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DESIGN OF A PROTOTYPE GAS JET PROFILE MONITOR FOR INSTALLATION INTO THE LARGE HADRON COLLIDER AT CERN*

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Abstract

The Beam-Gas Curtain or BGC is the baseline instrument for monitoring the concentricity of the LHC proton beam with a hollow electron beam for the hollow e-lens (HEL) beam halo suppression device which is part of the High-Luminosity LHC upgrade.

The proof-of-principles experiments of this gas-jet monitor have now been developed into a prototype instrument which has been built for integration into the LHC ring and is now under phased installation for operation in the upcoming LHC run.

This paper describes the challenges overcome to produce a gas-jet fluorescence monitor for the ultra-high vacuum accelerator environment. It also presents preliminary results from the installation of the instrument at CERN.

INTRODUCTION

The High Luminosity upgrade to the Large Hadron Collider (HL-LHC) is the flagship project at CERN [1]. The higher luminosity delivered to the experiments require higher bunch intensities which in turn imply more energy and particles in the beam halo, which must be managed. One solution to this problem is to locally pass the circulating beam through a hollow electron beam which interacts electro-magnetically with the protons in the halo and diverts them into an upgraded system of classical physical collimators [2]. For such a hollow electron lens (HEL) device to operate effectively, an overlap instrument which can observe both proton beam centroid and a 2D image of the electron beam is a requirement, both for commissioning and for monitoring during operations. The intense 5 A / 10 keV hollow beam is constrained by a 2 T solenoid field created by two 4.5 K superconducting magnets with the overlap instrument in between. As such, this instrument must also operate in the intense stray fields of these magnets, making observables based on charged particles practically impossible. This has led to the development of a beam-gas curtain (BGC) concept, where a 2D supersonic gas sheet is projected across the aperture at 45 degrees to the proton beam. Interactions between both the proton and electron beams create fluorescence photons which are not influenced by the magnetic field and can be observed by an ex-vacua optical system. This creates a direct image of the two beams, similar in concept to a physical beam observation screen. Following a period of development and collaboration between the Cockcroft Institute (CI), GSI Helmholtzzentrum für Schwerionenforschung (GSI) and CERN [3], [4], a prototype designed for installation in the LHC environment, called BGCv3 has been constructed and successfully commissioned at CI [5].

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COMPARISONS WITH EXPERIMENTAL DATA FOR PROTONS

The Image Intensifier is designed for single-photon detection; it comprises a photo-cathode (UV Enhanced S20) with a quantum efficiency of aprox. 8 % for the Ne-transition at 585 nm and aprox. 12 % for the N2+ transition at 391 nm and reasonable dark-count rate of 500 counts/s/cm^2 [6]. Photo-electrons are amplified by a double MCP leading to separated light spots for each photo-electron on the subsequent phosphor screen. A regular CMOS camera records the image and the centre of the spot is evaluated; the actual system is described in [7]. The Image Intensifier is an optimized version used at GSI-LINAC for regular operation [8]. The photon yield was investigated for several parameters such as gas pressure, gas species (such as N2, Ne, Ar, and Xe), beam ion, and beam energies; tests with the highest proton energy of 450 GeV were performed at CERN SPS [9]. It can be concluded that the photon yield scales basically with the energy loss in the residual according to the Bethe Equation; however, an uncertainty of at least a factor 5 remains related to systematic experimental imperfections. The signal strength at LHC top energy will be determined with the BGCv3 using a local pressure bump produced by a regulated gas inlet valve instead of the gas jet. At LHC energies, background contributions might be significantly different from lower energy investigations. The emitted synchrotron light is more intense and must be absorbed by the inner vacuum pipe [10]; methods for black coating were investigated in detail [11], and the LHC vacuum chamber was prepared accordingly. Optical interference filters with the passband centred at the florescence transitions will suppress this background in addition. Ionizing radiation from beam losses causes further background; in particular, neutrons or fast charged particles might penetrate the Image Intensifier body and cause secondary electron emission from the photo-cathode or within

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the MCP channels. The amount depends on the BGCv3 location and the actual beam conditions. Neutrons can be transported within the tunnel over several 10 metres related to their elastic scattering at the concrete walls [12,13]. These significant uncertainties in light yield and background can only be determined in the LHC machine at top energy.

EXPERIMENTAL PROGRAMME AT CERN

Overview

For practical reasons, experiments to-date have used a 0.6 mA, 5 keV electron beam of circular form. It is clear that validation with a hollow electron beam and at intensities close to nominal are required and this beam is available at CERN on a dedicated electron beam test stand (EBTS). Since data for the validation of such an instrument with high energy protons is also very limited and significant experimental uncertainties exist it is also planned to test this BGCv3 instrument in the LHC in two phases. In the first phase the BGCv3 optical system will be used to observe a static distributed 'gas bump' of up to 5×10^{-8} mbar which can be generated in the LHC. For phase 2, the full v3 instrument will be installed and operated with the supersonic gas curtain.

Validation of the Prototype

BGCv3 was successfully transported to CERN in March 2022. It was then re-commissioned with the same low intensity electron beam used at CI in order to cross-check the previous experimental results. In particular, pressures and pump-down times at the different stages of the system were measured and well-matched to performance at CI. The nozzle skimmer assembly was realigned at CERN to remove any possible displacement caused during the transport and a very high gas jet performance was reached, measured via an 1 mm aperture of a movable vacuum gauge [5] as shown in Figure 1. The validation was concluded with a successful

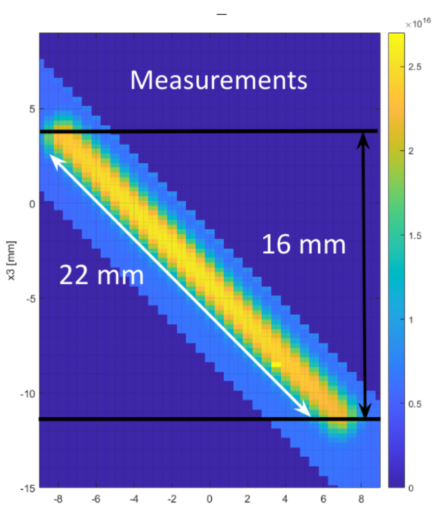

Figure 1: Measured gas jet profile on BGCv3 at CERN.

measurement of the image from the electron beam, again matching the expectation from CI, as shown in Figure 2. These first measurements with this instrument at CERN gives added confidence that when the BGCv3 is installed in the LHC gas jet and vacuum performance will remain as per the surface tests.

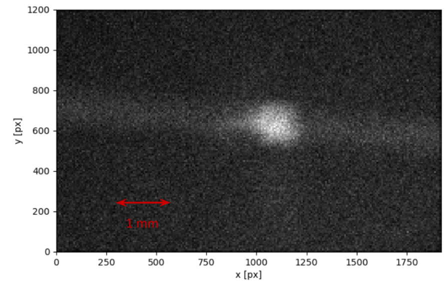

Figure 2: Observed electron beam on BGCv3 at CERN.

Preparation for Test with a Hollow Electron Beam

The BGCv3 is currently being validated for LHC vacuum operation requirements, checking the possible impact of system failures and re-starts. It will then be installed on the EBTS which will be fitted with an electron gun with a hollow aperture, designed specifically for this instrument. At the EBTS it will image this high intensity 5 A, 10 keV hollow electron beam which will be the first non-Gaussian e-beam measured by the BGC. These measurements will then be cross-checked by destructive screen measurements at the same location. Some distortion of the image due to the space-charge of the high-intensity hollow electron beam is expected and will be measured at the EBTS. These measurements will complement simulations [10] which predict measurable effects for a nitrogen gas jet and no effect for a neon gas jet. This is because the fluorescence transition for nitrogen comes from an ion, while for neon it is from a neutral atom emitter. Integration time for the measurements will be significantly reduced with these higher intensities which should have a positive impact on the instrument performance compared with current measurements. However, power limits of the EBTS will require pulsing of the beam to achieve these maximum peak currents. There are other results expected from these EBTS tests. There is a possibility of ions or electrons produced by the beam-gas interactions becoming trapped in the solenoid field. This will be investigated and if necessary, mitigation such as clearing electrodes added. It is also possible that turbo-molecular pumps used in the vacuum system may be affected by the stray fields. This will be monitored and pumps displaced or shielded for the final design if necessary. Finally, this period will be used to develop and test the vacuum control system that will be put in operation in the LHC.

Phase 1 Tests with the LHC Beams

To estimate the signal-to-noise ratio of the monitor for proton beam measurements, the measured cross-sections of Ne fluorescence excitation by protons at injection (450 GeV) and flat top (6.8 TeV)) energies are required. Therefore, an

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experimental setup was installed at the LHC with the aim of measuring these cross-sections and possibly also the 1D profile of the LHC beam. The installation utilizes an injection of Ne gas into the LHC beam pipe to create a distributed gas target for the LHC beam to interact with an optical system to measure the photons produced by the resulting fluorescence. The optical system is out of the LHC vacuum, behind a viewport and focuses the photons with an apo-chromatic triplet lens. As the cross-sections are expected to be low, in the order of 1×10^{-22} cm^2, single-photon detection is necessary, which is achieved by an intensified camera identical to the one used in BGCv3. The experimental setup was focused and tested in the LHC without beam. First distributed Ne injection has been tested with beam during commissioning. The cross-sections with protons at injection and flat top will be measured during the LHC physics fills this year.

DESIGN AND INTEGRATION INTO THE HEL

The BGCv3 interaction chamber was installed in the recent LHC shutdown as shown in grey in Figure 3. This test will already benefit from the extensive work in SR light background reduction that was performed on the interaction chamber design [11]. Later in run 3, the full BGCv3 instrument will be installed for phase 2 testing in the LHC. Space restrictions of this instrument were already challenging, with phase 2 parts to be added in green (see Figure 3). The key element of the BGC design is to keep a high density in the jet while minimising the background gas. This can only be achieved with efficient pumping in all stages of the curtain creation [14].

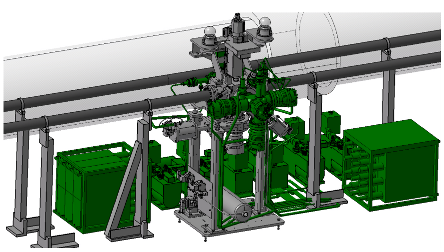

Figure 3: 3D model of BGCv3 in the LHC.

Design is ongoing to integrate the final instrument (BGCv4) in the HEL. The longitudinal space between the two superconducting cryomagnets is 200 mm. Transversely, one location of the HEL in the LHC will leave only 381 mm available, compared with the 593 mm available for BGCv3 (see Figure 3). A number of elements, such as gate valves are incompressible. When reducing the space from v3 to v4, attention must be given to minimise the loss of conductance for the gas molecules towards the pumps. Otherwise increased background gas density leads to reduced signal to noise ratio compared with v3 [15].

The two HEL magnets develop an attractive force of about 114 kN when powered. This force is compensated by 4 rods between the magnets (Figure 4) which need to be removed during BGC installation. While the rods are in contact and at cryogenic temperature, the 200 mm magnet interspace is at room temperature and pressure. In order to avoid icing of the connections, the rods will be housed in insulation vacuum and with multilayer thermal insulation to minimise radiation losses. Optimised edge-welded bellows with elastomer seals are proposed to assure the removal and reintegration of these rods. The Turbo Molecular Pumps (TMPs) have a rotation speed in the order of 1kHz and operate in the stray HEL magnetic field of up to 50 mT. Mu-metal shielding is being studied to allow for operation within the 5 mT magnetic limit specified by the pump supplier. Alternatively, NEG cartridge pumps could be substituted for the less-easily accessible pumps on the interaction and dump chambers which see a lower gas flow. This would limit operation to getterable gases such as nitrogen, but not neon.

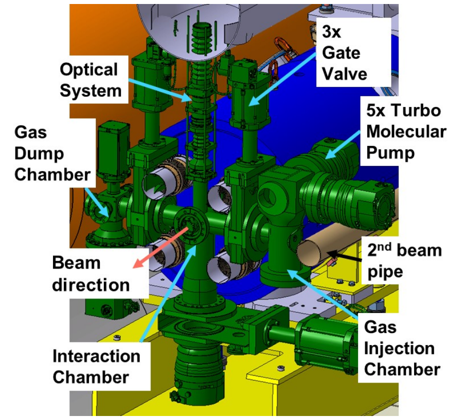

Figure 4: 3D model BGCv4 integrated in the HEL.

SUMMARY AND CONCLUSIONS

A BGC instrument, whose performance was specified in 2018 [3] has been designed, constructed and recently tested to nominal performance, but with a very low intensity electron beam [5]. This instrument is now at CERN and undergoing a series of tests, first with the nominal intensity electron beam and then with protons in the LHC to validate performance in final conditions. This extensive test programme will give the final input required to produce the series of devices for the HEL. It should also provide the first measurements of fluorescence with TeV protons.

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