BGV status and plans

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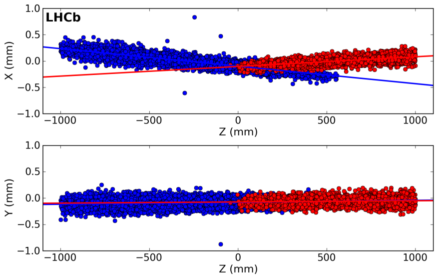
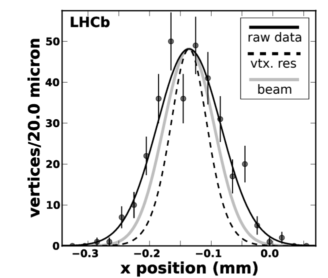
BI Technical Board

19 Nov 2015

Beam Gas Vertex monitor (BGV)

- Development of a transverse profile monitor for HL–LHC
- Based on the *beam-gas imaging technique* pioneered in LHCb
  JINST 7 (2012) P01010, JINST 9 (2014) P12005
- Measurement principle: Tracks → beam-gas interaction vertices → transverse beam profile (2D)
- Can provide also (at low rate): beam position and angle, relative bunch populations, ghost charge, abort gap population, longitudinal profile (needs timing detector with ∼50 ps resolution)



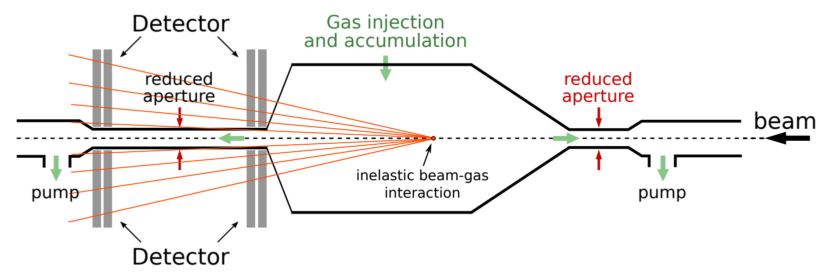


Development goals and approach

- **Phase 1**: demonstrate the potential by installing a prototype system on one beam at the LHC (BGV Demonstrator)
  - Make a sequence of measurements, full beam and b-by-b, also during ramp
  - Modest requirements on the measurement frequency, precision and accuracy
- **Phase 2**: build a full-blown BGV for each LHC ring
  - Bunch width resolution: < 5 % in $\Delta t < 1$ min
  - Absolute beam width accuracy: 2 %

- Collaboration required: BE-BI, TE-VSC, PH-LHCb, EPFL, Aachen
  - BGV Demonstrator Collaboration Agreement

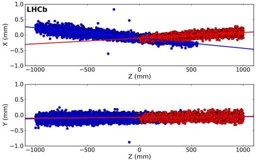
Demonstrator conceptual design

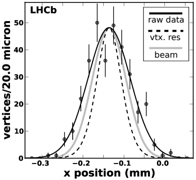


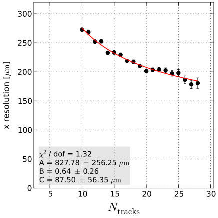
- Detector external to the chamber; No movable parts
- Expectations for the Demonstrator (see next slides):
  - Bunch width resolution: 5 % in Δt = 5 min
  - Absolute width accuracy: 10 %
- Beam size, aperture, target gas $\Rightarrow$ BGV size
- Critical design parameters: minimal approach to the beam, polar angle acceptance, and material budget (window $x/X_0 \approx 1$ %) [Ref.]

Beam width measurement and error 1/3

- Accumulate vertices over certain time Δt
- Determine beam angle in the $x-z$ and $y-z$ planes
- Fit a Gaussian to the transverse distributions
- The statistical precision on σ_{beam} is determined by the N_{vertices} used in the fit (scales as $1/\sqrt{2N}$)
  - Want high rate of interactions $\Rightarrow$ inject gas
  - Demonstrator designed to get $\sim$ 1 Hz of "good" vertices per nominal bunch (see details in the backup slides)
  - $\Rightarrow$ For Δt = 5 min, we get stat. precision $\approx$ 4 %
- The main systematic error on σ_{beam} comes from the vertex resolution
  - Want precise detector, minimum material, and high track multiplicity (see details in the backup slides)
  - Selecting high multiplicity events reduces the rate of "good" vertices







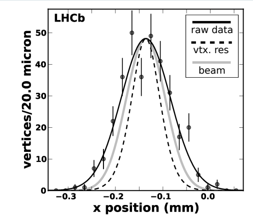
Beam width measurement and error 2/3

- For a beam with Gaussian transverse shape:

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

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

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

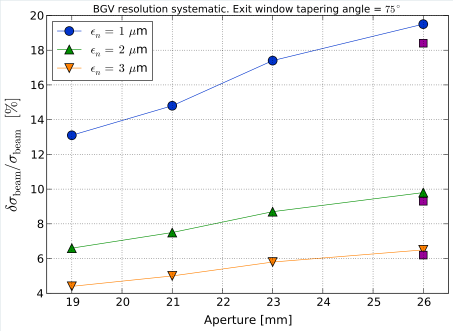


- The vertex resolution $\sigma_{\text{vtx.res}}$ depends on z_{vtx} and N_{tracks}
- It can be determined from data alone (track splitting method)
- The determination of the uncertainty of the vertex resolution $\frac{\delta\sigma_{\text{vtx.res}}}{\sigma_{\text{vtx.res}}}$ requires simulation (compare results of track splitting and MC-truth methods)
- For the BGV Demonstrator aim for $\frac{\delta\sigma_{\text{vtx.res}}}{\sigma_{\text{vtx.res}}}$ = 10 % (LHCb has achieved 5 %)
- σ_{beam} depends on E_{beam} and ϵ_n
  - Better accuracy for larger beam (at injection and with large emittance)

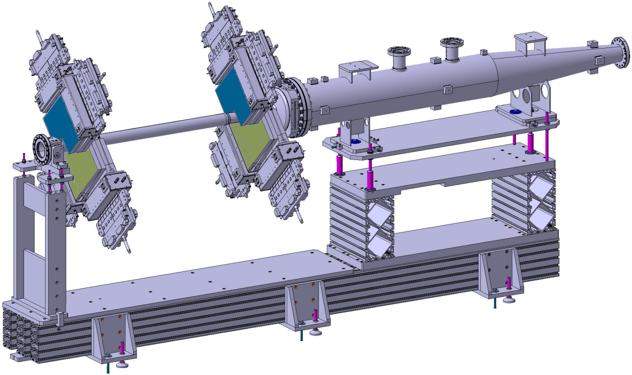
- Plot of the systematic error from vertex resolution
  - Made during the early design studies (later, the minimal aperture was fixed to 26 mm)
  - The plot is for $E_{\text{beam}} = 6.5$ TeV
- These results are obtained with a simplified simulation application
  - Thanks to Maria Kuhn for her contributions to these studies
  - More details can be found in BGV #20, BGV #22 and Emitt. meeting Nov 2013
- Strong cuts were applied on N_{tracks} (select 1 out of 1000 events)

For $\epsilon_n = 2\ \mu$m expect:

- $\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} < 5\ \%$ (0.45 TeV)
- $\frac{\delta\sigma_{\text{beam}}}{\sigma_{\text{beam}}} = 10\ \%$ (6.5 TeV)

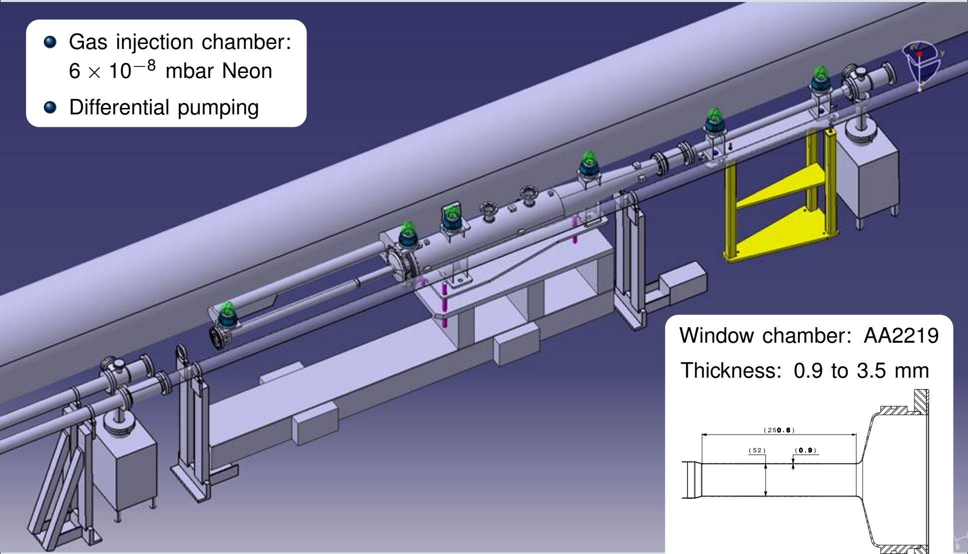


Overview



- **Vacuum system**: Designed and produced by CERN (+outsourcing)
- **Detector**: Scintillating fibres read out with SiPMs
  - Developed by EPFL and RWTH Aachen
  - Same technology as for the LHCb upgrade

Vacuum system 1/3



- Gas injection chamber: 6×10^{-8} mbar Neon
- Differential pumping

Window chamber: AA2219

Thickness: 0.9 to 3.5 mm

Engineering design

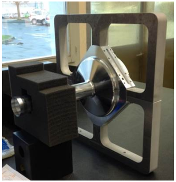
- N. Chritin (EN-MME) and
  P. Magagnin (BE-BI)

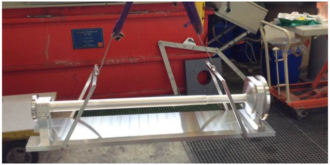
Production

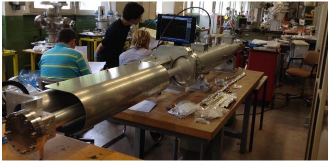
- Managed by the main workshop
- Window chamber most complex and delicate
  - Al block forging (Imbach, CH), machining and EB welding (CERN)

Treatment and Qualification

- Cleaning, copper plating and NEG coating (TE-VSC)
- RF test (BE-ABP), bakeout and vacuum qualification (TE-VSC)
- Metrology (EN-MME)

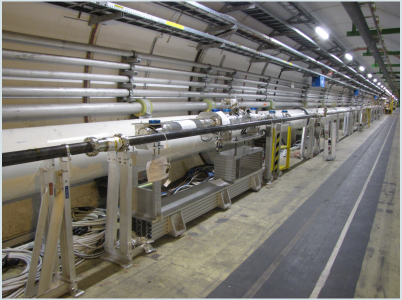


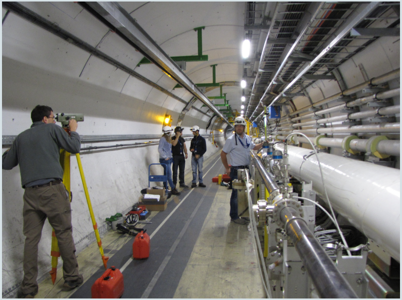




Vacuum system 3/3

- BGV chambers installed in July 2014 (EN-HE)
- Alignment (Survey) and bakeout (TE-VSC) done

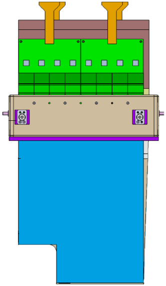


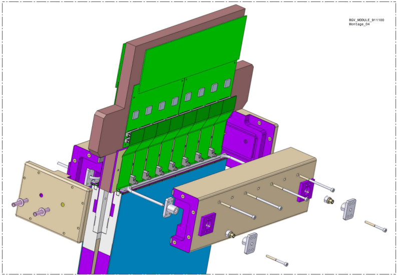


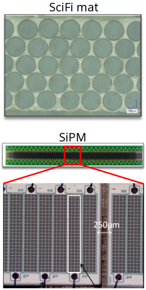
Additional systems:

- Chamber temperature monitoring (help from TE-ABT)
- Forced-air chamber cooling (against RF heating)
  - This year we observed T increase up to 2 °C (fill with 2200 bunches)

Detector 1/2



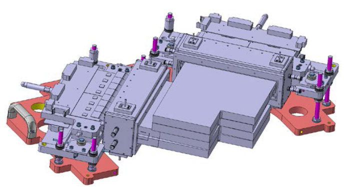


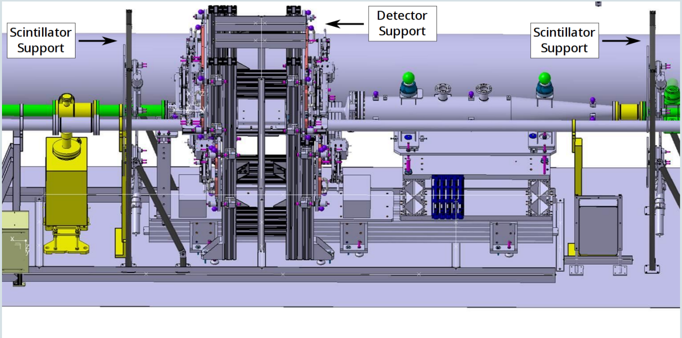


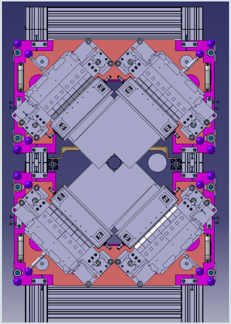
- Double sided detector modules – 2° "stereo" angle
- Fibre mattresses produced at Aachen, mechanics and electronics – at EPFL
- Scintillating fibre mattress
  - 260 × 340 mm
  - Optimized geometry (corner cut)
  - Fibre diameter 250 μm (Kuraray)
  - 4 and 5 layer mats
- SiPMs
  - 128–channel arrays (Hamamatsu)
  - Channel size = 0.25 × 1.2 mm
  - Noise increases with radiation
    ⇒ cooling to reduce SiPM noise
- Expected hit resolution: $\sim$ 70 μm

Detector 2/2

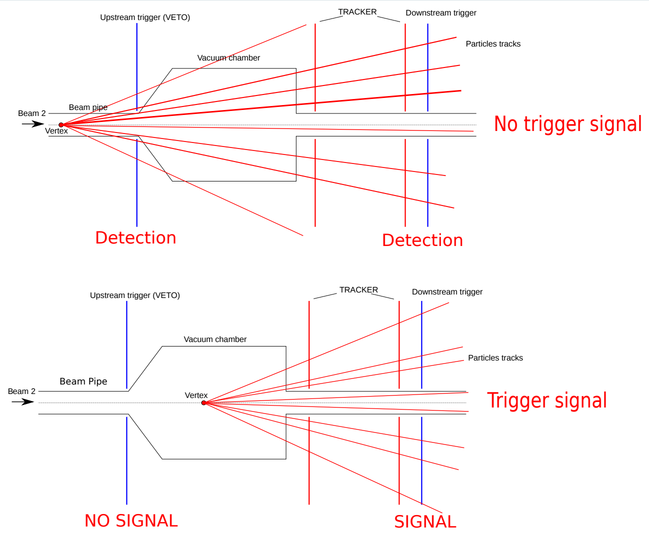
- Two modules fixed together on a common plate: “2-module assembly”
- **In total:**
  - 8 detector modules arranged in 2 “planes”
  - $8 \times 2048 = 16\,384$ channels







Trigger scintillators (Level–0 trigger) 1/2



Provide information which bunch-crossings should be read out (DAQ limited to 1 MHz)

4 scintillators

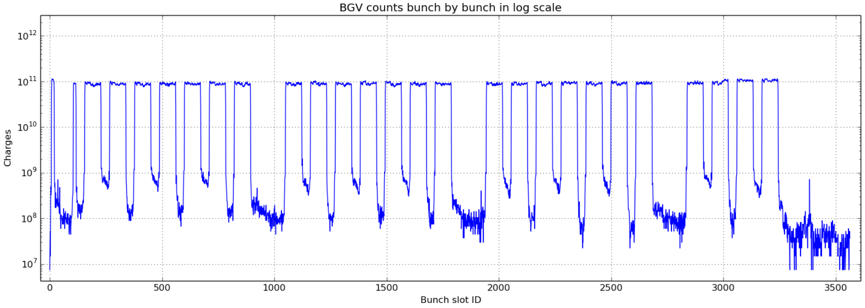
2 upstream of the gas tank: veto upstream events

2 downstream of the detector: require certain signal to readout the event

Events with losses from the other beam do not trigger

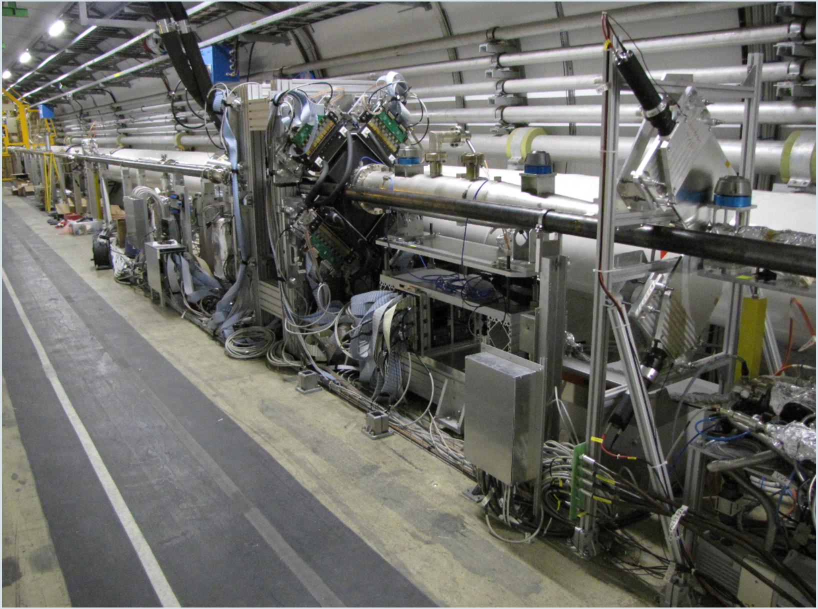
Trigger scintillators (Level–0 trigger) 2/2

- Can provide standalone measurement of the relative bunch populations and ghost charge
- Data shown for fill 4479 (Oct 2015)

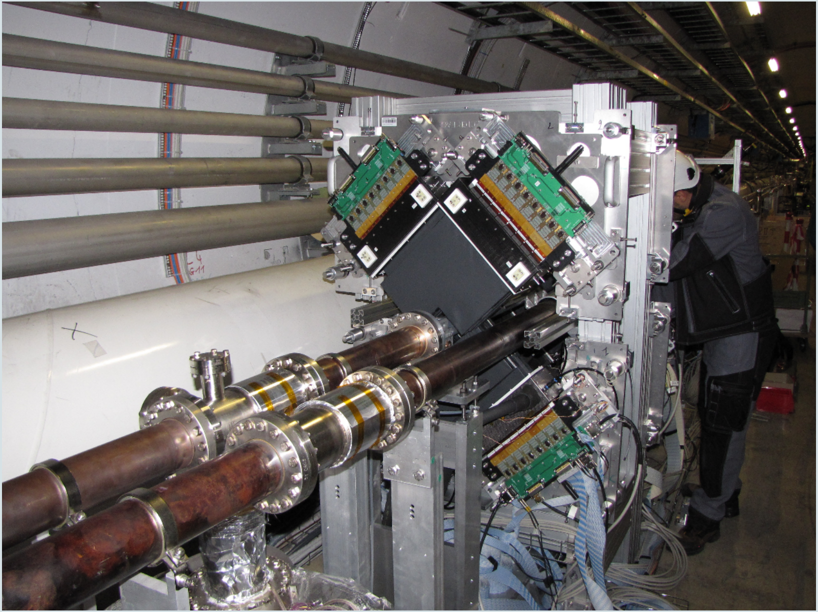


May 2013

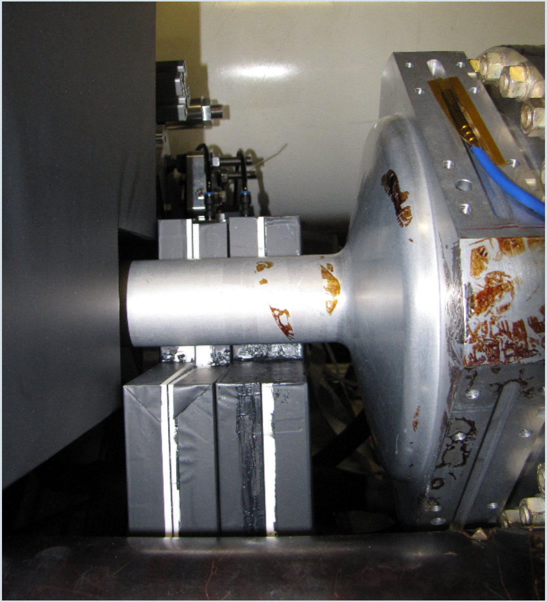
TS3 2015



TS3 2015

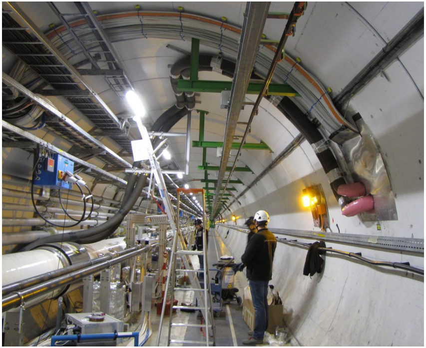


TS3 2015

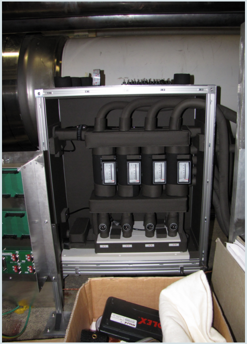


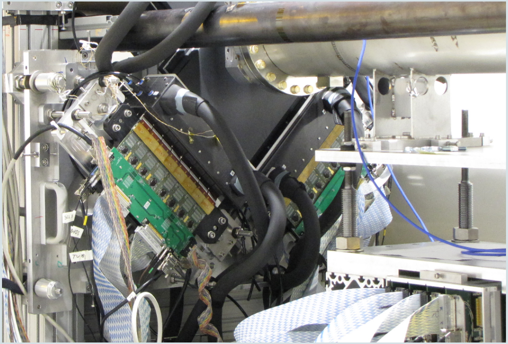
Detector cooling 1/2

- Developed system to cool the SiPMs down to $-40\ ^{\circ}C$
  - Will start without cooling, later decrease T gradually
- Standalone chiller in the service tunnel
  - Used C_6F_{14}, considering also Novec 649
- Transfer line and a distribution manifold in the LHC tunnel
  - Silicon tubes and Armaflex insulation



Detector cooling 2/2





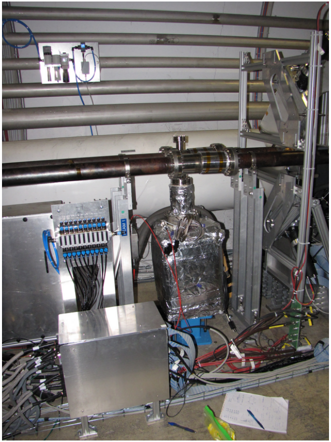
- Problem encountered: slow diffusion of the cooling liquid through the Silicon tubes
  - Considering possible solutions

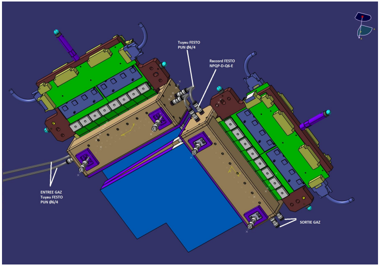
Dry air

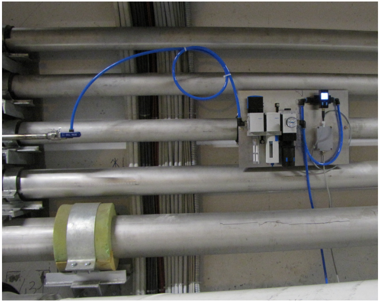
Using compressed air as dry air

Dew point = $-40\ ^{\circ}\mathrm{C}$, $p < 0.1$ bar

Thanks to EN-CV

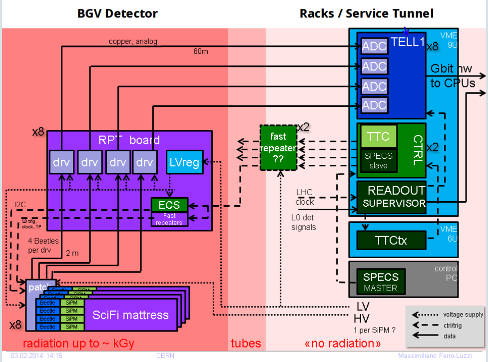


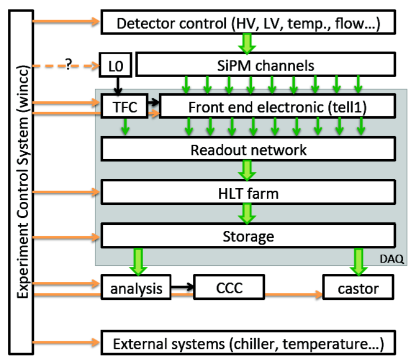




Readout & Control

- BGV readout based on LHCb VELO
  - 25 ns, 1 MHz maximum rate
  - Readout trigger provided by scintillators
- Control based on PVSS/WinCC-OA (copy LHCb)
  - Interface to LHC CMW to exchange data and commands (in preparation)



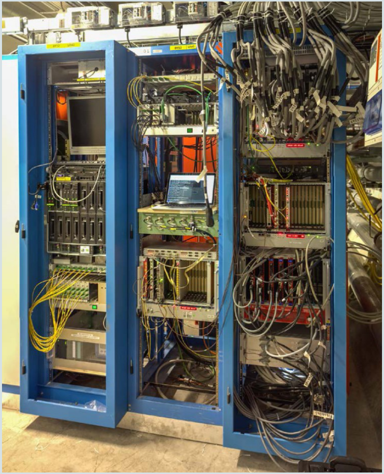


Readout specifics

- SiPM $\Rightarrow$ Beetle chip $\Rightarrow$ Repeater $\Rightarrow$ 60 m $\Rightarrow$ TELL1 board
- Beetle chip
  - Radiation tolerant analog readout chip developed for LHCb
  - Integrates 128 channels with low-noise charge-sensitive pre-amplifiers and shapers
  - Accepts trigger rates up to 1.1 MHz
  - The output is multiplexed onto 4 ports at 40 MHz (32 channels/port)
- TELL1 board
  - Readout board used in LHCb for optical or analogue data from the front-end electronics
  - 8-bit ADC sampling at 40 MHz
  - FPGA-based pre-processing (common mode correction and zero suppression)

DAQ

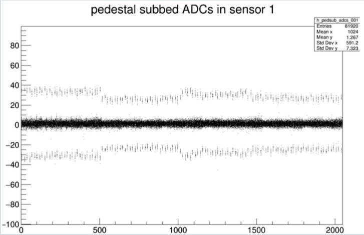
- DAQ installed in TS2 2015
- All systems functional
- A single chassis (HP ProLiant "Blade") hosts the control server and CPU boards
  - Thanks to BE-CO

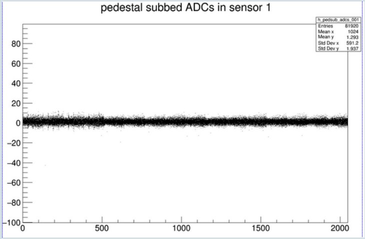


- Racks layout
- Rack photos

Readout commissioning 1/2

- ADC DELAY SCAN
  - Special data-taking configuration used to optimize the sampling time of the TELL1 boards with respect to the output produced by the Beetle chips
  - Scan the 16 possible fine delay settings on the TELL1 boards
  - Uses test pulses produced by the Beetle (no beam)
  - Data taken with bad and good ADC delay setting (Beetle headers visible)

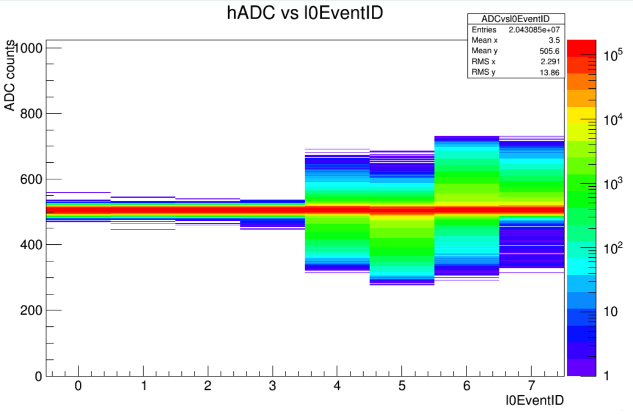




- PULSE SHAPE SCAN
  - Special data-taking configuration used to adjust the common TELL1/beetle phase with respect to the LHC clock
  - 25 steps of 1 ns – reproduce the pulse shape pattern (beam needed)
  - To be performed soon

Readout commissioning 2/2

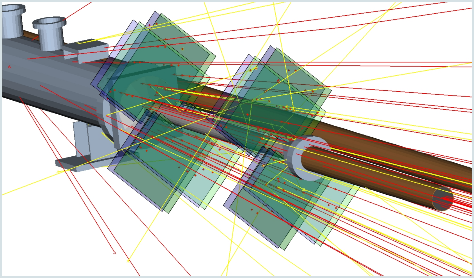
- L0 trigger latency
  - Optimal setting found (25-ns granularity)
  - Beetle pulse shape visible: starts negative, tail is positive, extends over a few 25-ns slots



“Physics” software

Based on the LHCb software framework

GAUDI: a set of SW components for developing event simulation, reconstruction, visualisation, etc. applications. SW development facilities and interfaces to 3rd party SW (e.g. PYTHIA and GEANT4). Used by several HEP experiments.

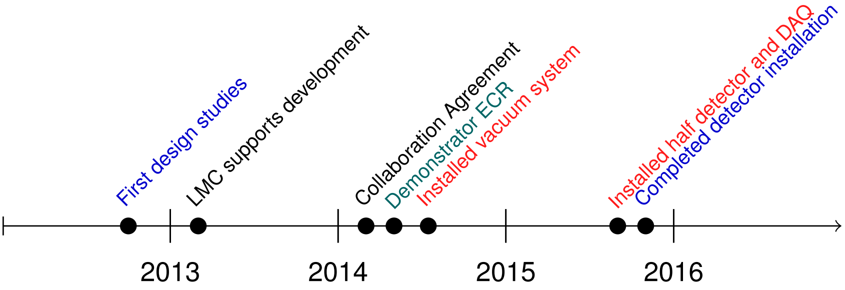


- Simulation
  - Generate beam-gas interactions
  - Geometry description and detector response
  - Develop event reconstruction algorithms
  - Study vertex resolution systematic
- Event reconstruction
  - Pattern recognition and track fitting
  - Vertex reconstruction
- Initial versions of the algorithms are ready

Status and next steps

- The BGV Demonstrator installation was completed in TS3 2015
  - Light-protection cover (“tent”) coming in YETS
- The detector and readout are in good shape
  - One electronics card to be replaced and a few cables to be checked
- Commissioning of readout ongoing
  - ✓ L0 trigger latency
  - ✓ ADC delay scan (beetle – TELL1)
  - Pulse shape scan (fine tuning of readout timing)
- Priority for this year: record raw data with good timing settings
- In parallel, work on the next steps
  - Treatment of raw signals, corrections, zero-suppressed readout
  - Track and vertex reconstruction
  - Develop online profile measurement application
  - Publishing and logging of event data and measurements

Milestones



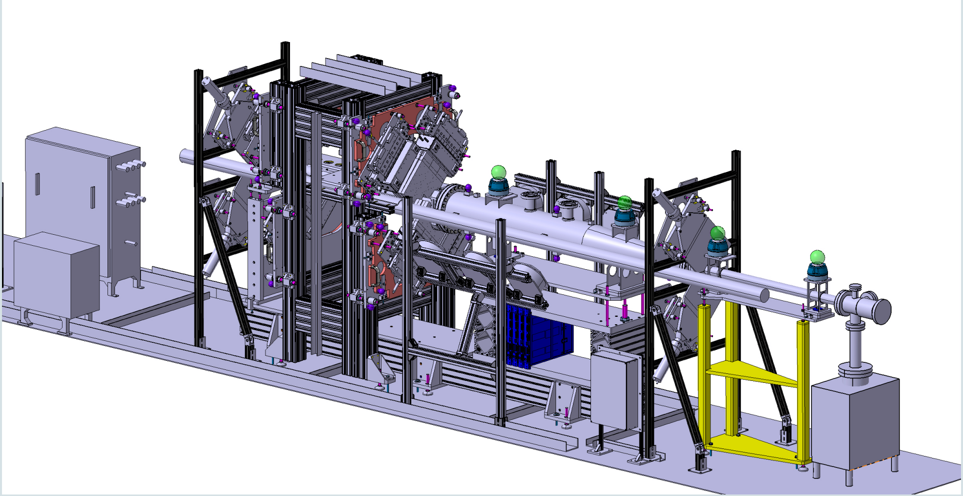
- **BGV TWiki:** `https://twiki.cern.ch/twiki/bin/view/BGV/`
- **BGV ECRs:** `https://edms.cern.ch/project/LHCMS183`
  - Space reservation, BGV Demonstrator, Cooling, and Tent
- **BGV presentations:**
  `https://twiki.cern.ch/twiki/bin/view/BGV/Presentations`

Additional Slides

Possible beam measurements

- Beam position and angle
- **Transverse beam profile**
  - Main interest for BI
  - Full beam and b-by-b, absolute scale, cover full LHC cycle
- Longitudinal profile
  - Need timing information ($\sim$50 ps resolution)
- Relative bunch charges
  - Compare rates between bunch slots
- Ghost charge, abort gap population
  - Normalize rate to filled bunch slots

Design layout

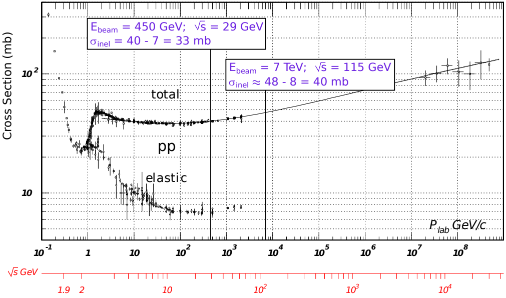


Rate of inelastic interactions

Per bunch:

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

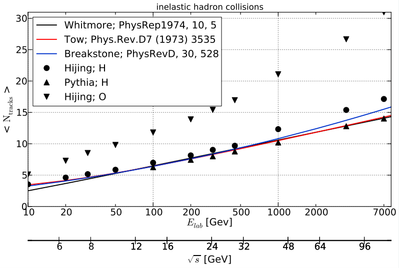
- $\rho(z)$ – gas density
- Inelastic proton-nucleus cross-section
  $\sigma_{\text{pA}}(E) \approx \sigma_{\text{pp}}(E) \cdot \text{A}^{2/3}$
  A – atomic mass
  In the case of ^{20}Ne:
  - $\sigma_{\text{pNe}}(450\ \text{GeV}) = 243$ mb
  - $\sigma_{\text{pNe}}(7\ \text{TeV}) = 295$ mb
- N – number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



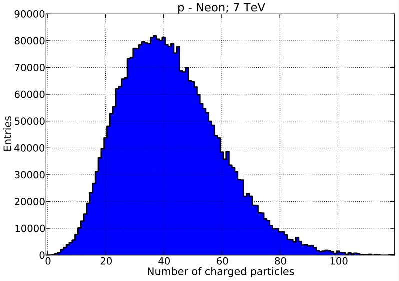
At the LHC, pressure of a few $\times 10^{-8}$ mbar over 1 m is needed to get $R_{\text{inel}} = 50$ Hz

Charged particle multiplicity

- Average number of charged particles
- "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 simulations with measurements of previous experiments

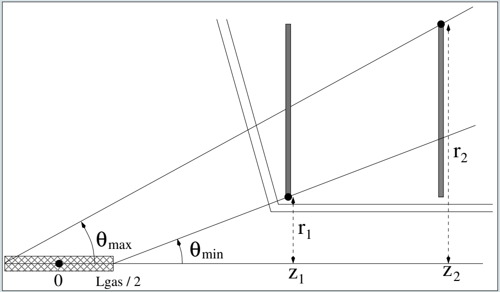


- Distribution of the number of charged particles



Angular acceptance

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

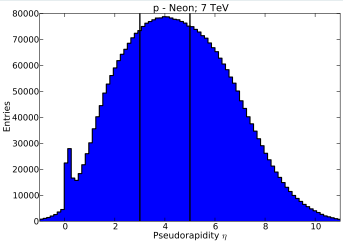


- **Aim at minimal r_1**

Values used in the design study:

- L_{gas} = 1000 mm
- θ_{min} = 14 mrad (η_{max} = 5)
- θ_{max} = 100 mrad (η_{min} = 3)

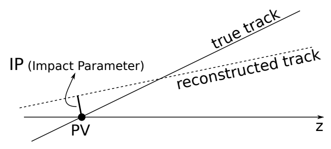
Simulated p – Ne collisions



Tracking precision

The magnitude of the impact parameter (IP), σ_{IP}, is determined by:

- σ_{MS} – IP induced by multiple scattering (MS)
  - Minimizing the amount of material (x/X_0) is essential
- σ_{extrap} – IP induced by detector hit resolution and extrapolation distance
  - Use high-resolution detectors and minimize the longitudinal distance (related to the aperture)



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

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

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

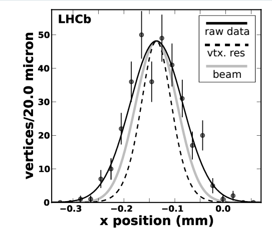
Vertexing precision – basic considerations

- For a beam with Gaussian transverse shape:

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

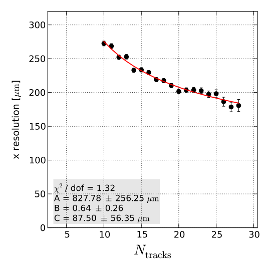
- When $\delta\sigma_{\text{raw}}/\sigma_{\text{raw}} \to 0$:

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



Therefore, it is important to have

- Small $\delta\sigma_{\text{vtx.res}}$ / $\sigma_{\text{vtx.res}}$: aim at 10 % (resolution parametrization)
- Small ratio $\sigma^2_{\text{vtx.res}}$ / σ^2_{beam}: preferably < 1

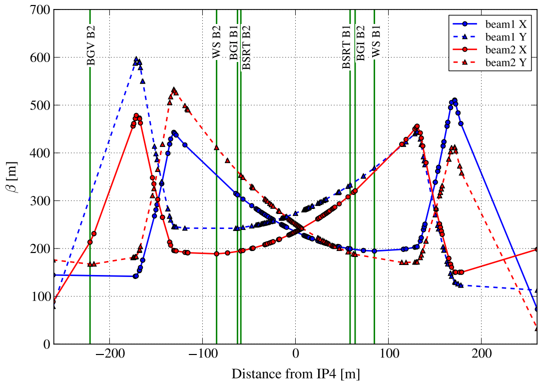


- The vertex resolution depends on:
  - N_{tracks} (vertex reconstruction)
  - z_{vtx} (extrapolation distance)

Optics and beam size

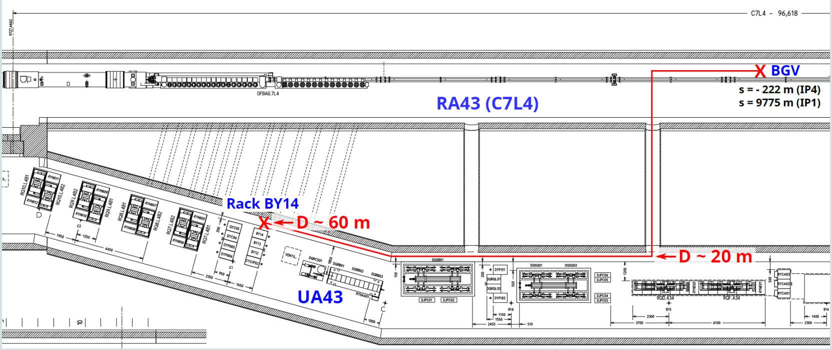
- Beam size at the BGV location (DCUM 9775 m)
- Using ϵ_n = 2 μm

	β [m]	σ_{beam} [μm] 0.45 TeV	σ_{beam} [μm] 6.5 TeV
x	210	936	246
y	170	842	222

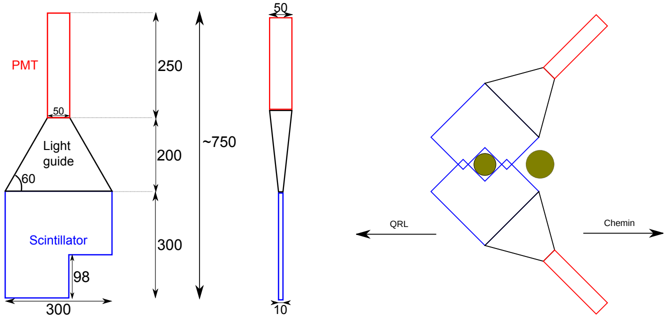


Cabling

- BGV located at DCUM ≈ 9775 m (C7L4)
- Readout electronics will be placed in racks BY12 – BY14
- Cabling campaign in May 2014
  - About 100 cables for detector readout, control, LV, HV, trigger
  - About 30 cables for vacuum pumps, gas injection, gauges (racks VY05,12,20)



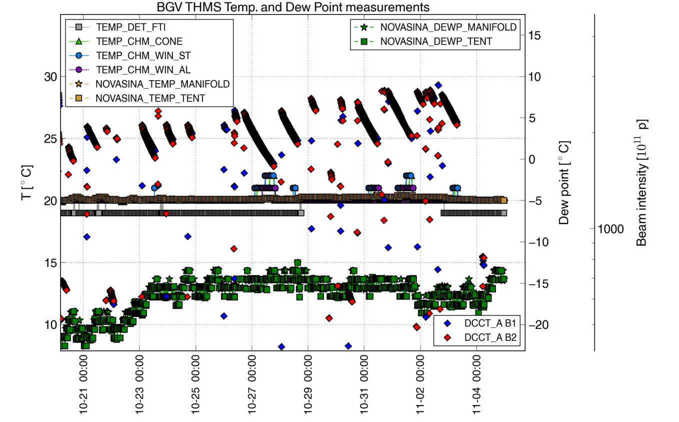
- Provide information which bunch-crossing should be read out (DAQ limited to 1 MHz)



Size of scintillating plates choosen to be 300mm and the cut-out is the same as the trackers 98mm.

Temperature and humidity monitoring

- In 2015 the maximum T increase of the BGV chamber was 2 °C
  - Seems like effect from the bunch length – at the end of the fills
- The dew point is very low (dry air exhaust in the LHC tunnel by EN-CV)
- More details: https://twiki.cern.ch/twiki/bin/view/BGV/THMS



Radiation monitoring

- Effort is made to monitor the radiation dose on the SiPMs
- RADMON *4LM19S* placed behind the far detector station
- Installed several pin diodes with known behavior under radiation
- More details: `https://twiki.cern.ch/twiki/bin/view/BGV/Radiation`