SIMULATIONS OF SPACE-CHARGE AND GUIDING FIELDS EFFECTS ON THE PERFORMANCE OF GAS JET PROFILE MONITORING

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Abstract

Gas jet based profile monitors inject a usually curtain shaped gas jet across a charged particle beam and exploit the results of the minimally invasive beam-gas interaction to provide information about the beam's transversal profile. One such monitor will be installed as part of the High Luminosity LHC upgrade at CERN in the Hollow Electron Lens (HEL). The HEL represents a new collimation stage in that it increases the diffusion rate of halo particles by placing a high intensity hollow electron beam concentrically around the LHC beam. The gas jet monitor will use the fluorescence radiation resulting due to the beam-gas interaction to create an image of the profiles of both hollow electron and LHC beams. In the case of a nitrogen curtain, the fluorescence of ionized nitrogen molecules is deployed due to its extremely high intensity. However, the high beam space-charge and strong guiding magnetic field of the electron beam cause significant displacements of the ionized molecules and thus image distortions. This work presents preliminary simulation results showing expected fluorescence images of the hollow electron profile as affected by space-charge and guiding fields using simulation tools such as IPMsim. The influence of the estimated electron beam and gas jet curtain parameters are investigated.

INTRODUCTION

During Long Shutdown 3 (LS3) the Large Hadron Collider will undergo the major High Luminosity (HL-LHC) [1] upgrade, which will include many new technologies including novel beam diagnostics.

Hollow Electron Lens (HEL) [2] will be part of the collimation upgrade aiming at removing the halo particles due to the higher stored beam energy per beam in the HL-LHC [3]. The HEL guides an magnetically confined hollow, low-energy, high-current, electron beam concentrically around the LHC beam. Doing so allows the HEL to actively control the diffusion speed of halo particles of the LHC beam and thus boost the performance of the existing collimation system [4].

To prevent unwanted losses it is important to constantly monitor both the electron and proton beam to ensure that they are indeed concentric at all times [4]. Such monitor will require the measurement to be non-invasive or minimally invasive due to the high HL-LHC beam power and strong magnetic guiding field.

A gas jet monitor exploiting fluorescence is therefore well suited for such environment and is foreseen to be installed at the HEL system for monitoring the beams' concentricity and transverse distributions [5,6]. The monitor [6–9] inserts a supersonic gas curtain into the path of the beams at 45° to observe the 2D transverse distributions from above as shown on Fig. 1.

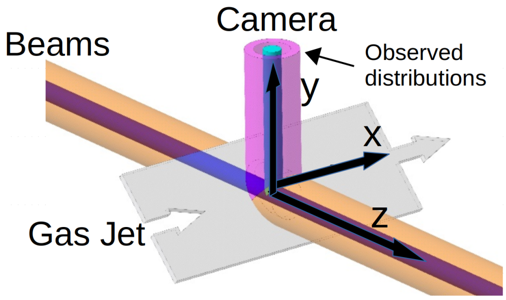

Figure 1: Gas Jet monitor principle outline and coordinate system [10].

The beam excites and ionizes the gas molecules through collisions while it is traversing the gas curtain. In case of nitrogen excited molecular ions are the most prominent fluorescence source. After excitation it takes some time [5, 6] until the molecules de-excite and emit fluorescence photons. During this time they move in the presence of external fields and are displaced from the position at which excitation happened. This displacement may have a significant effect on the final image [5, 11]. Moreover, due to the gas curtain being at 45° both with respect to the beams' axis and the optical axis of the imaging system the thickness of the gas curtain will broaden the observed distribution [11]. In this paper, the gas movement in the fields and their effects on the image are studied altogether with the effect of the thickness.

METHODS

The two the mentioned effects are entangled because the gas distribution causing the broadening also determines the initial positions (and velocities) of the excited gas molecules. These initial parameters are very important as the molecules' dynamics is sensitive to them due to the surrounding magnetic and electric fields.

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A script was written to calculate the initial parameters of the gas molecules from both the gas and beam distributions considering. It takes into account the angle and thickness of the gas curtain. The excited molecules's position and velocity was then directly imported into the IPMsim code [12, 13] to simulate the molecules' movement in the fields. The beam electrostatic self-field was calculated from the beam parameters while the magnetic field was set to a constant value in the longitudinal (beam) direction.

The gas, beam and excited gas distributions were all normalized to obtain constant number of particles for the simulations. Therefore, the presented profiles reflect the shape rather than the intensity of a simulated image.

The Gas Jet monitor will be firstly installed for experiments at the Electron Beam Test Stand (EBTS) at CERN and then later at the LHC. Therefore, different settings of expected guiding magnetic field strength, beam current and beam profile were probed. Also, the effect of the beam profile broadening was observed for two different curtain thicknesses. And, two working gasses, neon and nitrogen were considered with the corresponding fluorescence wavelengths 337.8 nm and 391.4 nm, respectively. The presented parameters summarized in Table 1 are relevant for EBTS, and LHC. However, for the LHC case, an additional effect caused by the LHC beam was omitted but will be considered in future studies.

Table 1: Studied Parameters

Parameter	**Value**
Magnetic field	
	B = 4.0 T
	B = 0.2 T
Beam current	
	I = 5 A
	I = 1 A
Curtain Thickness	
	d = 3 mm
	d = 1 mm
Beam profiles	
	Homogeneous hollow ring
	Skewed hollow ring
Working Gasses	
	Nitrogen
	Neon

RESULTS

Through out this paper the coordinate system is taken as: z - longitudinal, direction of the beam; x - horizontal, direction of the gas jet; and y - vertical, direction of the optical system as shown in Fig. 1.

For the calculations the gas distribution was considered to be homogeneous inside of the curtain boundaries. The initial distribution of excited gas molecules was then calculated using the beam distribution. An example of 3 mm thick gas curtain (top row), homogeneous hollow 5 A electron beam (middle row) and the calculated distribution (bottom row) is shown in Fig. 2. One can see that the observed y (vertical) projection of the calculated distribution is smeared by the thickness of the curtain while the longitudinal projection shows no such effect as expected.

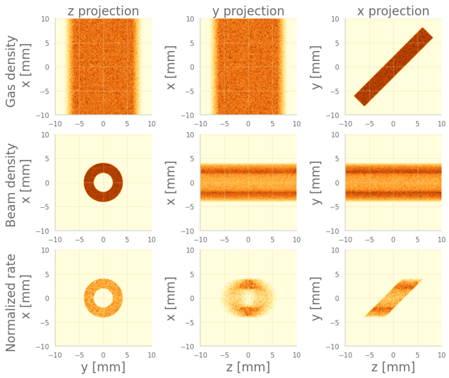

Figure 2: Example of the initial molecule parameters calculations (bottom row) from a homogeneous 3 mm thick gas curtain (top row) and 5 A homogeneous hollow electron beam (middle row).

It is, therefore, possible to compare the effects of the smearing (due to curtain thickness) and distortion (due to gas molecules' movement) by studying z (without smearing) and y (with smearing) projections. An example of simulated results using 1 mm thick nitrogen curtain, 5 A homogeneous hollow electron beam and 4 T longitudinal magnetic field is shown in Fig. 3.

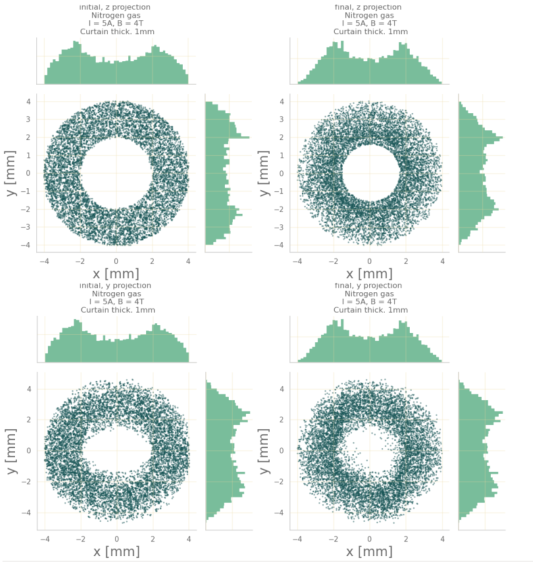

Figure 3: A showcase of studied effects: Top left - No smearing or distortion, Top right - Only distorted, Bottom left - only smeared, Bottom right - both smeared and distorted.

As can be observed when only the distortion is simulated the effect is rather visible and affects both vertical and horizontal distributions symmetrically. However, when coupled with the smearing the distortion becomes suppressed in the vertical distribution. At the same time the, horizontal distribution is unaffected by the smearing, as expected from the geometry, and the distortion effect is clearly visible.

The expected maximum values of magnetic field an beam current are 4 T and 5 A, respectively. However, the monitor will also be tested at the EBTS at lower magnetic fields and electron beam currents. The effects were, therefore, also studied at $B = 0.2$ T and $I = 1$ A. The comparison of the final distributions is shown in Fig. 4. The distortion at $B = 0.2$ T and $I = 5$ A is still pronounced although with slightly different characteristics, however, at $I = 1$ A the distortion is barely visible. This suggests that the beam current, and subsequent strength of its field, plays dominant role in the distortion with comparison to the magnetic field strength.

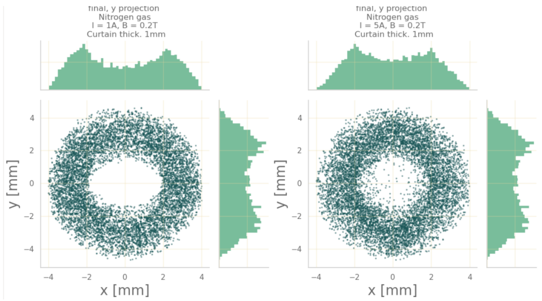

Figure 4: Results of simulations at $B = 0.2$ T and $I = 1$ A (left) and $I = 5$ A (right).

One could use thicker gas curtain to possibly increase the final signal, however, in return the smearing effect will be also amplified. Results of simulation with 3 mm thick gas curtain are shown in Fig. 5. It is visible that with 3 mm curtain thickness the distribution is significantly smeared, however, the centre can still be identified.

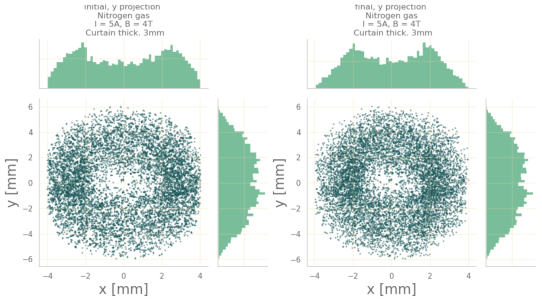

Figure 5: Results of simulations with 3 mm thick gas curtain. Initial (left) and final (right) positions of the excited gas molecules.

The expected beam profile from the hollow electron gun is not necessary homogeneous as measurements suggests [14]. A profile, called in this work a *Skewed hollow ring*, based on the measured profile shape has been used in the simulations to observe. This profile (left) and the results of its smearing and distorting are presented in Fig. 6 (right).

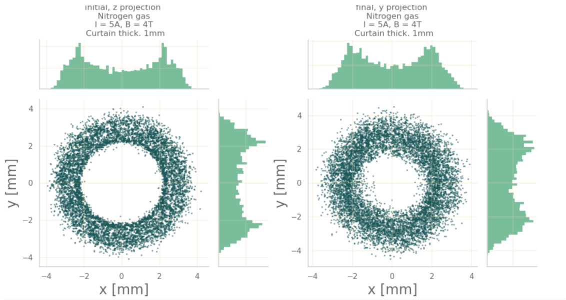

Figure 6: Results of simulations with a skewed hollow electron profile. Initial (left) and simulated - distorted and smeared (right) distributions

Simulations using neon ion, with florescent wavelength 337.8 nm, were also studied as neon is still one of the considered possibilities for the working gas. The results, depicted in Fig. 7, show minimal distortion due to the lower expected time-life of 11 ns [5], while the smearing is independent of the gas as expected.

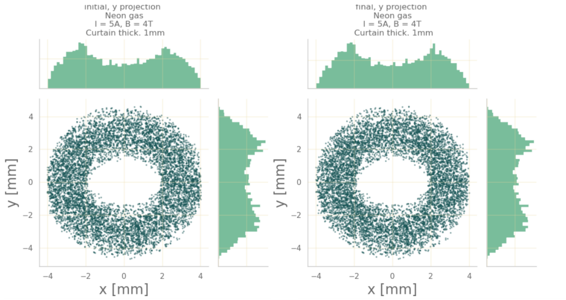

Figure 7: Smeared neon distribution (left) and simulated - distorted and smeared (right) distributions.

CONCLUSIONS

Simulations of fluorescence image of hollow electron profile were set up and carried out studying the smearing and distorting effects on the image due to gas curtain thickness and excited gas molecule movement. The simulations showed that the smearing effect dominates over the distortion in the horizontal distribution. At the same time, for the gas curtain thinner than 1 mm the smearing seems not to disturb the profile greatly. In the case that it would be beneficial to use thicker gas curtain for increased signal the symmetry should still allow the centre to be identified. However, if the profile would also be of an importance a reconstruction of the profile would be needed which would require a future investigation.

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