25
Xenon	131	0.140	7	2.6

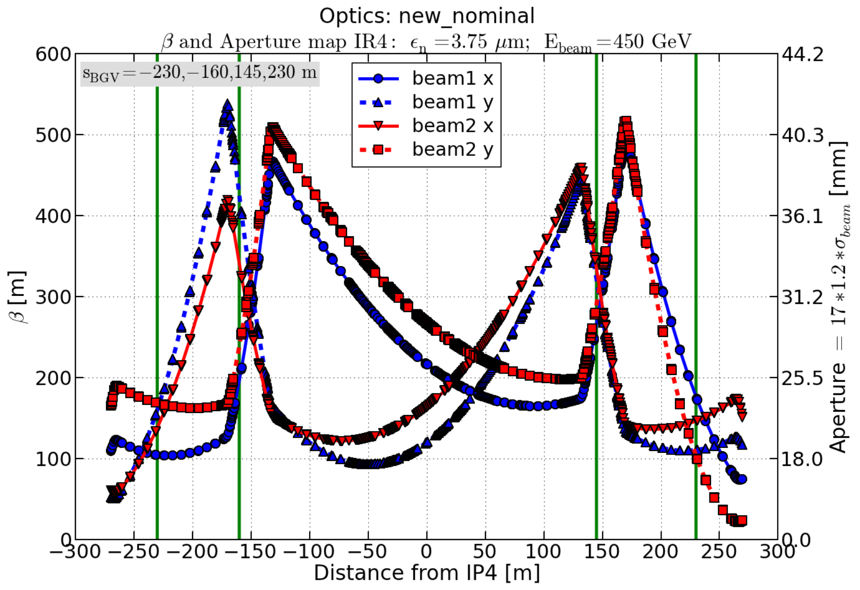
Gas target design (2)



Possible layout and pressure profile simulations – G. Bregliozzi



β, Nominal Optics



Application of the method in other machines?

- Not obvious if the method can be applied in a non-hadron collider
  - Expect much lower inelastic cross-section
  - Electron beams have much lower size
- Lower center-of-mass energy of the collisions results to lower charged particle multiplicity
  - Need a dedicated study/simulations of the expected fraction of “good” events
- Smaller accelerator radius $\Rightarrow$ higher f_{rev} $\Rightarrow$ higher beam-gas rate per bunch
- Short accelerator cycles (say, 1 s) may be a problem for bunch-by-bunch measurements

parameter	PS		LHC	
	1.5 GeV	20 GeV	450 GeV	7000 GeV
Δz [cm]	100			
$\sigma_{\mathrm{pNe}}^{\mathrm{inel}}$ [mb]	147	228	243	295
N_p / bunch	1.5×10^{11}			
f_{rev} [kHz]	477.7		11.245	
pressure [mbar]	10^{-7}			
R_{inel} [Hz]	2633	4084	102	124