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NON-INVASIVE BEAM PROFILE MONITORING FOR THE HL-LHC HOLLOW ELECTRON LENS

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Abstract

A Hollow Electron Lens (HEL) is currently under development for the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC). In this device, a hollow electron beam co-propagates with a central proton beam and provides active halo control in the LHC. To ensure the concentricity of the two beams, a non-invasive diagnostic instrument is currently being commissioned. This instrument is a compact version of an existing prototype that leverages beam induced fluorescence with supersonic gas curtain technology. This contribution includes the design features of this version of the monitor, recent progress, and future plans for tests at the Cockcroft Institute and the electron lens test stand at CERN.

INTRODUCTION

The High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) aims at increasing the luminosity of the LHC by a factor of 10 beyond the original design value [1]. The beam losses in the accelerator are expected to increase with this increase in luminosity. Therefore, to ensure that daily operation is not affected and to protect the equipment within the LHC from these losses, a series of upgrades to the collimation system of the LHC is necessary.

An important part of these upgrades is a Hollow Electron Lens (HEL) [2] that surrounds the primary proton beam over a length of several meters. The core of the proton beam remains unaffected, yet the halo particles experience a smooth and controlled scraping. Superconducting solenoids are used in the HEL to maintain an electron current of 5 A at 10 keV beam energy.

A "Beam Gas Curtain" instrument (BGC) is currently under development in the framework of HL-LHC WP13 for beam diagnostic in the HEL. This monitor measures the position of the LHC proton beam by utilising beam induced fluorescence in a gas curtain following interaction with the proton beam.

A first prototype of this monitor type was successfully commissioned and tested at the Cockcroft Institute (CI) using a laboratory electron beam [3] in a collaboration between CERN, GSI and the University of Liverpool. The knowledge gained from this prototype monitor ultimately informed design and manufacturing of a second prototype currently being assembled at the CI. This paper first presents the concept of profile monitoring using a gas curtain, summarizes the design characteristics of the new instrument and describes experimental plans.

PROFILE MONITORING USING A GAS CURTAIN

The BGC relies on the production of a supersonic gas by a combination of a nozzle and a series of skimmers. The gas jet is formed as high pressure gas expands through a nozzle into the first of a series of vacuum chambers. The jet is then collimated and shaped into a thin curtain by a series of skimmers [4, 5].

The gas curtain crosses the primary beam to be analyzed at an angle of 45° with respect to the direction of propagation of the beam, causing Beam Induced Fluorescence (BIF). The fluorescence radiation is then detected via a dedicated imaging system to assess the profile of the beam.

In the existing setup at the CI [3], the gas curtain density and thickness were measured using a movable pressure gauge [6]. Furthermore, the profile of the laboratory electron beam with a current of 0.66 mA at an energy of 5 keV was measured using neon, argon and nitrogen gas curtains. The root mean square beam widths determined with these three gases were in good agreement with each other. Moreover, the signal intensity, i.e. the number of photons per second, detected from each gas was consistent with the estimated values based on known fluorescence cross-sections [7], and the parameters of the imaging and detection system for each gas [8].

Based on the outcome of these studies, a new BIF monitor has been designed, assembled and is currently being commissioned with a laboratory electron beam at the CI.

HEL MONITOR

The system consists of 3 separate sections as shown in Fig. 1. Due to the space limitations in the LHC, the total length of the device has been reduced from 2 m to only 1 m. This compact design has the additional benefit of reducing the distance between the nozzle and the interaction point by approximately 0.2 m, thus increasing the gas curtain density and hence the signal strength at the interaction point.

A cross section of the injection chamber including the nozzle-skimmer assembly is shown in Fig. 2. The nozzle is a copper plate, fitted onto a stainless steel holder with an aperture of 30 µm.

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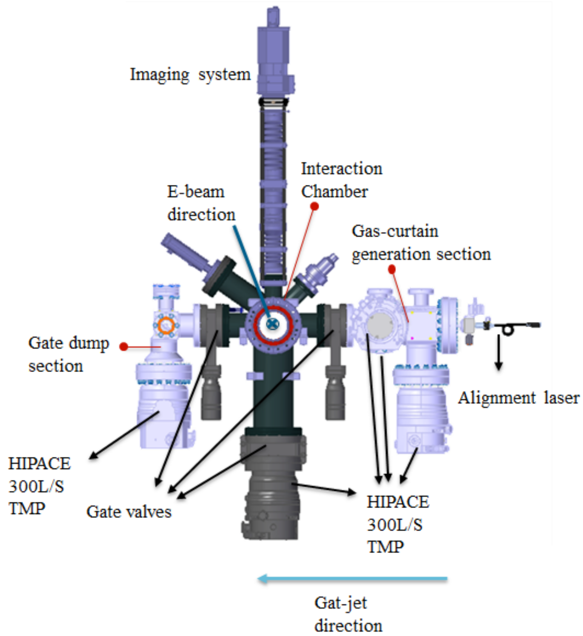

Figure 1: Design of the new gas jet monitor.

The skimmer assembly holds the nozzle, as well as two conical skimmers with diameters of 180 µm and 2 mm respectively. A third skimmer placed 169 mm from the nozzle shapes the gas jet into a thin curtain used for profile monitoring. The injection chamber is divided into three volumes by two bellows which isolate the volume between each skimmer and allow for differential pumping. Each volume is pumped by a HiPace 300 L/s Turbo-Molecular Pump (TMP) connected to a nXDS20i dry scroll pump from Edwards. Based on the experience gained from optimization studies on the prototype, the nozzle and the 1st and 2nd skimmers are aligned on a bench and then mounted in the vacuum chamber. The position of each of these components is fixed relative to the others, minimizing misalignment errors.

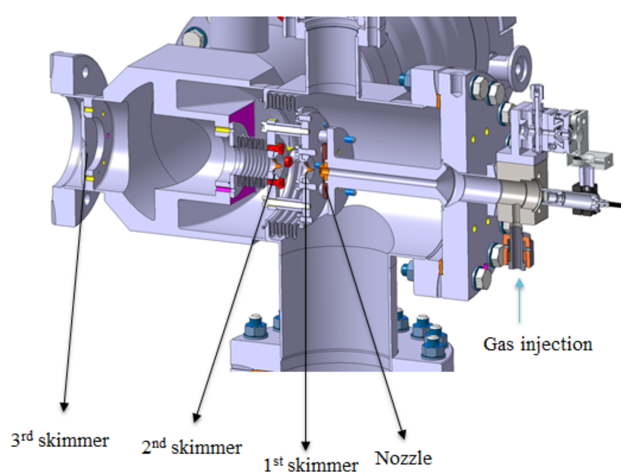

Figure 2: Cross section of the injection chamber and the nozzle-skimmer assembly.

Two different variants of the interaction chamber have been designed and built. One variant was already installed in the LHC during the 2020 shutdown and the second variant will be used in the CI and the HEL test stand. They are both shown in Fig. 3. In this version the interaction point between the gas curtain and the beam is located at a distance of 395 mm from the nozzle. Also attached to the interaction chamber, are three gate valves that can separate the interaction chamber if needed. The imaging system is similar to the first prototype and details can be found in [9, 10].

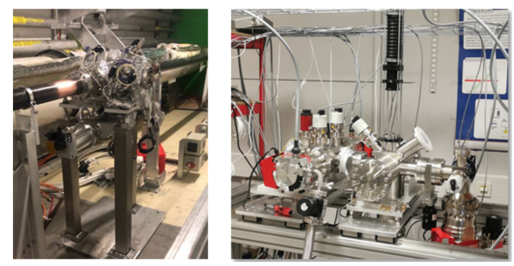

Figure 3: The LHC intallation of the interaction chamber (on the left) and the CI assembly (on the right).

Initial vacuum tests at the Cockcroft Institute on the first BIF prototype have shown that the pressure in the interaction chamber can be maintained at 10^{-9} mbar up to an inlet pressure of 10 bar.

The background light in the interaction chamber is mainly from the emission of of the filament of the electron gun. However, for the instrument that will be integrated in the LHC, Synchrotron Radiation (SR) will be the main source of background. To increase the signal to noise ratio, a filter with a bandwidth of 10 nm, centred at the 585 nm for Neon is used. In addition to this, the interaction chamber has been coated with amorphous carbon with an expected reflectively of 10-15%. Furthermore, a custom plate [8] with a reflectivity of only 0.2-0.5%, centred at 585 nm is placed directly in front of the camera, at the bottom of the chamber, as shown in Fig. 4.

To ensure that the camera is focused on the interaction point between the gas curtain and the charged beam, a camera calibration target is used. This target has sharp, high resolution marks and high contrast between the marks and the substrate. It consists of a series of lines with different thicknesses and spacing varying from 0.12 mm to 1 mm, positioned in a cross layout as shown in Fig. 4. The markings are of gold deposited on a electro-chemically blackened copper substrate.

The gas curtain leaves the interaction chamber through a fourth skimmer into the so-called dump chamber, exiting the system through the blades of a TMP. The fourth skimmer placed between the the interaction chamber and the dump chamber reduces back scattering of gas molecules into the interaction chamber. As with the previous monitor design, a mirror connected to a retractable bellows drive and a camera are used to align the third skimmer with the nozzle.

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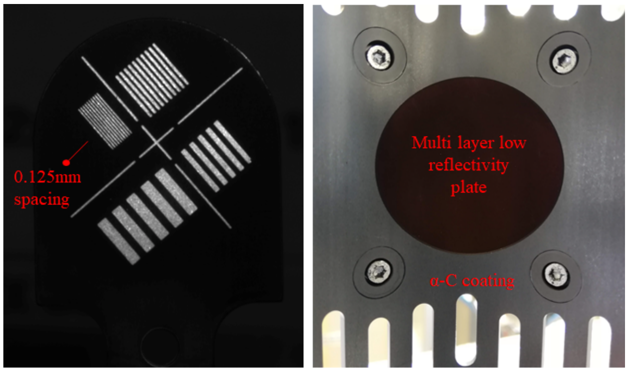

Figure 4: The camera calibration target (on the left) and the coated plate (on the right), placed in the interaction chamber.

SIMULATION OF STRAY RADIATION INCIDENT ON CAMERA

To predict the signal to noise ratio of the monitor integrated in the LHC, the fluorescence resulting from beam-gas interaction was compared to the anticipated background synchrotron radiation.

The gas fluorescence was simulated in MolFlow+ [11], with an elliptical-shaped facet representing the area where the gas jet crosses the beam under a 45° angle. Each point of the facet acts as an isotropic light emitter. The amount of emitted light was estimated from the proton and electron beam currents, the gas jet thickness and density, as well as the excitation cross section of neon at 585 nm to be $5.7{\times}10^8$ photons/sec. Taking into account the reflectivity data for the chamber walls and the bellows proceeding the camera as provided by the manufacturer, we estimate that $2.5{\times}10^5$ photons/sec reach the camera directly (signal), and a further $6{\times}10^5$ photons/sec after at least one reflection from the walls or bellows (background).

The main source of the synchrotron radiation reaching the camera is the 9.5 m long D4 dipole of 1.57 mrad bending angle, whose centerpoint is located 81.15 m upstream of the BGC instrument. Using the HL-LHC nominal beam parameters of 7 TeV beam energy and 1.1 A beam current, this dipole leads to $5.5{\times}10^{15}$ photons/sec emitted in the $585{\pm}5$ nm range visible to the camera. An identical dipole (D3) located 9.1 m upstream of the BGC instrument is too close to contribute to the background as its full SR fan traverses the instrument without hitting the surface of any chamber.

Due to the extremely small probability of an SR photon to scatter into the camera lens plane (one photon out of 10^{11} generated), the simulation had to be performed in two iterations. First, in SynRad+ [11], photons entering the camera arm got “detected” at a certain plane and their spatial and angular distribution stored. Then, a second simulation was carried out in MolFlow+ using the stored photon data. Due to the blackening of the camera arms, approximately 1 out of 10^4 photons reach the camera lens plane, as shown in Fig. 5. The final estimate of $1.5{\times}10^6$ photons/sec is high, especially with the additional background of $6{\times}10^5$ photons/sec from the previous paragraph. The sum of the two is in fact almost a magnitude higher than the signal calculated in the previous point. This issue is therefore subject to further optimizations. One mitigation modality under consideration is to apply sawtooth machining on the upstream LHC wall. This would reduce SR background to $3{\times}10^5$ photons/sec, comparable to the signal.

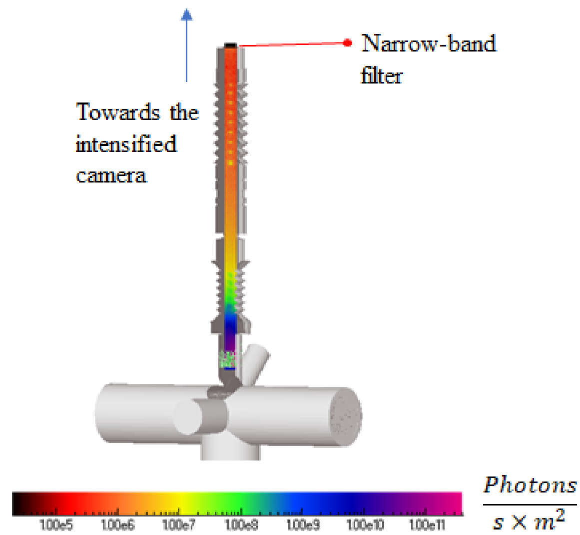

Figure 5: Simulations in MolFlow+ showing the number of photons reaching the narrow-band filter.

OUTLOOK

In this contribution, recent progress in the development of a BIF profile monitor within the BGC collaboration has been discussed. Some of the central design features of the monitor have been presented, as well as simulations of the expected signal to noise ratio of the monitor which will be integrated in the LHC.

In a next step, gas curtain movable gauge based density measurements as well as fluorescence measurements will be carried out at the CI with nitrogen and neon gas curtains. This will give a detailed insight into the monitor’s performance.

The monitor will then be shipped to CERN for fluorescence measurements at the HEL test stand. Furthermore, the interaction chamber already installed in the LHC will be used for fluorescence measurements using residual gas to estimate fluorescence cross sections and corresponding integration times at proton energies up to 7 TeV. Subsequently, the gas generation chamber and the dump chamber will be integrated with the LHC interaction chamber and used for measurements with gas curtain and the proton beam.

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