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PERFORMANCE OF THE BEAM GAS CURTAIN AS EMITTANCE MONITOR AT THE LARGE HADRON COLLIDER

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Abstract

The Beam Gas Curtain (BGC) is an instrument for transverse diagnostics in operation at the Large Hadron Collider (LHC). The transverse beam profile is obtained by imaging the fluorescence light resulting from the interaction between the beam and a thin supersonic neon gas jet. This technique can provide minimally invasive and absolute measurements of LHC high-intensity beams, throughout the full machine cycle. It is therefore a potential candidate to complement the limitations of existing LHC transverse diagnostic systems. This contribution highlights the results obtained during the ongoing LHC Run 3. The instrument configuration has been optimized for best performance by combining observations in two spectral ranges of the fluorescence signal: a yellow range, originating from the fluorescence of neutral neon atoms, and a UV range, emitted by ionic neon species. The measurements show good agreement with other profile monitors and enable real-time tracking of the average beam emittance during LHC physics fills. Finally, an overview of planned upgrades is presented, aimed at further improving system performance and progressing towards a fully operational instrument.

INTRODUCTION

Accurate monitoring of the transverse emittance of circulating particle beams is a key requirement for the operation of accelerators. At the Large Hadron Collider (LHC), transverse diagnostics are provided by two operational devices: wire scanners (BWSs) and synchrotron radiation telescopes (BSRTs). The BWSs serve as the reference instruments for absolute beam size measurements; however, being interceptive devices, their use is restricted to low-intensity beams [1]. The BSRTs offer non-invasive diagnostics and are employed for continuous emittance monitoring in regular operation. However, BSRT performance is constrained by its diffraction-limited regime, and regular calibrations against the BWSs are necessary to preserve its accuracy [2]. Moreover, BSRT measurements are not reliable during the energy ramp, due to characteristics of its synchrotron radiation source. In addition to the diagnostics provided by beam instrumentation, luminosity scans performed at the two main LHC Interaction Points, IP1 (ATLAS) and IP5 (CMS), are also available to estimate the transverse beam distribution and offer an independent reference for the average emittance of the two colliding beams [3]. However, since luminosity scans interrupt regular data-taking, they are performed only occasionally.

An instrument capable of providing a reliable, real-time, and absolute measurement of the average beam emittance during high-intensity operation would be valuable for overcoming the limitations of existing diagnostics. The Beam Gas Curtain (BGC) is a Beam Induced Fluorescence (BIF) monitor that is currently under investigation for this purpose [4]. The instrument generates a thin supersonic jet of neon that intercepts the particle beam. The beam–jet interaction produces fluorescence light, which is collected by an imaging system to assess the transverse beam distribution.

BEAM IMAGE FORMATION

The operating principle of the BGC is illustrated in Fig. 1. A gas jet, rotated by 45°, intercepts the beam, and the resulting BIF photons generated in the interaction region (highlighted in yellow) are focused by a lens and detected with an intensified camera.

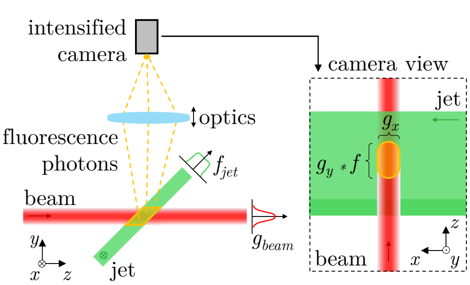

Figure 1: Schematic of beam-image formation in the BGC.

Assuming a Gaussian horizontal beam distribution g_x, the horizontal beam emittance can be immediately obtained from the measured image size σ_{meas} by accounting for the magnification M and an optical resolution term σ_{res}

$$\varepsilon = \frac{\gamma}{\beta}\sigma^2 = \frac{\gamma}{\beta}\left(\frac{\sigma^2_{\text{meas}}}{M^2} - \sigma^2_{\text{res}}\right), \qquad (1)$$

where γ is the beam relativistic factor, β the betatron function, and the dispersion contribution is neglected.

In the vertical direction, the jet density profile f_{jet} must be taken into account, since the profile of the interaction region is given by the convolution $g_y * f_{\text{jet}}$, being g_y the vertical beam distribution. The jet profile can be approximated by an almost constant plateau with Gaussian-decaying edges. The plateau width is a design parameter, determined by the

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geometry of the skimmers that collimate the jet [5]. A thicker jet improves the signal-to-noise ratio but reduces vertical resolution, while a thinner jet provides better resolution at the cost of signal intensity. The current design is optimized to suppress the central plateau and produce an approximately Gaussian jet profile with $\sigma_{\mathrm{jet}} \approx 200\,\mu\mathrm{m}$. This also simplifies vertical beam size retrieval: assuming Gaussian profiles for both beam and jet, the convolution $g_y * f_{\mathrm{jet}}$ is also Gaussian with variance $\sigma_y^2 + (\sqrt{2}\sigma_{\mathrm{jet}})^2$, where the $\sqrt{2}$ factor stems from the 45° jet angle. The vertical emittance can still be computed using Eq. 1, with the jet thickness included in σ_{res} as an additional resolution term.

VISIBLE AND UV CONFIGURATIONS

Beam-induced fluorescence of neon occurs primarily in two regions of the optical spectrum [6,7], as shown in Fig. 2.

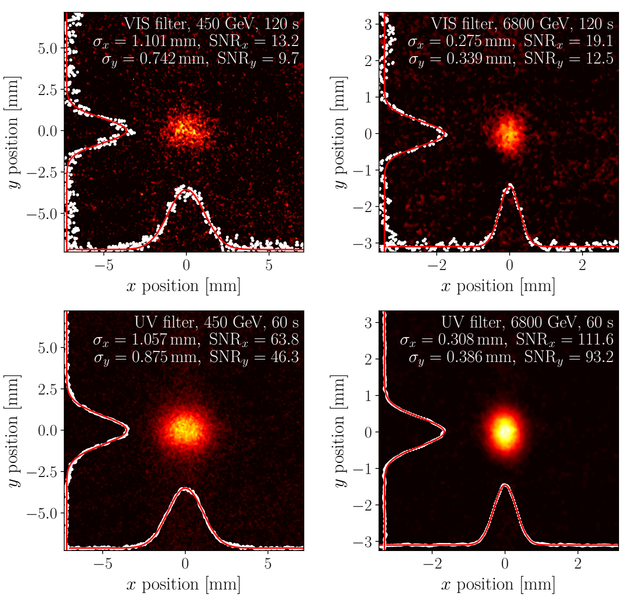

Figure 2: Samples of typical BGC images from a fill with 4×10^{14} protons. The top row shows images of the visible configuration at injection and flat-top energy with 120 s integration. Below, images in the UV configuration with 60 s integration. Profiles are overlaid with their Gaussian fits.

A visible line at 585 nm is emitted by excitation of neutral Ne atoms, with a lifetime of 16 ns. The neutral transition and short decay time ensure negligible spatial-resolution degradation from the drift of the emitting species. In the visible configuration, the resolution correction is limited to the optics term, measured as a constant $\sigma_{\mathrm{res,VIS}} \approx 65\,\mu\mathrm{m}$. Exposures of a few minutes are required to achieve profiles with an acceptable signal-to-noise ratio $SNR \gtrsim 10$.

A second group of lines appears in the UV range, around 340 nm, originating from transitions of Ne^{+} ions, with the most prominent line having a lifetime of about 6 ns. The more intense UV emission, combined with a better sensitivity of the detector in this range, allows profiles with $SNR \gtrsim 50$ to be obtained in about one minute. However, the ionized neon is subject to space-charge effects that degrade the overall UV spatial resolution. The UV resolution has been experimentally assessed as $\sigma_{\mathrm{res,UV}} \approx 160\,\mu\mathrm{m}$, at a beam intensity of 3×10^{14} protons.

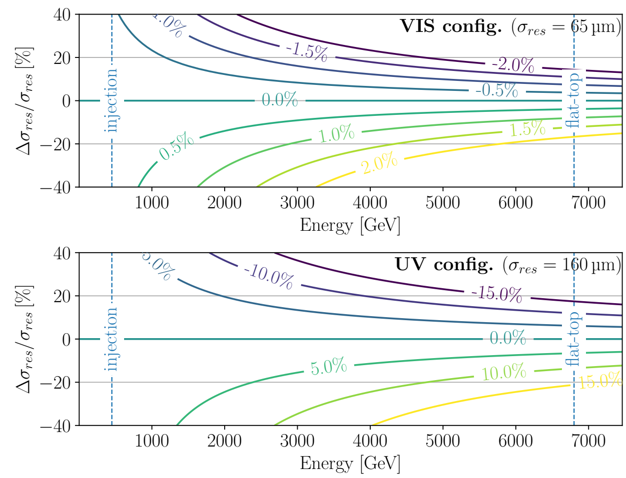

Figure 3: Emittance error $\Delta\varepsilon/\varepsilon$ as a function of the beam energy and the uncertainty on the resolution $\Delta\sigma_{\mathrm{res}}/\sigma_{\mathrm{res}}$, with typical resolution of VIS and UV configurations. Operational emittance of $\varepsilon = 2\,\mu\mathrm{m}$ and $\beta = 220$ m assumed.

The relative emittance error $\Delta\varepsilon/\varepsilon$ due to uncertainty in resolution $\Delta\sigma_{\mathrm{res}}/\sigma_{\mathrm{res}}$ can be derived from Eq. 1 as

$$\frac{\Delta\varepsilon}{\varepsilon} = -\left[2\frac{\Delta\sigma_{\mathrm{res}}}{\sigma_{\mathrm{res}}} + \left(\frac{\Delta\sigma_{\mathrm{res}}}{\sigma_{\mathrm{res}}}\right)^2\right]\left(\frac{\sigma_{\mathrm{res}}}{\sigma}\right)^2, \quad (2)$$

where σ_{res} and σ are the true resolution and beam size respectively. Figure 3 shows the impact of resolution uncertainty for the two configurations. In regular operation, the visible and UV configurations are used together to maximize signal strength while preserving the accuracy of the absolute emittance measurement. At 450 GeV, the brighter UV configuration is preferred, as the beams are sufficiently large for the emittance error to be minimally affected by uncertainties in the exact resolution. At 6800 GeV, beams become smaller, and uncertainties of 10 % in the UV resolution, such as those caused by space charge effects, can produce emittance errors exceeding 10 %, whereas the visible configuration remains much more accurate. A BGC self-calibration procedure was therefore introduced for flat-top operation, in which the BGC normally runs in UV mode to provide the best profiles, but its resolution is regularly corrected to match the size measured by the visible configuration, which is expected to be more reliable. The UV configuration is also employed during the energy ramp to provide as many measurement points as possible in this transient.

RESULTS

The BGC has been regularly operated since 2024 [8], and an example of emittance measurement throughout a regular physics fill is reported in Fig. 4.

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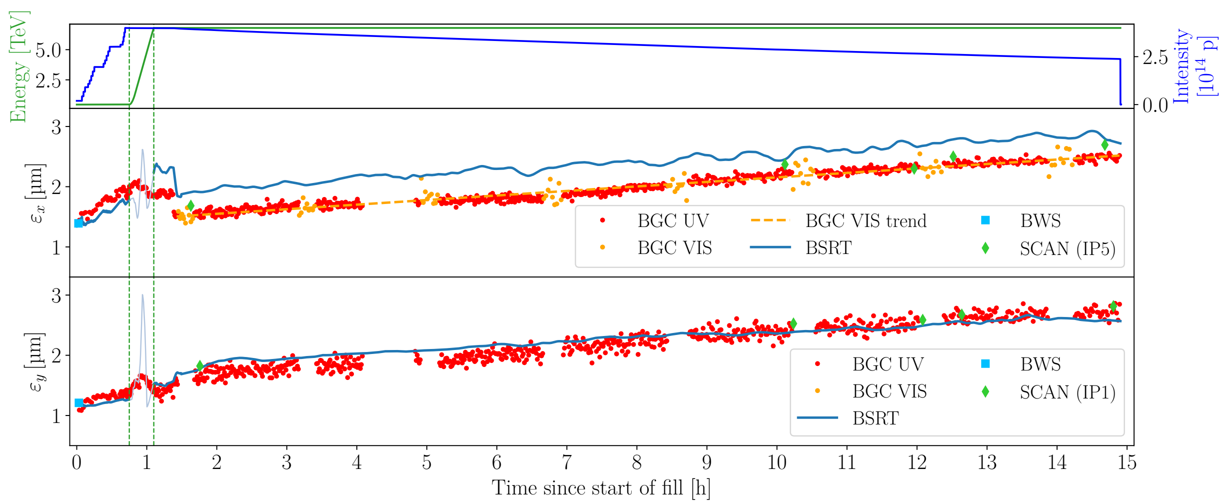

Figure 4: Emittance evolution during fill 10875 of the 2025 proton run, as measured by different systems. The top plot shows the beam energy and intensity. Below, the horizontal and vertical emittances. BGC measurements are compared with BWS scans acquired on the first injected bunches, BSRT measurements at injection and flat-top energies, and estimates from luminosity scans performed while in collision.

At 450 GeV, the horizontal and vertical emittances measured by the BGC agree within the 10 % target required for operation [9], matching both BWS and BSRT measurements.

During the energy ramp, although no other diagnostics are available for comparison, the BGC provides a realistic emittance evolution for both planes. In contrast, BSRT measurements are affected by artifacts from variations in the synchrotron radiation source.

At 6800 GeV in the horizontal plane, the combination of visible and UV measurements enables accurate tracking of the emittance evolution. The quantitative agreement with luminosity scans demonstrates that the BGC self-calibration provides reliable absolute measurements. Although in this fill the BSRT suffers from a calibration drift that leads to an overestimation of the emittance, the relative trend remains consistent with the BGC. In particular, both instruments detect the sudden drop at 1.5 h from the start of the fill, caused by beta beating when the beams begin colliding, and report a consistent emittance growth throughout the stable-beams phase. This fill represents a typical case in which a reliable absolute emittance value could be used as an independent reference to correct the BSRT baseline, without subtracting machine time for a dedicated BSRT calibration fill.

At 6800 GeV in the vertical plane, high-quality profiles are necessary to accurately resolve the beam size, which becomes comparable to the jet thickness. Measurements from the visible configuration are too noisy, and the best results are obtained using UV profiles only. Instead of the self-calibration method used for the horizontal direction, a constant empirical correction of $\sigma_{\text{res}} \approx 300\,\mu\text{m}$ is applied, accounting for the jet thickness, the optical resolution, and the broadening due to space-charge effects. This correction is chosen to reproduce the measurements from luminosity scans and from the BSRT immediately after calibration. Since the vertical measurement therefore relies on a calibration against other diagnostics, investigations are ongoing to assess the long-term reproducibility of this correction factor, which is essential for reliable operation.

CONCLUSION AND OUTLOOK

The BGC can operate as an average emittance monitor at the LHC. In the present configuration, it provides absolute measurements throughout the full machine cycle for the horizontal direction, agreeing within the accuracy target of 10 % with other diagnostics. Absolute measurements are also achievable for the vertical plane at injection energy; however, the finite jet thickness limits the accuracy for small beam sizes at flat-top energies. In this case, an empirical correction is required to obtain consistent values.

The ongoing LHC run will continue until mid-2026, during which the BGC will operate regularly to collect statistics and assess the long-term reliability of both its measurements and the instrument. Tests with nitrogen injection, instead of neon, are planned to evaluate signal quality with a different gas species. In parallel, a new BGC design is being developed for the next run, featuring two independent optical lines to observe the two beam directions separately. This configuration intrinsically suppresses the jet-thickness contribution that currently affects the vertical plane and enables the self-calibration procedure to provide absolute measurements in both directions. With spatial resolution no longer limited by jet thickness, a thicker jet can be used to increase signal strength and reduce the integration time. If deployed, the BGC absolute average measurements could be combined with the BSRT relative bunch-by-bunch measurements to provide more robust transverse diagnostics for machine operation.

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