Recent progress on the commissioning of a gas curtain beam profile monitor using beam induced fluorescence for High Luminosity LHC

M. Ady[1], P. Forck[2], R. Jones[1], N. Kumar[3], S. Mazzoni[1]†, I. Papazoglou[1], C. Pasquino[1], A. Rossi[1], S. Sadovich[1], A. Salehilashkajani[3], G. Schneider[1], S. Udrea[2], R. Veness[1], C. Welsch[3], H. Zhang[3]

[1]CERN, Geneva, Switzerland [2]GSI, Darmstadt, Germany [3]University of Liverpool and Cockcroft Institute, Warrington, UK

For the high-luminosity upgrade of the Large Hadron Collider ("HL-LHC"), active control of proton beam halo will be essential for safe and reliable operation. Hollow Electron Lenses can provide such active control by enhancing the depletion of halo particles, and are now an integral part of the high luminosity LHC collimation system. The centring of the proton beam within the hollow electron beam will be monitored through imaging the fluorescence from a curtain of supersonic gas. In this contribution we report on the recent progress with this monitor and its subsystems, including the development of an LHC compatible gas-jet injection system, the fluorescence imaging setup and preliminary test measurement in the LHC.

BGC preliminary studies

BGC models and simulations

- **Gas curtain generation in the BGC consists of several stages separated by skimmers, selecting only the central, co-linear part of the gas jet while rejecting the rest.**
- **Molflow+ was used to simulate the pressure distribution after the final skimmer, Figure 1 shows the density profiles at skimmer 3 for different second skimmer shapes before the interaction point.**
- **Gas curtain thickness may limit the spatial resolution of the BGC beam diagnostics To estimate its influence, a simplified 2D model was developed, with the assumption that: (1) the curtain is considered to have a lateral extension much larger than the beam under investigation and the same gas density throughout the width of the curtain, (2) the refractive index of the curtain can be considered equal to that of vacuum (i.e. $n_C = 1$) and (3) the charged particle beam has radial symmetry. Under these conditions the detected intensity profile can be calculated (see [1] and references therein).**
- **When considering a charged particle beam with a Gaussian transverse profile of RMS width σ, and a curtain with parabolic density distribution, the observed profiles are presented in Figure 2 for curtain thicknesses d = 0.1·σ, σ, and 2·σ. At d = 2·σ the increase of the profile width in the image is clearly visible, with the observed RMS width ≈ 1.2·σ. According to this model, the profile is expected to be reproduced with relatively good accuracy if d is kept below 2·σ. However, if increasing the signal strength is of a higher priority one has to consider that signal amplitude saturation occurs due to the recorded profile's FWHM increasing with the curtain's thickness. The model shows that curtain thicknesses beyond d ≈ 5·σ bring no benefit in terms of signal strength.**

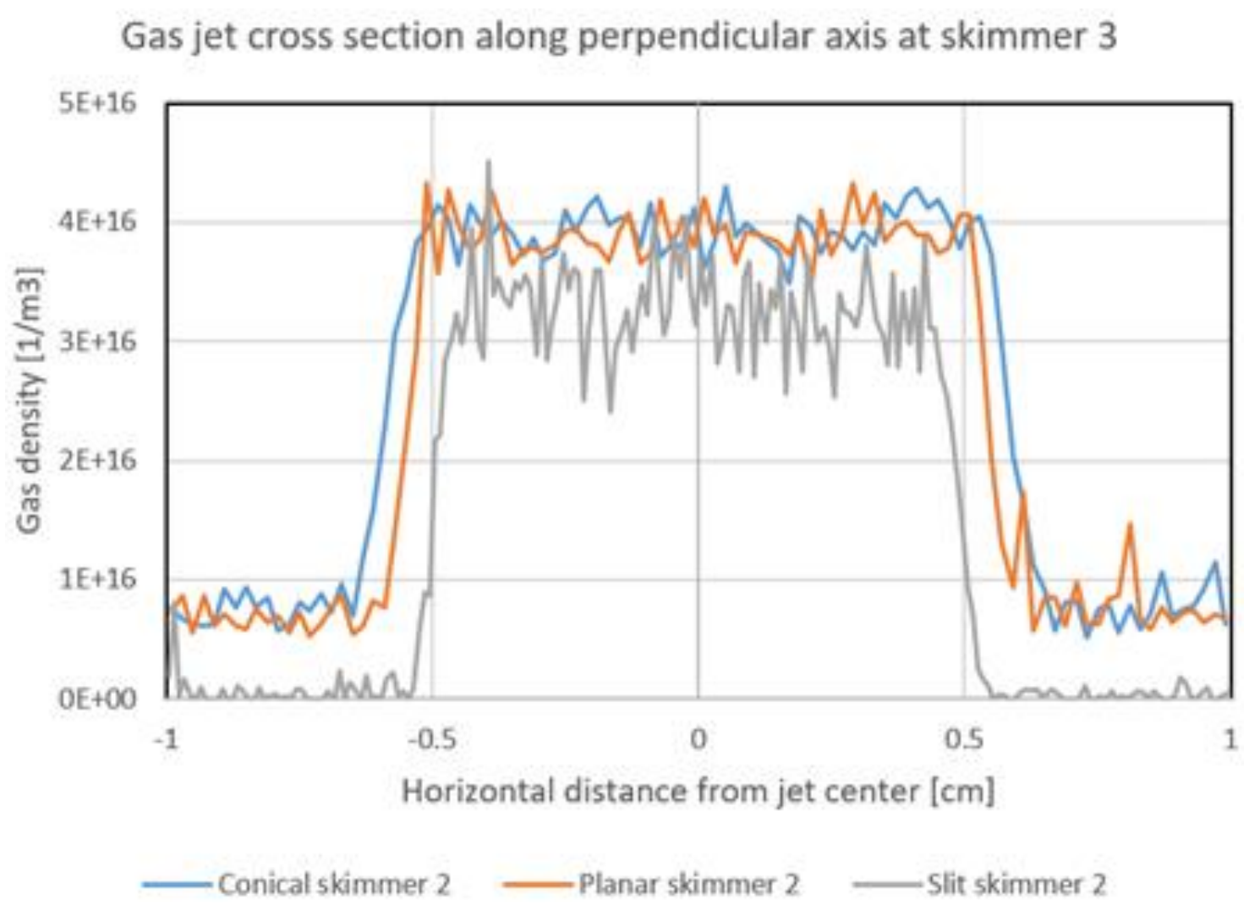

Figure 1: density profiles for different second skimmer shapes before the interaction point

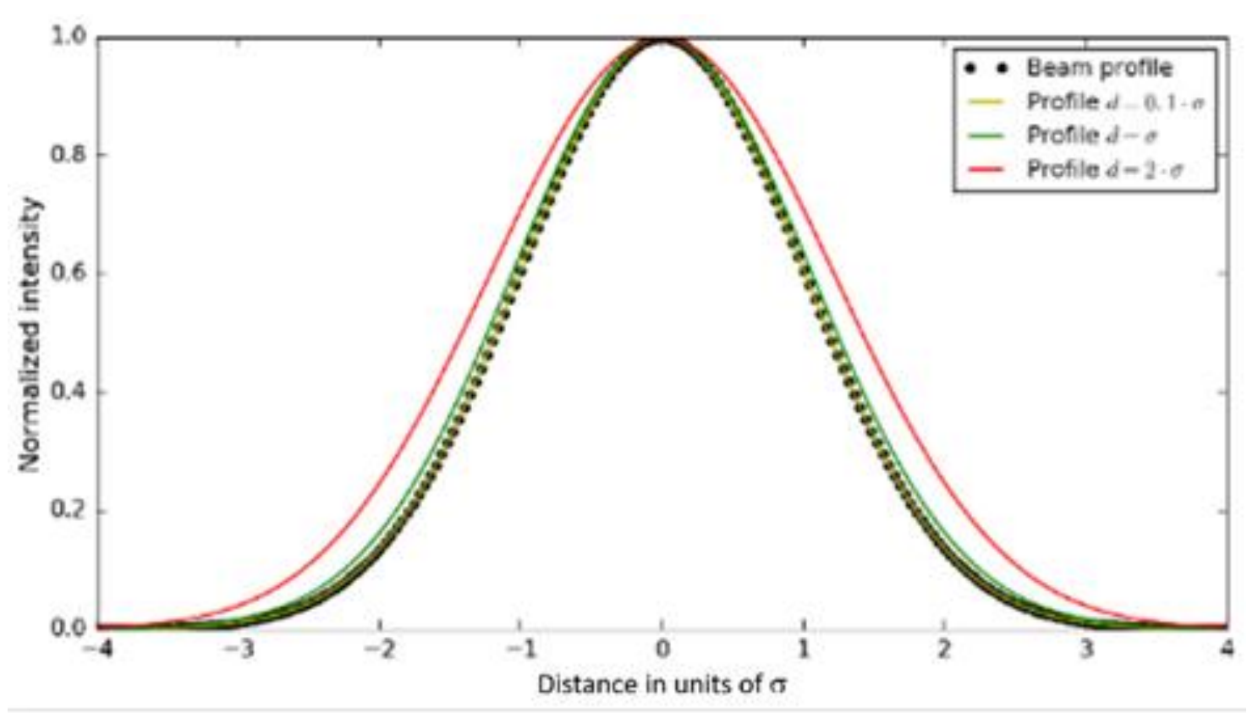

Figure 2: Recorded profiles estimated based on the present 2D model as a function of the curtain thickness d.

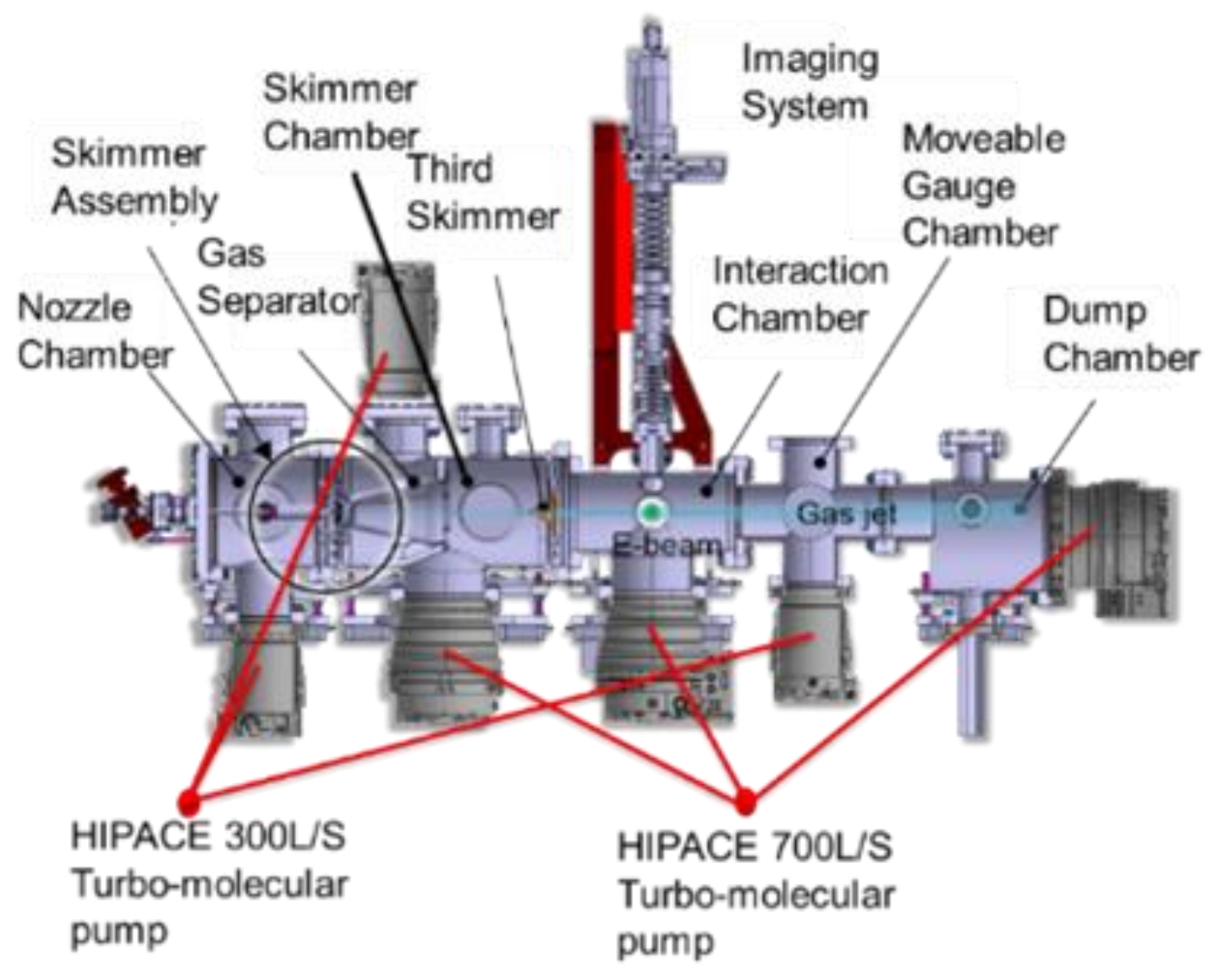

Figure 3: Schematic view of the prototype BGC monitor at the Cockcroft Institute

Electron beam measurements with the BGC lab model

- **A laboratory model of the BGC is installed at the Cockcroft Institute, UK (see Fig. 3). The instrument can generate a gas curtain with a density around ~10^{16} molecules/m^3 within a size of 8 x 1.5 mm^2. interaction chamber pressure of ~10^{-9} mbar. The profile of a 5 keV electron beam was recently measured using Nitrogen (N2), Neon (Ne) and Argon (Ar) gas where the wavelengths of the fluorescence photons are centred at 391.4 nm, 585.4 nm and 476.5 nm respectively. A photon-counting method was used to create the image from the fluorescence generated from the gas-beam interaction.**
- **Unlike N2, the wavelength of the fluorescent photons emitted from both Ne and Ar are in the same range of the spectrum as the electron gun filament emissions. (increase of background noise), mitigated by a small, blackened aluminium foil with an opening diameter of 3 mm was therefore placed between the electron gun and the interaction region in the vacuum. The normalised intensity plots of nitrogen, neon and argon are displayed in Fig. 4, showing a good agreement between the three profiles.**
- **The photon detection rate is approximately 10 time lower for Ar and Ne when compared to N2 under similar conditions (smaller cross-sections and, for Ne, also lower photo-cathode efficiency). The number of photons detected can be estimated [2] for each gas to the correct order of magnitude based on gas curtain density, cross section, e-beam current and optical properties. A comparison between the theoretical estimations and the measured photon number shows a reasonable agreement, as shown in Table 1 for a gas-curtain density of 2.5x10^{-16} m^{-3} (HEL and lab expected). and a current of 0.65 mA and 5KeV energy (measured).**

Emitter	HEL expected	Lab conditions	Measured
N_2	3.4x10^6	8.8x10^2	1.7x10^1
Ne	2.5x10^4	6.5	1.6
Ar	2.3x10^4	6.0	1.3

Table 1: Comparison of the fluorescence photon rate (in counts/s) for different working gases for the prototype BGC monitor and the final electron lens BGC monitor

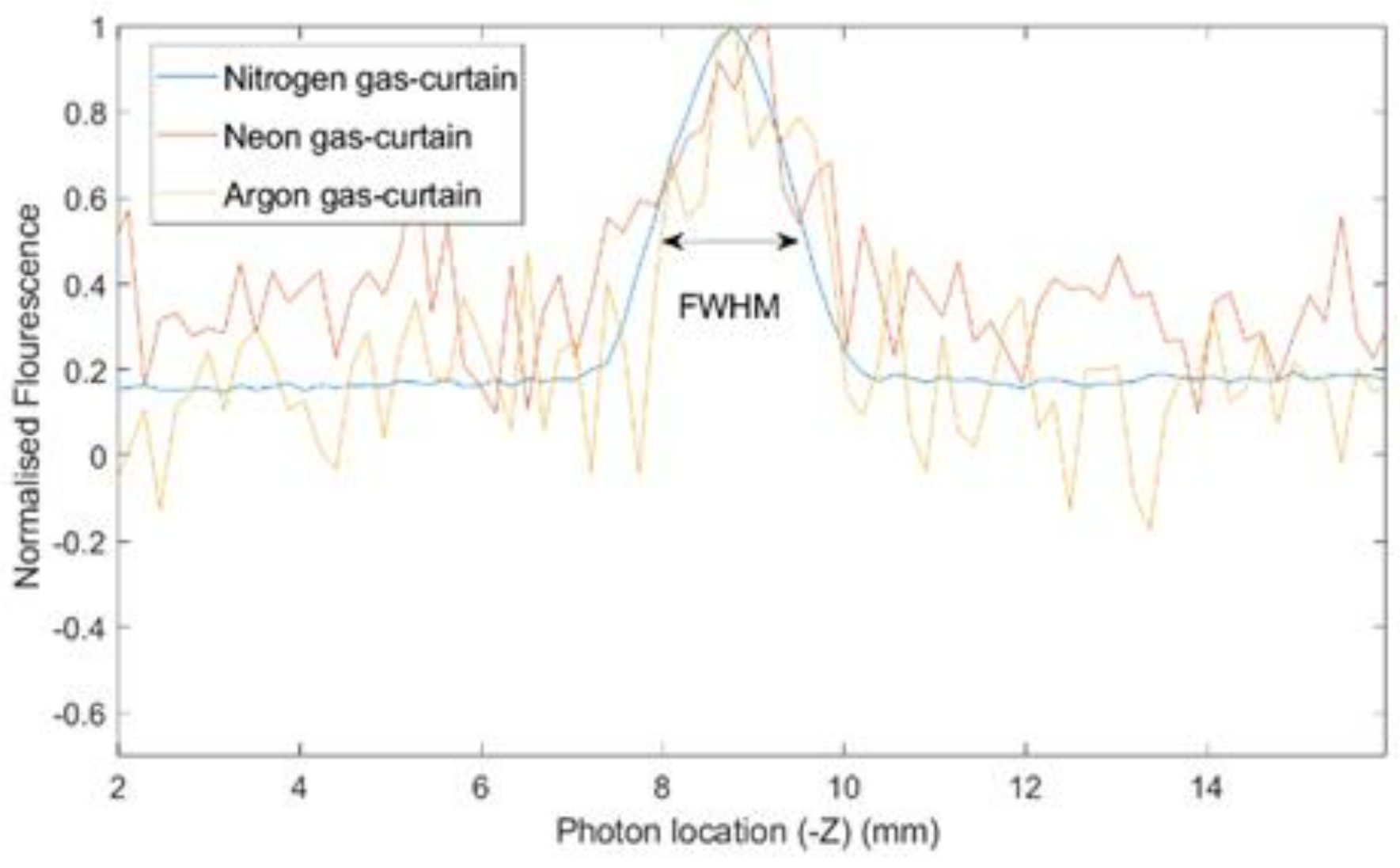

Figure 4: Normalised intensity plots of nitrogen (400 s integration time), neon and argon (4000 s integration time)

LHC fluorescence tests

- **A Beam Induced Fluorescence (BIF) test instrument was installed in 2018 in the LHC. The optical instrument is composed of two 50 mm diameter, 300 mm focal length doublets that project the image of the center plane of the beampipe onto a single micro channel plate (MCP) intensified camera with a Multialkali photocathode. A remote controlled filter wheel allows a neutral density (ND1 – ND2) or a bandbass (340 +/- 40 nm, 585 +/- 40 nm) filter to be inserted in the light path. The entire optical instrument is enclosed in a light tight container. A gas injection system allows Neon gas to be introduced inside the beam pipe up to a pressure of approximately 5x10^{-8} mbar.**
- **Measurements were performed in the second half of 2018 with both protons and Pb ions, at energies ranging from 450 Z GeV to 6.5 Z TeV. Fig. 5a shows the fluorescence image of Pb ions at 450 Z GeV with a very long (1286 s) exposure time. Optical background and showers generated by beam loss have been subtracted from the image. The fluorescence signal appears as a streak at the very top of the image. Figure 5b shows a Gaussian fit of the vertical profile of the fluorescence image averaged over 10 mm. The resulting width (mm) could not be directly cross-checked with another instrument as no other profile measurement device can currently measure a nominal Pb ion beam at injection energy. It is possible however to deduce that the average transverse beam size could not have been greater than 2.1 mm (derived from high energy measurements). The fluorescence measurement is therefore consistent with such a value.**
- **Measurements with Pb ions at high energy and with protons at both injection and high energy are inconclusive due to an insufficient signal to noise ratio. For protons at high energy (the relevant case for HEL alignment), the main source of noise is synchrotron radiation reflected from the copper beam pipe surface opposite to the viewport. This resutls in a background 10^4 times higher than the one measured for the Pb ions at injection.**

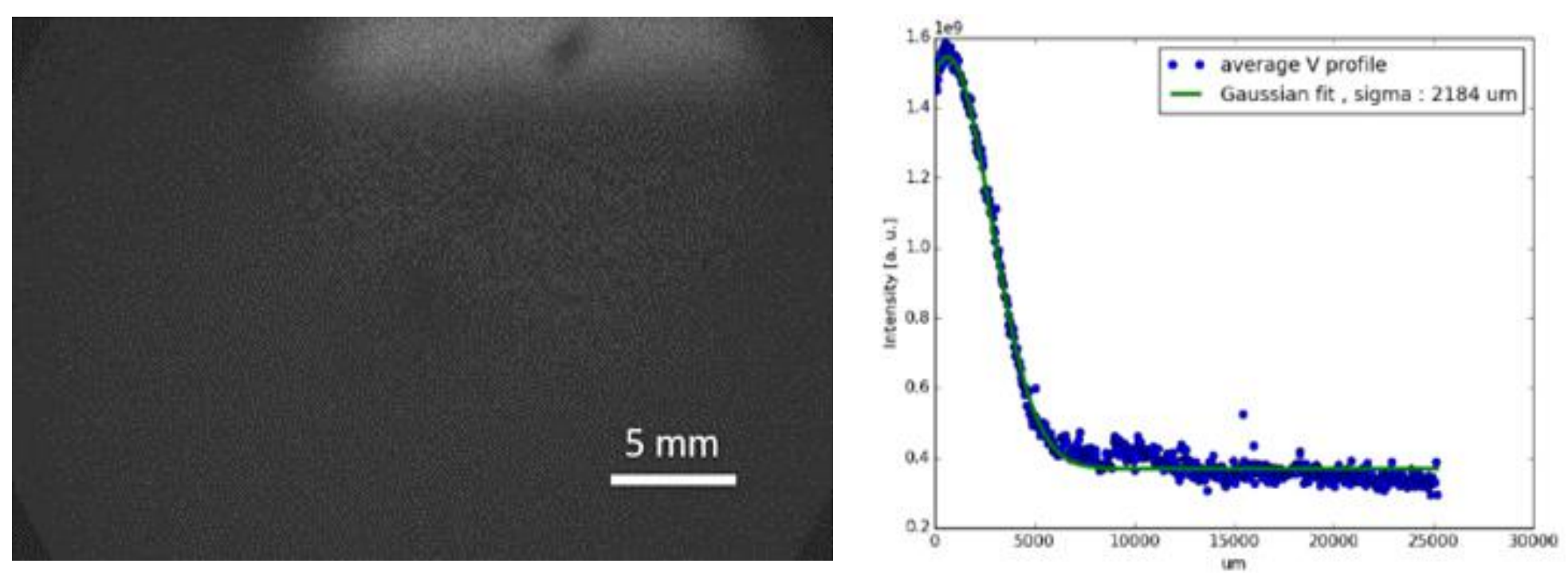

Figure 5: Left: Fluorescence image of Pb ions at 450 Z GeV with an integration time of 1286 s .Right: Fit of the vertical profile averaged longitudinally over 10 mm.

Installation of BGC prototype in the LHC

- **The first phase of installation includes the main gas curtain interaction chamber, a simple gas injection system and the optical instrument used for previous fluorescence measurements. In order to minimise optical background the entire vacuum chamber is blackened with amorphous carbon coating (see Fig. 7), with a reflectivity of about 10-15% [3], while in front of the camera, a specially designed plate is inserted with a vacuum compatible, multilayer coating to give a reflectivity of 0.2-0.5% at the wavelength of interest (585.4 nm).**
- **In phase 2 the full BGC instrument will be installed, including the supersonic gas curtain generation and the final optical system (see Fig. 8). The selected working gas is injected at a pressure of 10 bar through a 30 mm nozzle. The jet is then shaped with a series of 3 skimmers, resulting in a final equivalent pressure in the 10^{-7} mbar range (corresponding to a density of 2.47x10^9 cm^{-3}) while the background pressure is expected to be in the 10^{-9} mbar range.**
- **A gas dump system is placed on the opposite side of the gas injection system in order to collect the gas curtain after the beam interaction to maintain as low as possible a background pressure in the interaction chamber. A slit aperture matching the gas curtain dimensions is placed at the entrance to the dump chamber, which allows the gas jet to enter but prevents the majority of any reflected gas from re-entering the interaction volume. This gas is then extracted using a high conductance pump.**
- **The gas injection system and gas dump are scheduled for testing at the Cockcroft Institute in 2020, with a subsequent test on the HEL test stand at CERN foreseen in 2021, before installation in the LHC.**

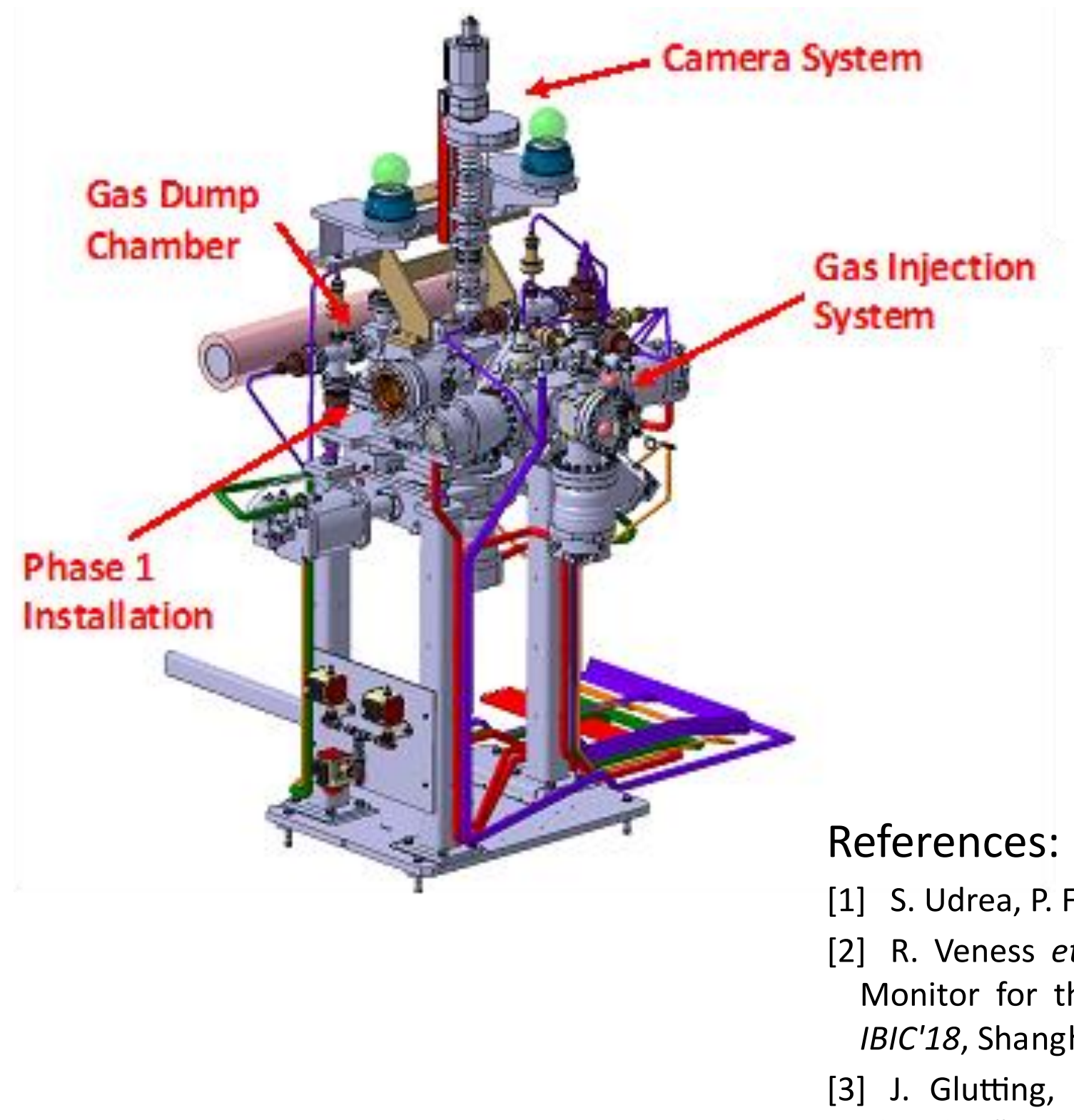

Figure 8: Phase 2 of the final BGC demonstrator

References:

[1] S. Udrea, P. Forck, "CERN e-lens Milestone 1.6 report"

[2] R. Veness *et al.*, "Development of a Beam-Gas Curtain Profile Monitor for the High Luminosity Upgrade of the LHC", in *Proc. IBIC'18*, Shanghai, China, Sep. 2018, pp. 472-476

[3] J. Glutting, "Blackening Investigation for the BGC Interaction Chamber", https://edms.cern.ch/document/2052543/2,

† email: stefano.mazzoni@cern.ch