Beam Gas Vertex (BGV) profile monitor for HL-LHC

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Acknowledgments: Bernadette Kolbinger, James Storey

BGC Collaboration Meeting, 31/03/2022

Introduction: instrument principle and context

Design status

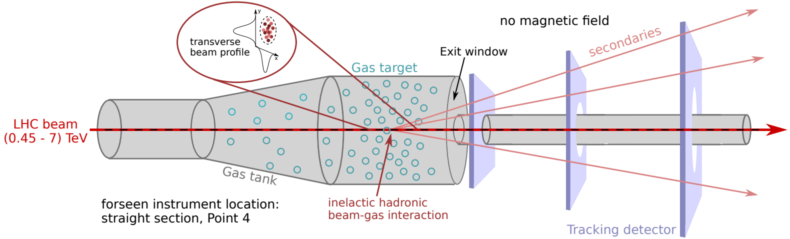
Gas target

- Possible options
- Zoom on the gas jet option

Summary

Introduction

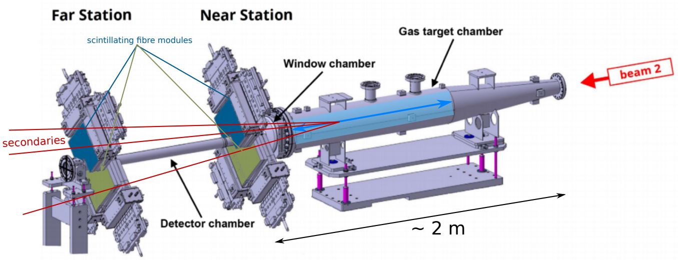
- **Non-invasive transverse beam profile monitor** based on the reconstruction of vertices of inelastic hadronic beam-gas interactions.
- Provide **continuous emittance and beam profile measurement** throughout the LHC accelerator cycle (450 GeV to 7 TeV).



- Consists of: a **gas target**, a forward **tracking detector** and computing resources dedicated to event reconstruction.
- **Transverse beam profiles** inferred from density of reconstructed **primary vertices of beam-gas interactions**.

History – BGV demonstrator device

- Installed, commissioned and operated in LHC Run 2 [1].



- Tracking detector based on scintillating fibre stations (LHCb SciFi tracker).
- Neon gas target of $\approx$1.8 m length and $10^{-8}\mathrm{mbar}$ ($10^{15}\mathrm{Ne/m^3}$, interaction rate $\approx$200 kHz).

☑ Successful beam size measurements (200 – 800 μm) throughout the LHC cycle with required precision. Bunch-by-bunch measurements.

☑ Measurements coherent with other beam size measuring devices.

☐ Reconstruction of beam-gas interaction vertices not possible $\rightarrow$ no beam profile measurement.

- **Demonstrated the feasibility to use inelastic beam-gas interactions to measure the beam size, and highlighted points that need improvement for a future design.**

Motivation and requirements

Beam size review in October 2019 [2]: confirmed the need for a new transverse beam profile for HL-LHC, with the following specifications:

- Beam size measurement **accuracy** $\leq 5\%$
- **Bunch-by-bunch** measurement **precision** $\simeq 1\%$, in $1\,\mathrm{min}$ time scale
- Transverse **profile** measurement throughout the **full energy cycle** and independently of the beam **intensity**

$\rightarrow$ **New BGV design**, to be detailed in a report by Summer 2022

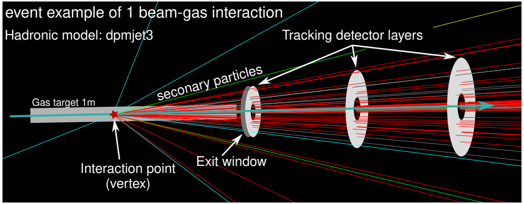
Design mindset: simple instrument, maintainable by a small number of people, minimise R&D

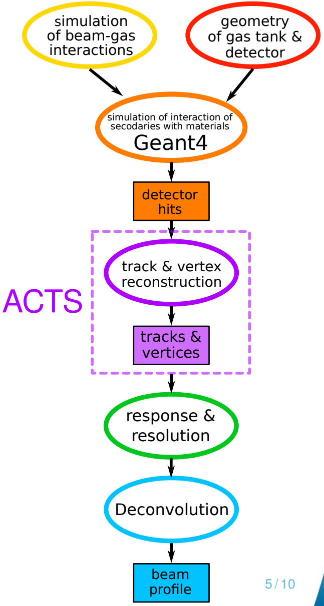
Approach: Implement a **detailed simulation model** to guide the future instrument's design, understand tracker and gas target requirements, and assess achievable performance; consider integration requirements in parallel (location, impedance, radiation impact, etc.).

BGV design status - I

Recent progress:

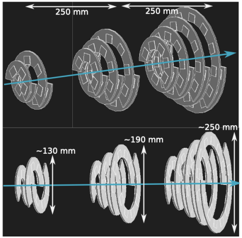
- Implementation of the **simulation tool**, using most recent community-driven tools, in contact with developers to implement each module (CRMC, PyG4eometry, Geant4);
- Extensive efforts to build the **event reconstruction algorithm**; work in progress to **unfold the beam profile** from measured/simulated vertex distribution → provide a profile measurement without any assumption on the beam shape;
- **Performance study** (B. Kolbinger): no showstopper for a distributed gas target and pointing towards high resolution detectors and compact tracker [3];

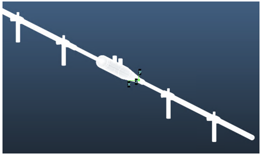


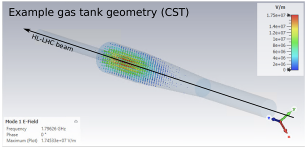


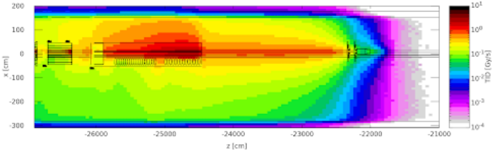
BGV design status - II

- Decision for a **TimePix hybrid pixel** detector based **tracker** (collaboration with Oxford University: D. Hynds and R. Plackett ⏩ pictures);
- **Read-out** mock-up [4] proposed by H Sandberg, based on the BGI system;
- **Gas tank** and neighbouring chambers shape, to optimise the tracker acceptance and reduce impedance compared to the demonstrator structure;
- **Gas target** choice: (cf. next slides);
- Assessment of expected **radiations** levels ongoing (FLUKA simulations, D. Prelipcean) [5].









Gas target system

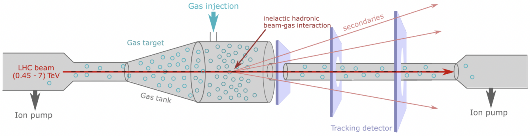
2 main options[1]:

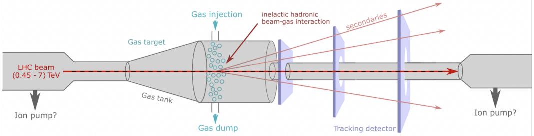
Distributed gas target [6]: **extended pressure bump**

- $\Delta z \approx 1\,\mathrm{m}$
- $P_{distrib.} \sim 10^{-8} - 10^{-7}$ mbar;
  $\rho_{distrib.} \sim 10^{15}$ Ne/m^3

Gas jet target [7] : **localised pressure bump**

- $\Delta z \approx$ few cm or mm
- $P_{GJ} \sim 10^{-6} - 10^{-5}$ mbar;
  $\rho_{GJ} \sim 10^{17}$ Ne/m^3





- In terms of **performance**, simulations showed that a **localised target** would allow to use a higher fraction of beam-gas interaction events to achieve the desired vertex resolution.
- The gas jet option also focuses BG interactions in the acceptance zone, removing the unnecessary gas profile tails $\rightarrow$ less background and radiations.
- However, to limit the instrument **cost and complexity**, the **distributed target** will be proposed as a **baseline**, and **gas jet** option as an **upgrade** possibility, to enhance instrument performance if needed.

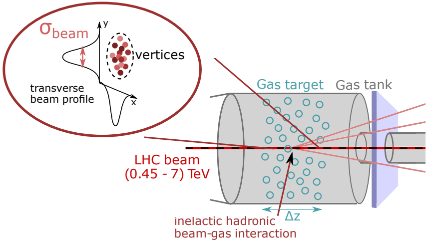
[1] Pressure and density values correspond to those required to achieve 1-2% of beam width measurement precision on maximum 2 min integration time

cf. backup

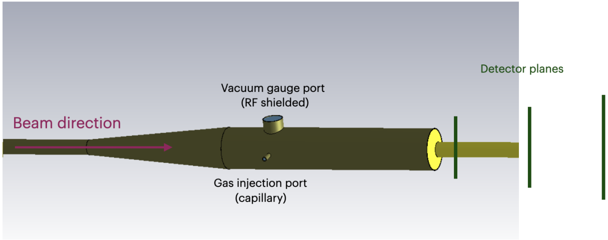
Zoom on the gas jet option

Homogeneity requirements for an **unbiased** beam **profile measurement**:

- Transversely, over few mm around the beam location
- Maximum acceptable $\frac{\Delta\rho}{\rho}$ is to be estimated
- Over the time scale of $\approx 1\ \mathrm{min}$ (measurement integration time),
- Confident knowledge of the transverse density profile (possibly measured)



The **gas tank** has to be shaped to host both a **distributed target** and a **gas jet target**, in compliance with **impedance** and **performance** constraints (as little material as possible on the path of secondary particles).



There should be no space constraint at the BGV locations to fit a gas jet system.

Vacuum simulations and design studies will be needed to finalise the design of a gas jet BGV.

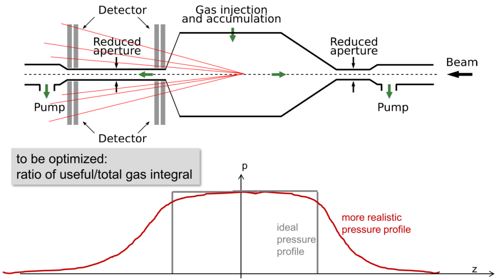
Summary

- Past years work focused on preparing a **design proposal** for the **future BGV instrument**, based on simulation studies and considering main integration aspects.
- Current activities consist of finalising remaining points and preparing a **Design Report** for this Summer. A **review** is foreseen later this year.
- In case the BGV is approved, it will likely be operated with a distributed target at first, and additional work will be required to study the possibility of implementing a gas jet target as an upgrade.

Thank you for your attention!

Back up

Demonstrator gas injection system



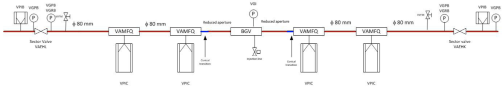


Figure 5: Schematic layout of the vacuum sector B7L4.R. The element at the center, labelled "BGV", represents the BGV gas tank. On its sides will be installed vacuum chambers with reduced diameter and two sets of VAMFQ vacuum assemblies housing the 500 l/s ionic pumps.

The chosen gas for the BGV demonstrator is Neon, as already used for the BGI in the LHC. The pressure inside the tank is fixed to about 6×10^{-8} mbar of Neon. Four 500 l/s ionic pumps will grant a sharp pressure decrease outside the tank and the averaged pressure in the B7L4.R vacuum sector will be in the 10^{-9} mbar range. At both extremities of the BGV tank, reduced-aperture beam vacuum chambers will help to confine the Neon gas in the tank. All the vacuum chambers and also the BGV tank will be NEG coated to reduce as much as possible any dynamic pressure increase due to synchrotron radiation, ion and electron induced desorption.

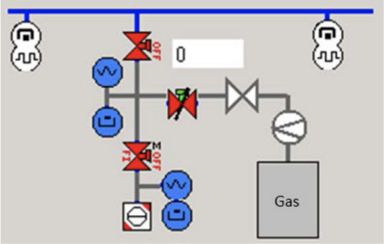
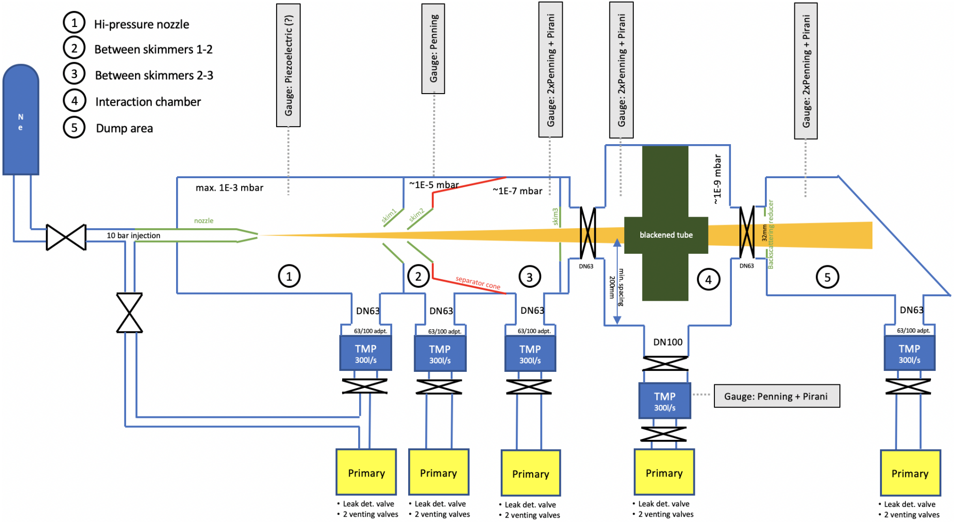


Figure 6: BGI Injection system as it appears in the PVSS application for remote control of the Neon injection. The same injection system will be used in the BGV tank.

(Figures from the BGV demonstrator ECR)

BGC gas injection system



(Scheme from Marton Ady, WP12 meeting 30/04/2020)

Collision rate

Inelastic collision rate:

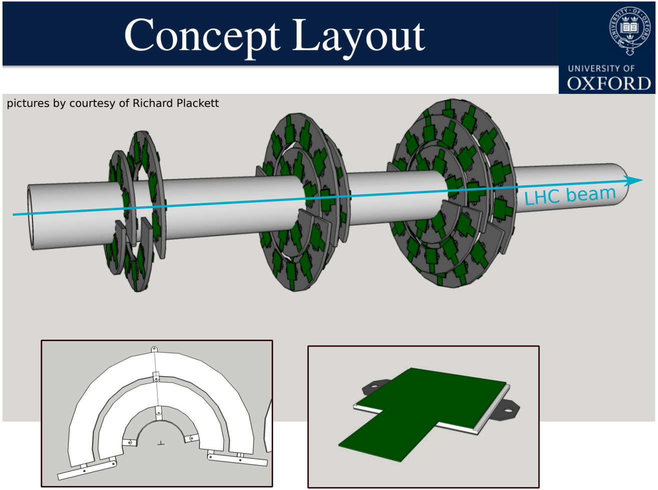
- The total **rate of inelastic beam-gas collisions per proton bunch**: $R_{\text{inel}} = f_{\text{rev}}\ N\ \sigma^{\text{inel}}_{\text{p-gas}}\ \rho_{\text{gas}}\ \Delta z$
- where $f_{\text{rev}} = 11245$ Hz (revolution frequency of the bunches), $N = 2.2 \times 10^{11}$ [8] the nominal number of protons per bunch, $\sigma^{\text{inel}}_{\text{p-gas}}$ the inelastic cross-section of the interaction (ranging from ≈240 mb to 300 mb between 450 GeV to 7 TeV), ρ_{gas} the gas density and Δz the length of the gas in the direction of the beam.
- Protons at an energy of {450, 7000} GeV, a neon gas with a pressure of 10^{-7} mbar and $\Delta z = 1$ m → $R_{\text{inel}} = \{147, 184\}$ Hz.
- Total, for 2760 bunches in the HL-LHC: $\{0.41, 0.51\} \times 10^6$ Hz.

Event rates based on generic BGV (preliminary):

- Generic BGV: accept events with a number of tracks above 5. Of 500 000 simulated initial collisions with a proton energy of {450, 7000} GeV, {69 %, 71.4 %} have a reconstructable vertex (at least 2 tracks registered) whereas {7.96 %, 17.1 %} show ≥ 5 tracks.
- → inelastic rate per bunch of {11.7, 31.4} Hz of useful events. For the whole LHC train, this would result into rates of $\{0.32, 0.87\} \times 10^5$ Hz.

(calculation from BGV tracker report, B. Kolbinger)

A BGV tracker based on silicon hybrid pixel detectors?

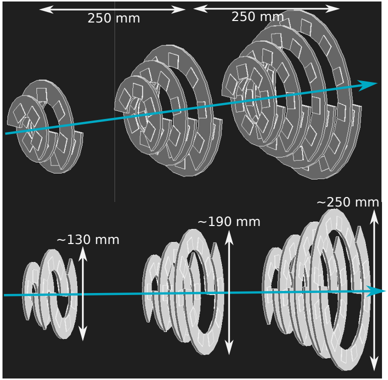


carbon fibre support

timepix4 chip + silicon sensor
(~25 mm x ~30 mm)

- Tracker proposal, based on Timepix4 hybrid pixel detectors, work in progress with University of Oxford.

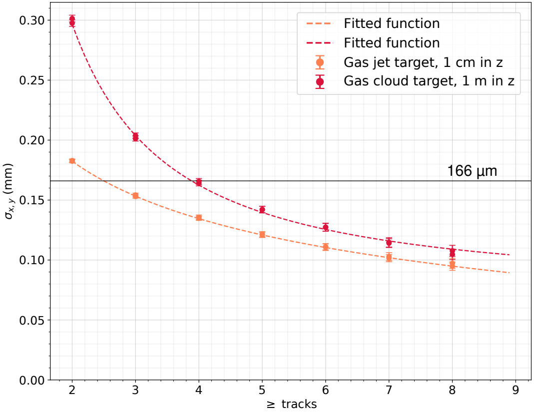
Preliminary Geant4 geometry:



(pictures from BGV HL-LHC 11th collaboration meeting presentation, B. Kolbinger)

Instrument performance comparing distributed and gas jet targets

Target **vertex resolution** $\sigma_{x,y}$ to match spec. beam size accuracy $\frac{\delta\sigma_{beam}}{\sigma_{beam}}$: $\sigma_{x,y} \leq 166\,\mu\text{m}$



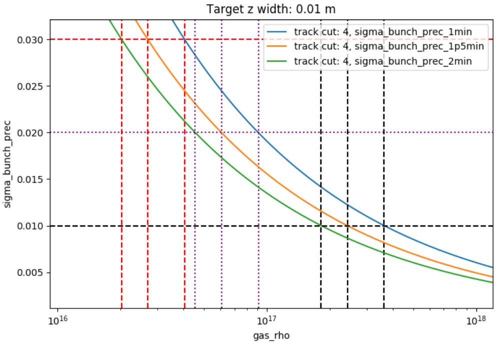
Vertex resolution vs. number of tracks per event, for different gas targets, assuming the same integrated density (Courtesy B. Kolbinger)

Achievable for events with:

- $\geq$ 4 tracks in the case of 1 m long gas target $\rightarrow$ 30% of beam-gas interactions
- $\geq$ 3 tracks in the case of 1 cm long target $\rightarrow$ 44% of beam-gas interactions (37% of those in the tracker acceptance)

$\Rightarrow$ A thinner gas target allow to use a larger fraction of the total events to reach the desired beam size accuracy

Gas density requirements for a $\Delta z \approx 1\ \mathrm{cm}$ spread gas jet target

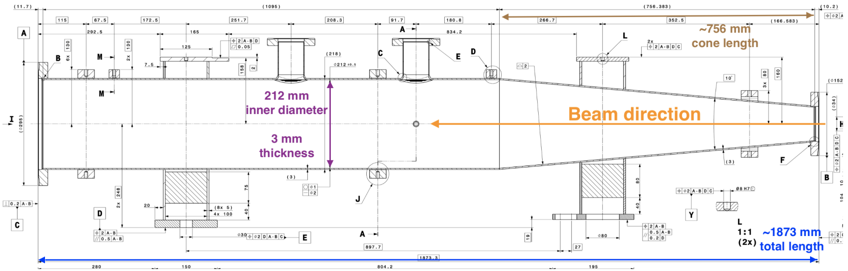


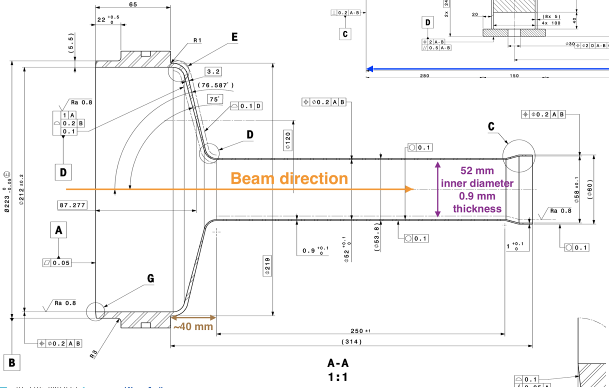
Density requirements for a $\Delta z = 1\ \mathrm{cm}$ gas jet target:

- in the order of $10^{17}\ \mathrm{Ne/m^3}$ to achieve 1% precision for a $1\ \mathrm{cm}$ long gas target (black vertical lines),
- from 2% precision (red and pink lines), the required density gets closer to the BGC values ($10^{16}\ \mathrm{Ne/m^3}$)

← Bunch-by-bunch average precision vs. target gas density for different integration times ($\Delta z = 1\ \mathrm{cm}$ long target, cut on events with $\geq$ 4 tracks (Courtesy B. Kolbinger)

Demonstrator tank

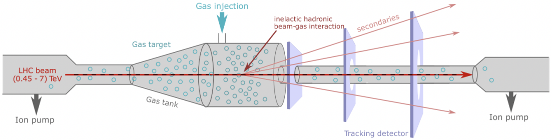




Gas target and tank shape

For instrument simplicity and cost reduction: distributed target as baseline (compliant with performance needs and discussed with R. Kersevan in Feb. 2022)

- Gas injection on the tank via a capillary ("cell" storing the gas)
- Restricted aperture sections on both sides
- 2 ion pumps upstream and downstream



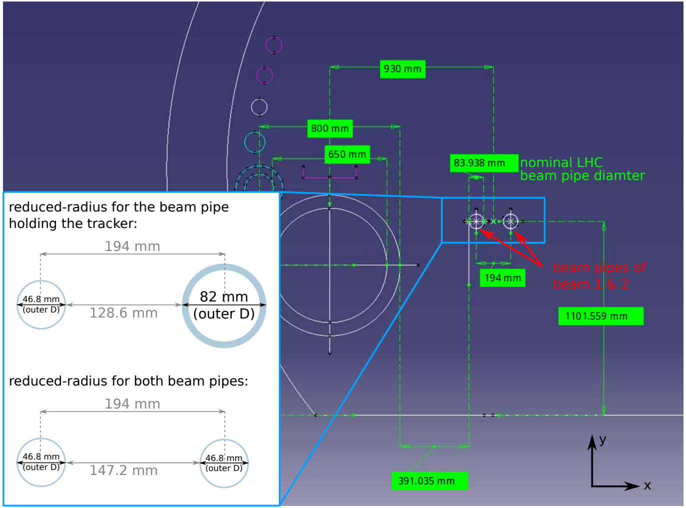
The future instrument geometry is being shaped to host a distributed gas target similarly to the demonstrator, balancing between integration and performance needs. Compared to the demonstrator (see EDMS folder with mechanical drawings), it has:

- Smaller tank diameter (212mm to 130mm ID), shorter central part (2003 to 1188 mm)
- Smaller diameter and shorter restricted aperture sections (52mm to 45mm ID)
- Exit window foreseen to be similar (Al alloy, 75 angle and thickness gradient from 3.2 down to 0.9 mm, possibly thinning down the outer 3.2 mmpart)

	restricted ap. section	up. taper	tank	exit window	restricted ap. section
Demonstrator ID	52mm ID		212mm ID		52mm + 58mm ID
Demonstrator length	1108mm	813mm	1150mm	40mm	250mm+925mm
Future BGV ID	45mm		130mm		45mm
Future BGV length	500mm (or shorter)	477mm	700mm	11.4mm	700mm

Location and space constraints

- Space reserved for BGV at Long Straight Section 4.
- One of the two future BGV devices is foreseen to be at the same location as the BGV demonstrator.



References

[1] A. Alexopoulos et al. "Noninvasive LHC transverse beam size measurement using inelastic beam-gas interactions". In: *Physical Review Accelerators and Beams* 22.4 (2019), p. 042801. DOI: 10.1103/PhysRevAccelBeams.22.042801.

[2] Maxin Titov and Leszek Ropelewski. "LHC Beam Size Measurement Review 2019". URL: https://indico.cern.ch/event/837340/.

[3] B. Kolbinger et al. "The HL-LHC Beam Gas Vertex Monitor - Performance and Design Optimisation using Simulations". In: *presented at the 10th International Beam Instrumentation Conf. (IBIC'21)* (Pohang, Korea). JACoW Publishing, 2021.

[4] Hampus Sandberg. "BGV Readout Mockup". EDMS no 2677605. URL: https://edms.cern.ch/document/2677605/.

[5] Daniel Prelipcean. "BGV beam-gas collisions at IR4 and related radiation levels and heat loads". February 2022. URL: https://edms.cern.ch/ui/file/2698515/1/22_02_17_TCC_-_BGV_Beam_gas_collisions_at_IR4_and_related_heat_loads_on_cryo_system_16x9_pptx_cpdf.pdf.

[6] Benedikt Wurkner. "Measurement of the LHC beam profile using the Beam Gas Vertex detector". 2019. URL: https://cds.cern.ch/record/2702690.

[7] Raymond Veness et al. "Development of a Beam-Gas Curtain Profile Monitor for the High Luminosity Upgrade of the LHC". In: (2019), WEPB16. 5 p. DOI: 10.18429/JACoW-IBIC2018-WEPB16. URL: https://cds.cern.ch/record/2716030.

[8] O. Aberle et al. *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN Yellow Reports: Monographs. Geneva: CERN, 2020. DOI: 10.23731/CYRM-2020-0010.