

Full-cycle, noninvasive emittance monitoring with the beam gas curtain monitor at the LHC

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The large energy range and high intensity of current hadron accelerators, such as the Large Hadron Collider (LHC) and its planned high-luminosity upgrade, pose great challenges to beam measurements. The Beam Gas Curtain presents an accurate, minimally invasive profile monitor with a large energy range for high-intensity beams, by exploiting fluorescence from a supersonic gas jet interacting with the accelerator particle beam. In this paper, we report for the first time the proton and lead ion beam transverse profile and emittance continuously measured throughout the whole LHC energy range.

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I. INTRODUCTION

The Large Hadron Collider (LHC) has been operational for over a decade, yielding groundbreaking discoveries, including the Higgs boson [1,2]. The success of these discoveries relied heavily on the smooth operation of the collider, which ensured sufficient integrated luminosity to achieve the required precision. Central to this operation are the beam profile and emittance monitors—key components of the LHC's beam instrumentation. These monitors are critical for maintaining and optimizing beam quality, as well as for preventing undesirable beam dumps.

Few beam profile monitors can be used for measuring the LHC beams due to the destructive beam power across all stages of operation. The high-luminosity upgrade of the LHC [3] even brings new challenges for such diagnostics, including the need for higher resolution and enhanced device safety. These challenges stem from the reduced beam emittance and increased beam intensity, which demand more precise and robust measurement methods.

Optical diffraction radiation [4–6] has been developed for the noninvasive measurement of the beam profile, but its application in the LHC remains prohibitive due to the difficulty and risk of operating small aperture slits in the high-intensity rings. A Beam Gas Ionization (BGI) monitor [7], previously

installed at the LHC, suffered from beam heating issues originating from beam coupling impedance and was eventually decommissioned. Emittance scans at each interaction point can measure the convoluted beam size and then emittance at varying energies and higher intensities; however, the measurements cannot decouple the measurement for both beams and have other resolution and accuracy limitations [8–11]. Most importantly, they cannot provide continuous measurements while the physics experiments are running at those detectors.

Synchrotron radiation (SR) is commonly used for beam profile measurement for most high-energy electron synchrotrons [12–14] and a handful of ultrahigh-energy proton synchrotrons [15,16]. Presently, continuous beam size measurements at the LHC rely on detecting synchrotron radiation in the visible spectrum, using the Beam Synchrotron Radiation Telescope (BSRT) [17]. The BSRT suffers from uncertain magnification and resolution due to the drift of the optical system with multiple mirrors and lenses, as well as the diffraction effect, where the point spread function (PSF) is comparable to the measured beam size. Regular calibration of the magnification and resolution for BSRT with another trustworthy device, such as wire scanners [18–20], is required. To avoid wire breakage [21,22], the wire scanners can only work with a maximum of 20%–25% and 6%–7% of an LHC beam with 3.2×10^{14} protons during injection and collision, respectively, and thus each BSRT calibration usually needs 4–8 h of dedicated beam time. Moreover, for the LHC, the source of synchrotron radiation is complex, evolving as the beam energy is ramping up. Photons are produced from a dedicated undulator at the injection energy of 450 GeV and from a dipole magnet for energies above 2 TeV. This transition introduces uncorrectable distortions of the measured signal during the ramping phase. For lead ion beams, the intensity of visible SR is too low at injection energy to be detected,

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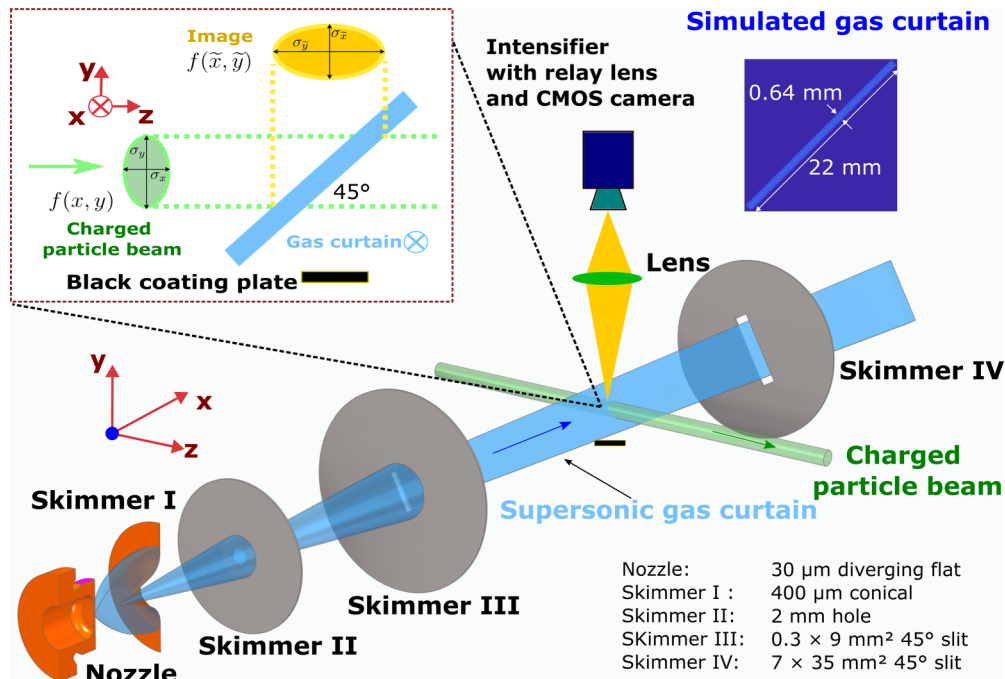


FIG. 1. The measurement principle, gas curtain formation, and gas jet density distribution.

becoming measurable only toward the end of the energy ramp. Due to the tight schedule for the ion run, the calibration is normally impossible.

We report in this paper on the first beam imaging measurements with the LHC beams (both proton and lead ion) using a Beam Gas Curtain (BGC) monitor. The main advantage of the BGC is that it can accurately and independently measure the absolute transverse beam profiles during the full cycle of the LHC operation, including beam injection, energy ramp-up, and flat-top energy stage, for both protons and ions with negligible effects on the LHC machine performance. The BGC relies on the fluorescence from the interaction between the beam and a supersonic gas sheet that we refer to as a “curtain” due to its thin and flat shape. Gas jets or curtains used in diagnostics were proposed before [23–25], and some tests have been performed in low-energy and low-intensity machines [26–30]. However, the BGC monitor is the first gas-curtain-based profile monitor implemented for high-energy or high-intensity beams and successfully used daily in the control room, even with the LHC detectors turned on. It features no space-charge distortion, compared with other gas-based profile monitors [31] and a high resolution of $\sim 55 \mu\text{m}$.

II. WORKING PRINCIPLE OF BGC MONITOR

The working principle of the BGC monitor is illustrated in Fig. 1. The hadron beam and the supersonic neon curtain propagate perpendicularly. The curtain is oriented at 45° to allow a 2D transverse beam profile measurement. Atoms in the curtain are elevated to excited states by the beam-gas interaction, and when they return to the ground state, they emit fluorescent photons [32,33]. Neon, with a strong fluorescence line at 585.4 nm, was selected for this monitor due to its neutral emission and short lifetime of 16 ns. As a neutral emitter, it is unaffected by the space charge of the incident beam, and

the relatively large cross section ensures efficient detection. Nitrogen, emitting at 391 nm with a 60 ns lifetime, was also considered due to its potentially higher cross section, which allows for shorter integration times. However, the nitrogen emitter is ionized and thus susceptible to displacement by the beam’s space charge during its decay time [31], introducing a beam size uncertainty of up to 30%. The images of the fluorescent photons collected by an optical system at a solid angle with an optimized integration time were used to reconstruct the profile for the original beams. The optical system utilizes an apochromatic triplet lens, a $585 \pm 10 \text{ nm}$ optical bandpass filter to maximize the signal-to-noise (S/N) ratio, and an intensified camera system.

As shown in the enlarged part of Fig. 1, the detected beam distribution $f(\tilde{x}, \tilde{y})$ will be a convolution of the beam transverse distribution $f(x, y)$ and the gas curtain distribution. For a uniform gas curtain with a thickness of h , the detected distribution in the x axis $f(\tilde{x})$ equals the beam distribution $f(x)$. In the y axis, $f(\tilde{y})$ will be elongated due to the thickness of the gas curtain, and the real beam size can be corrected from the detected distribution as

$$\sigma_y = \sqrt{\sigma_{\tilde{y}}^2 - h^2/(12 \cos^2(\pi/4))}. \quad (1)$$

Later, we will use x, y to replace $\tilde{x}, \tilde{y}$ if not mentioned specifically. A multilayer sputtering-coated plate (shown as a black coating plate) with 0.2% reflectivity is attached underneath the interaction point to reduce the reflection of the background light, including synchrotron radiation and other stray photons reflected multiple times by the interior pipe surface.

The neon curtain was generated by a supersonic gas jet source. Neon gas with stagnation pressure of 6 bar flows through a $30 \mu\text{m}$ round diverging flat nozzle into a median vacuum region $\sim 5 \times 10^{-3} \text{ mbar}$ as a continuous supersonic gas jet is formed. The gas jet is then collimated by three

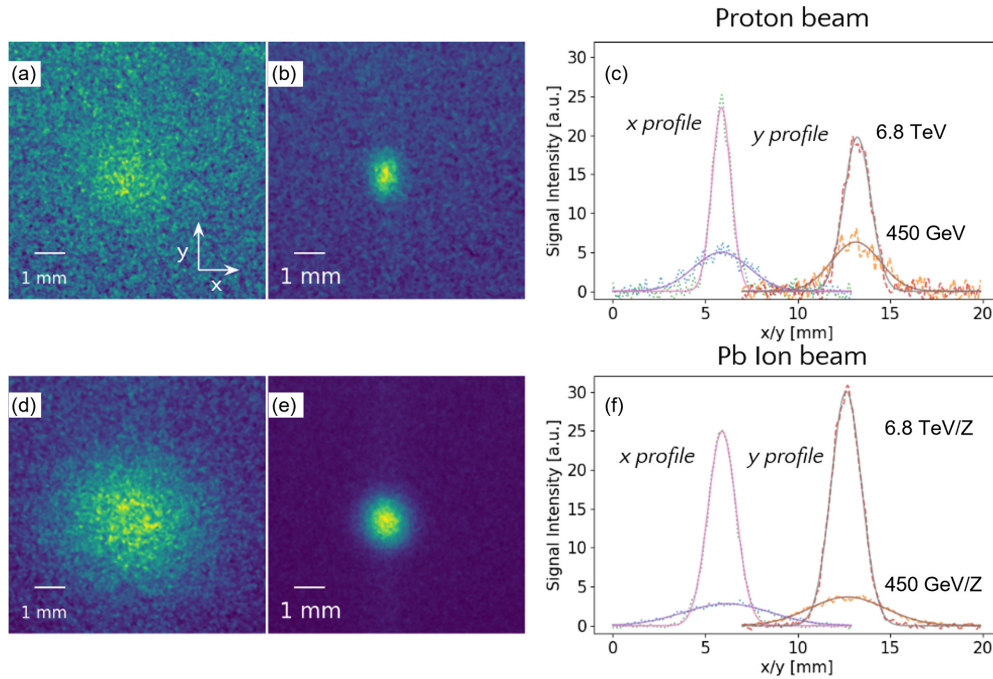


FIG. 2. Full-intensity LHC beams measured by the BGC monitor with 2 min integration time: proton beam (a) at the injection energy of 450 GeV with 3.35×10^{14} charges and (b) at flat-top energy of 6.8 TeV with 2.20×10^{14} ; lead ion beam (d) at the injection energy of 450 GeV/Z intensity of 1.52×10^{13} charges and (e) at flat-top energy of 6.8 TeV/Z intensity of 1.44×10^{13} charges, and the corresponding horizontal profile (left) and vertical profile (right) including Gaussian fits of the proton beam (c) and lead ion beam (f).

consecutive skimmers, a conical skimmer with a tip opening of $400 \mu\text{m}$, a round hole skimmer with a radius of 2 mm, and a slit skimmer with a size of $0.3 \text{ mm} \times 9 \text{ mm}$ orientated at 45° to create a gas curtain in the interaction point. At the entrance to the dump chamber a fourth slit skimmer with a size of $7 \text{ mm} \times 35 \text{ mm}$ and tilted 45° was used to reduce the backflow of the supersonic neon atoms back into the interaction chamber, preserving its vacuum quality. The four skimmers separate the vacuum area into five differential pumping regions, and each region is equipped with a turbo molecular pump to keep the pressure in the interaction within the strict vacuum requirement for the LHC operation. A complete set of simulations and measurements [34] was done to check the vacuum compatibility of this device with the LHC environment. Simulations show that a gas curtain with a quasiuniform distribution and a size of $0.64 \text{ mm} \times 22.0 \text{ mm}$ can be achieved. Direct measurements of a gas curtain at the interaction point showed a flat central area with $\pm 5\%$ peak-to-peak variations.

III. MEASUREMENTS OF LHC BEAMS

A. Beam profile measurements

Figure 2 presents typical BGC measurements, 2D pictures, and transverse profiles for protons and lead ions both at injection and collision energies. Pictures (a), (b), (d), and (e) were produced by stacking 2400 images, each with an exposure time of 50 ms. The exposure time was chosen to achieve the best S/N ratio by avoiding photocathode saturation. The total integration time for these pictures is 120 s. In the pictures, the gas curtain moves horizontally from left to right, while the LHC beam travels vertically from bottom to top.

The measurements display significant differences in the background noise levels between each measured beam condition. The background noise arises from various sources, including photocathode dark counts, stray light within the beam pipe, reflected SR, and photoelectrons generated at the intensifier due to beam losses upstream of the instrument. As shown in Figs. 2(a)–2(f), the signal produced by the full-intensity lead ion beam has a higher S/N ratio compared to the proton beam due to lower SR and reduced background from beam losses. Additionally, when the S/N ratio is large enough, a faint signal from the interaction between the background gas and the beam can be observed, as seen in Fig. 2(e). Figures 2(c) and 2(f) display the horizontal and vertical profiles after the linear background has been removed.

The profiles were fitted with a Gaussian distribution to determine the beam sizes. The Gaussian shape assumption of the LHC transverse profile is typically sufficient for the desired precision of tens of micrometers. The primary sources of error in the beam size measurements arise from the system's PSF, the single-photon spot size from the intensifier, fitting error, the thickness of the gas curtain, and the fluctuation of the gas curtain density. Other potential sources of error, such as beam jitter and turn-to-turn position differences, can be considered negligible. Fitted beam sizes are corrected for systematic errors by subtracting in quadrature contributions from PSF and single-photon spot size, measured to be 45 ± 3 and $32 \pm 4 \mu\text{m}$, respectively. The gas curtain thickness introduces another source of systematic error, affecting only the vertical axis, as described in Eq. (1). Optimizing the gas curtain thickness involves balancing the systematic error, signal strength, and impact on the vacuum. The third skimmer used at the LHC is 0.3 mm wide for measurements here and produces a

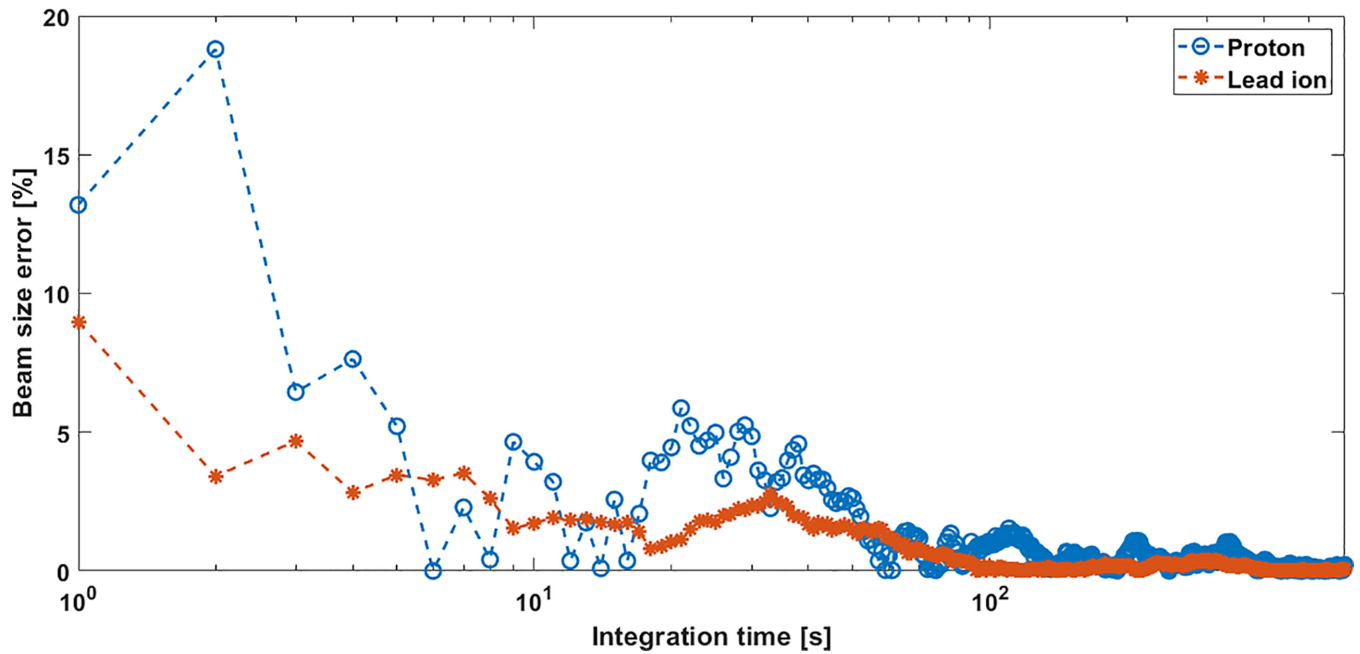


FIG. 3. Systematic studies of the relative beam size error dependency on integration time, based on measurements of LHC beams at top energy and full intensity using the BGC monitor.

0.64-mm-thick gas curtain at the interaction point with peak-to-peak fluctuations of $\pm 5\%$ in the central area. According to simulations, the vertical beam size measurements can then be adjusted by applying a correction factor of $260\text{ }\mu\text{m}$. The use of a thick gas curtain initially allows the high signal level to compensate for a possibly overestimated fluorescence cross section, which is currently extrapolated by six orders of magnitude from the available data. A new third skimmer with a 0.2-mm-wide slit is currently installed to achieve better resolution in the y plane.

A systematic study was conducted to characterize the monitor's precision by examining the dependency of the beam size error for both proton and lead ion beams on the integration time. Figure 3 illustrates the relative statistical beam size uncertainty of LHC beams at full intensity and top energy. The beam size error is defined as the percentage ratio of the variation from the true size with a given interaction time and the true size. The true size is regarded as a mean value with longer integration times from 400 to 600 s. For proton beams with an intensity of 3.79×10^{14} charges, an integration time of 60 s is sufficient to achieve approximately a 5% beam size error. In comparison, the lead ion beam with an intensity of 2.42×10^{13} charges requires only about 5 s of integration time to reach a beam size error of approximately 3.5% due to its higher signal-to-noise ratio. At injection energy of 450 GeV/Z, the lead ion beam requires 20–30 s of integration time to reach $\leq 5\%$ error due to its larger transverse beam size.

B. Emittance validation

The performance of the BGC monitor can be evaluated by comparing the measurements to other existing methods in the LHC. However, the beam size measurement cannot be directly compared between instruments due to the different locations.

In a given machine with a known beta function β , the transverse beam size measurements σ can be used to calculate the transverse emittance ϵ using the following equation:

$$\epsilon = \gamma \cdot \sigma^2 / \beta, \quad (2)$$

where γ is the Lorentz gamma factor. According to Liouville's theorem, the emittance remains constant under conservative forces, and measurements done at different locations in the LHC, such as the BSRT and the emittance scans at the CMS and the ATLAS experiments, can thus be compared. Meanwhile, emittance is a key beam quality parameter that should be continuously monitored and analyzed to ensure optimal machine performance.

Figure 4 compares the BGC emittance measurements over the entire LHC beam fills with BSRT measurements and a limited number of emittance scans at the interaction points. The purple square and orange circle represent the beam size and the emittance measured by the BGC monitor with a 120 s integration time for the proton beam and 40 s for the lead ion beam, separately. Systematic errors related to the PSF and photon size were subtracted from the Gaussian-fitted beam sizes. As illustrated earlier in Fig. 2, a lower S/N ratio occurs during the beam injection process when the beam intensity is low and the beam size is large. However, the overall measurement uncertainty decreases as the beam intensity increases during injection and the beam size reduces during acceleration. The emittance rises slowly during injection due to the intrabeam scattering effect [35]. At the injection stage, there are no emittance measurements available from other methods for the lead ion beam or the measurement is far off due to the calibration issue, such as the BSRT measurements for the proton beam.

The beam size will continuously reduce while the energy ramps up, as measured only by the BGC monitor for both

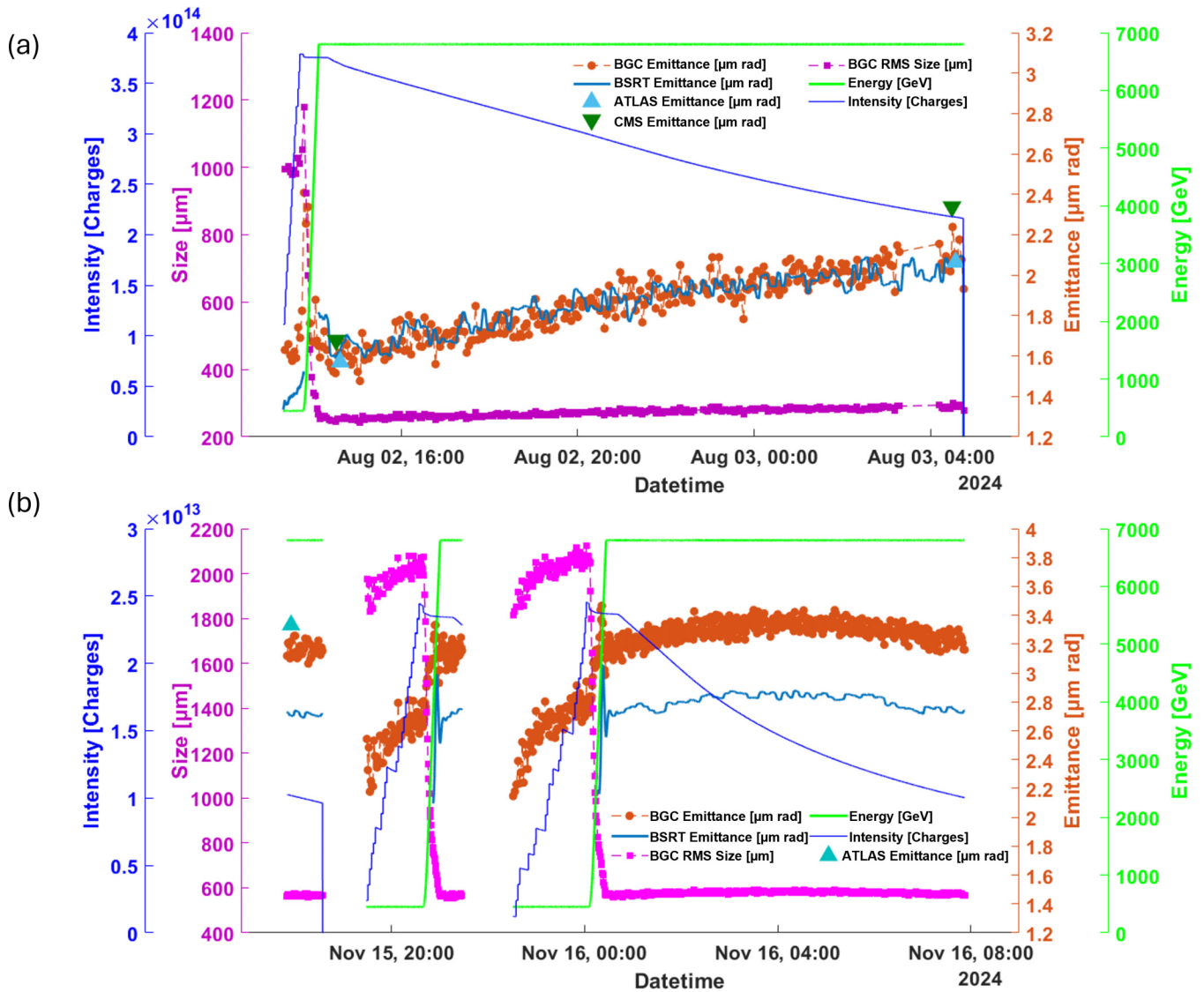


FIG. 4. Horizontal emittance measurements from the BGC monitor for (a) the LHC proton beam (120 s integration time) and (b) the lead ion beam (40 s integration time), and BSRT, ATLAS, and CMS emittance scan along with beam energy, beam intensity, and beam size measured by the BGC monitor. The data (~ 14 h) cover a full proton beam fill and several lead ion fills, from injection through energy ramp-up to beam collisions and beam dump. The statistical uncertainty from beam size is below 10% at collision energy.

beams. There is an artifact spike for proton beam emittance data in the energy ramping-up process due to the emittance calculated from Eq. (2) using average beam size and average energy with limited data points. The long integration time chosen here is due to a reduced S/N ratio from a sudden rise in the background due to beam losses and synchrotron radiation for the proton beam measurement. This spike is not visible from the lead ion data with a shorter integration time and thus more data points. At the end of the energy ramping up, the spike visible both at BGC and BSRT is typically caused by the change of the beta function from the nominal value due to optics tuning.

Throughout the collision stage of the proton beam fill, the BGC measurements align with the calibrated BSRT measurements within the 10% error, tracking the gradual rise in emittance. The BGC measurements also agree with the emittance scans at the interaction points of both ATLAS and CMS

at the beginning of the collisions, maintaining a consistency of approximately 10% for both the BGC and the experiments. At the end of the fill, additional emittance scans were conducted, showing continued agreement between the BGC and the ATLAS within their errors. Although CMS recorded a visibly larger value, it remained within its 10% error margin from BGC measurements. This agreement was repeatable across different fills during the 2024 proton run, as shown in Fig. 5.

During the short lead ion run in 2023 and 2024, the measurement from the BGC monitor was also compared to the very limited data of the emittance scans, revealing repeatable agreement within the 10% uncertainty for the full-intensity 6.8 TeV/Z lead ion LHC beam. Note that the BSRT for lead ion fills was not calibrated due to the short period of the ion run. Therefore, the measurement from it can be used only as a

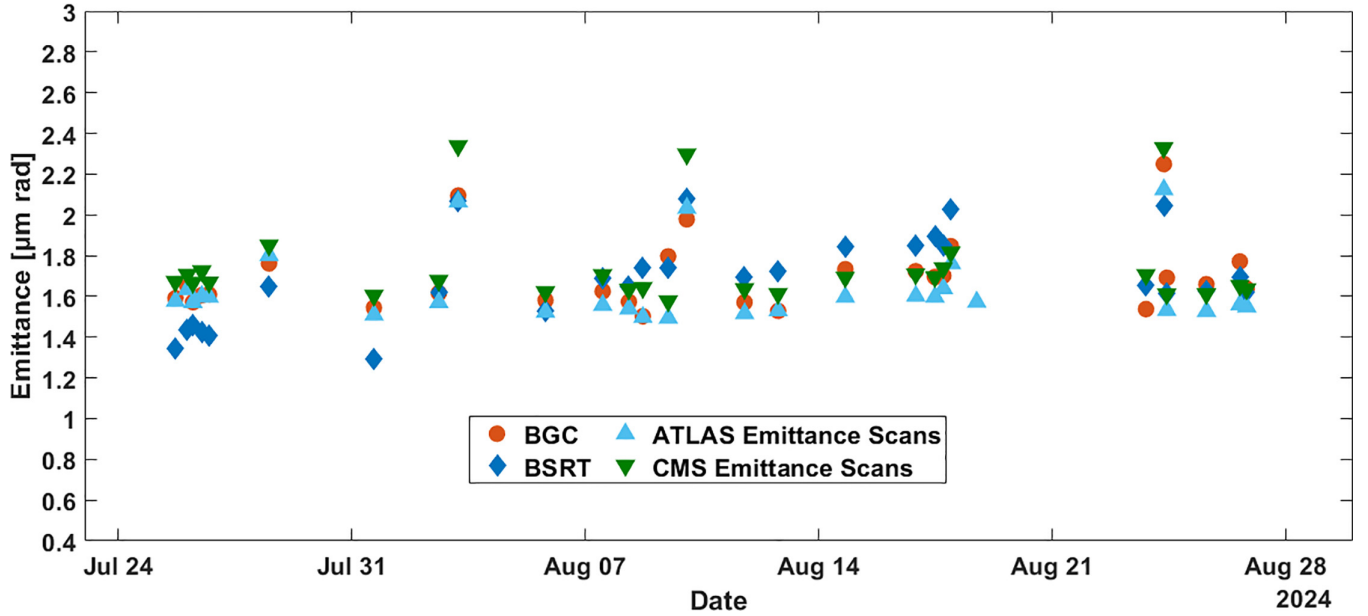


FIG. 5. Comparison of emittance measured from the BGC, BSRT, ATLAS, and CMS for the LHC proton beams.

relative comparison, which shows a similar trend to the BGC monitor. This leaves the BGC monitor as the only continuous emittance monitor during the ion run.

As a conclusion, this provides strong evidence for the accuracy of the BGC monitor, as the matched measurements from the BSRT and emittance scans were independent of the BGC. Furthermore, the stability of the BGC measurements was demonstrated by consistent agreement across various beam intensities, fills, and particle species, including both the proton and lead ion beams.

IV. CONCLUSIONS

In summary, we have reported on the Beam Gas Curtain monitor, a fluorescence-induced transverse profile monitor based on a supersonic neon gas curtain, and its first operation at the LHC for transverse profile and emittance measurement. This development directly addresses limitations of existing systems in LHC, such as the BSRT, wire scanners, and BGI monitors.

First, the BGC monitor provided absolute and independent measurements of the averaged transverse profile and emittance for the full-intensity LHC proton and ion beams. These beam parameters can also be measured continuously throughout the entire beam cycle, from injection at 450 GeV/Z, through the energy ramp-up, up to the flat-top energy of 6.8 TeV/Z and until the beam dump to cover a complete LHC fill for the lead ion beam. Such measurements were demonstrated for proton beam fills at the injection and collision energies as well. Second, the monitor's accuracy of absolute emittance measurements was demonstrated by comparisons with independent measurements from the BSRT and emittance scans at the ATLAS and CMS experiments, with results showing agreement within respective measurement errors. The stability of the monitor was further confirmed

by the repeatability of this agreement across different fills, intensities, and for both proton and lead ion beams. Last but not least, the BGC was optimized to meet the stringent LHC requirements for high vacuum quality, minimal beam disturbance, and other constraints. Validation tests demonstrated the monitor's minimally invasive properties, with LHC operators deeming the BGC effectively transparent to the beam. The monitor achieved approximately 3.5% error on transverse size measurements with a 5 s integration time for the full-intensity lead ion beam at 6.8 TeV/Z. For the full-intensity proton beam at collision energy, an integration time of 60–120 s was typically required to achieve a beam size error below 5%.

Due to the simplicity and robustness of the monitor and no requirement for repeated calibrations, it was quickly integrated into the LHC control system for daily operational usage. Ongoing advancements and optimizations will be made to further enhance the monitor's performance. Tests using nitrogen as a working gas, as well as exploring different fluorescence spectral peaks, are considered to be conducted at the LHC, with the potential to improve the S/N ratio and thus reduce the integration time. The optical system can also be refined to reduce radiation-induced background, a significant factor in proton beam measurements at the LHC. Additionally, adjustments to the gas curtain thickness by changing the skimmer geometry are considered to achieve the optimal balance of accuracy and S/N ratio.

The BGC design and usage of a supersonic gas curtain in ultrahigh-vacuum conditions show potential for other high-intensity, high-power facilities, including the Facility for Antiproton and Ion Research, the European Spallation Source, and the Electron Ion Collider. Adaptation to medical accelerators is also underway. Another promising direction under discussion is integrating the gas curtain with beam loss monitors, which could enable beam halo measurements.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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