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LHCspin: Unpolarized gas target SMOG2, and prospects for a polarized gas target at the LHC

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This paper is dedicated to the memory of Prof. Willy Haeberli for his pioneering development of polarized sources and targets and his scientific leadership in establishing the experimental study of spin as a major research field worldwide in twenty-first century physics.

The status of the first phase of LHCspin is discussed, based on an unpolarized gas target – SMOG2 -, an upgrade of the previous SMOG system. It consists of an openable 20 cm long storage tube in front of the VELO detector. A known gas flow from a gas feed system is injected into the tube's center, producing a localized triangular density distribution. First tests of the SMOG2 system with LHC beam and H_2 , He, Ne and Ar gas have been performed. The target system and the precision for setting the target areal density are presented. - In the second part, design considerations for a polarized gas target at the LHC are presented. The fact that the initial tests worked as expected is a strong confirmation that the storage cell/tube is a viable concept compatible with LHC conditions. For the beam stability, very few coatings of surfaces close to the LHC beam are accepted. The SMOG2 cell is coated with amorphous Carbon (a-C). It is an open question whether this coating might be used for a polarized target cell. In order to circumvent the coating problem, a free-beam PGT within the present VELO-vessel has been presented. This could be a reasonable starting point for a Spin program at the LHC.

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1. Introduction

The LHCb Spectrometer detects particles from collisions at IP 8. Vertices are reconstructed with the help of the Vertex Locator (VELO). The overlap of the colliding bunches is measured via scattering on the residual gas. In the past, a gas injection system (SMOG) for Ne (He, Ar) has been used, creating a ≈ 10m long pressure bump to improve the luminosity measurements. In addition, SMOG enabled Fixed-Target measurements, e.g., a pioneering measurement of antiproton production in pHe fixed target collisions [1].

As a first step towards a polarized gas target, the LHCspin group has added a storage cell within the VELO vessel, upstream of the detector, called SMOG2. A complete system has been installed in 2020 and has been operated with the current LHC beam for the first time in November 2022, and first results were presented [2]. The SMOG2 target is going to demonstrate the feasibility of a SC in the LHC. A future project, a polarized gas target (PGT) close to the VELO detector, is under study. Preliminary ideas for the PGT are presented here.

2. Storage cell in the molecular flow regime

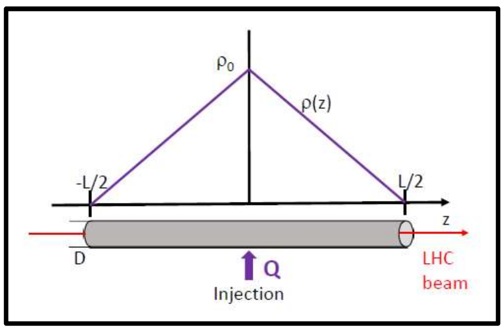


Figure 1: Principle of a storage cell (/ tube)

The Storage Cell (SC) as a spin-polarized gas target has been proposed by Haeberli [3]. Gas is injected in flight via an injection tube, or by a capillary, both in the center of a straight beam tube, with the fast ion beam on axis. SMOG2 [4] works with unpolarized gas only, supplied by a gas feed system. Fig.1 shows a storage tube as employed for SMOG2. The relation between flow rate Q [mb l/s] and areal density θ [pt./cm^2] is given by ½ ρ_0 L, (L = length of beam tube) and $\rho_0 = Q / C_{tot}$, C_{tot} being the total gas conductance of the beam tube from the center outwards. This leads in the molecular flow regime to a triangular density distribution with ρ_0 at the center. The areal density depends on length L, inner diameter D , atomic weight M and temperature T. With L = 20 cm, D = 1.0 cm and T =300 K, the following densities are expected:

Gas	H_2	He	Ne	Ar	Kr
Areal density in $10^{12}/cm^2$	4.3	6.0	13.4	19.0	27.4
Scale factor	7.6	10.7	24	34	49

The table shows the SMOG2 target densities for different gases at 300 K and the fixed flow rate $Q_0 = 1.30 \cdot 10^{-4}$ mb l/s, the fixed flow rate of SMOG. The dependence on the molecular mass M comes from the √{T/M} factor in the conductance formula, leading to higher densities for the heavier gases. The Scale factor *SMOG2 : SMOG* shows the improvement of the target density by using a storage cell.

3. The SMOG2 storage cell in the VELO-vessel

In Fig.2, the principle of operation of the SMOG2-target in the VELO-vessel is shown. TheSMOG2 cell (length L, inner diameter D, openable!) consists of two halves, rigidly connected to the two Detector Boxes. Prior to beam injection and tuning, it opens with the boxes, and closes during stable beam operation. The gas is directly injected into the cell center producing a triangular pressure bump with volume density ρ_0 in the center. The target areal density $\theta = \rho_0 \cdot L/2$ can be up to two orders of magnitude higher than for SMOG at the same gas flow rate. The cell is completed by openable conducting surfaces, with smooth variation of the cross section to avoid excitation of Wake Fields.

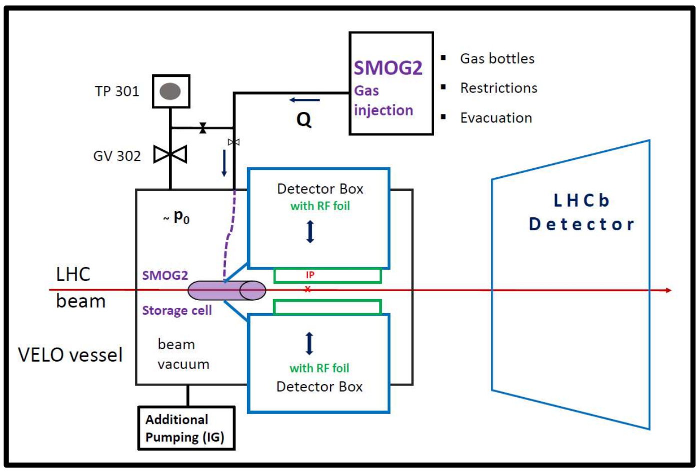


Figure 2: Principle of the SMOG2 target

The design and construction of the target [4] was performed by the Ferrara group. Fig. 3 (right) shows a (virtual) view of the closed cell with wings and flexible Wake Field Suppressor (WFS, foreground). The two halves of the cell are rigidly attached to the frame of the RF foil (green), which moves with the dark grey detector boxes in and out. In Fig. 4 (below) the open cell is shown with holding mechanism (pink), the two halves of the cell with conical extension, and the flexible WFS (yellow). The capillary from the gas feed system enters in the center of the right cell half.

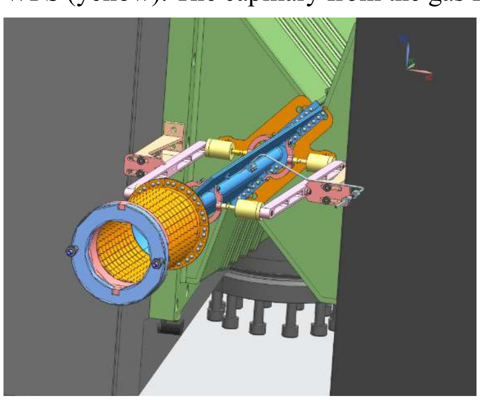


Figure 3: SMOG2 system, attached to the RF-foil

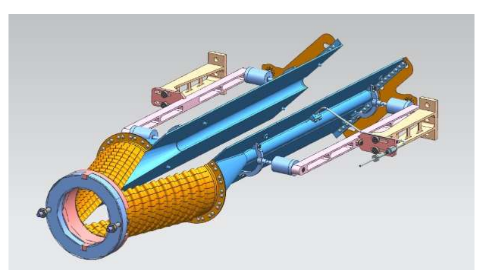
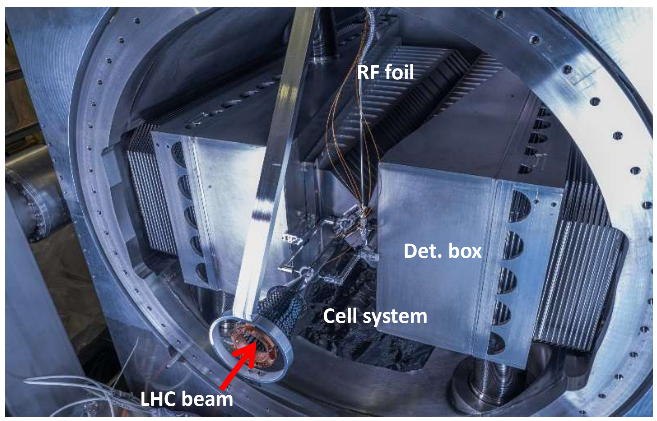


Figure 4: Open cell

An important goal of SMOG2 is to measure cross sections more precisely than with SMOG. The areal density θ can be calculated in two ways: (i) analytical (see sec. 2) and by numerical simulations of the gas flow in the Molecular Flow regime, assuming wall collisions only, with re-emission according to a cosine-law. The precision can be estimated by a comparison of both methods [5]. In case of a straight beam tube (L = 20 cm, I.D. = 1.0 cm) with injection at the center, the analytic method predicts a linear fall-off towards the open ends. The Simulation agrees within about ± 7 cm from the center, and exhibits a slight overshot towards the ends. The ratio $\theta_{sim}/\theta_{ana}$ is 0.998 for H_2, and 0.999 for Ar. A more realistic simulation must include the effect of the RF-foil, which hinders slightly the flow at the downstream end of the beam tube. The ratio $\theta_{sim}/\theta_{ana}$ is 1.022 for H_2 and Ar, different from one, because in the analytic model the presence of the RF-foil was neglected. This result allows for an easy estimate of the target areal density. For the final error, all uncertainties of the parameters of the SMOG2 system, like Geometry L, D, temperature T, and intensity I have been considered [5]. The main sources of the systematic error are from the tube diameter D (milled to 20 µm in precision) and intensity I delivered by the Gas Feed System (both about 1%). For H_2 and Ar, investigated in detail, a relative systematic error can be given as $\Delta\theta/\theta = 1.4\%$.



The SMOG2 system has been installed in 2020. The photo shows the upstream end of the VELO vessel with elliptical flange removed. Starting in June 2022, several runs with open VELO detector took place. In November, measurements with closed VELO and gas injection were performed, and the expected triangular density profile of the SMOG2 cell detected for the first time [1].

4. Design considerations for a polarized gas target at the LHC

The main arguments to be considered are:

The physics accessible at LHC (no polarized beam) is Single Spin Azimuthal Asymmetries (SSAA), measured with *transverse polarization of the target* S_T and Φ-dependence of the final-state hadrons, as demonstrated e.g. by HERMES.

It requires a polarized gas target (PGT) similar to HERMES, incl. Atomic Beam Source (ABS), Storage Cell (SC) target with strong transverse guide field, target gas analyzer (TGA) and polarimeter (BRP), and a powerful differential pumping system.

All narrow openings in the LHC, like the VELO detector, are openable during injection and tuning ($r_{min} \approx 27$ mm at IP8). This holds for the PGT set-up as well, with cell, wake field suppressors, detectors, and other obstructions close to be beam.

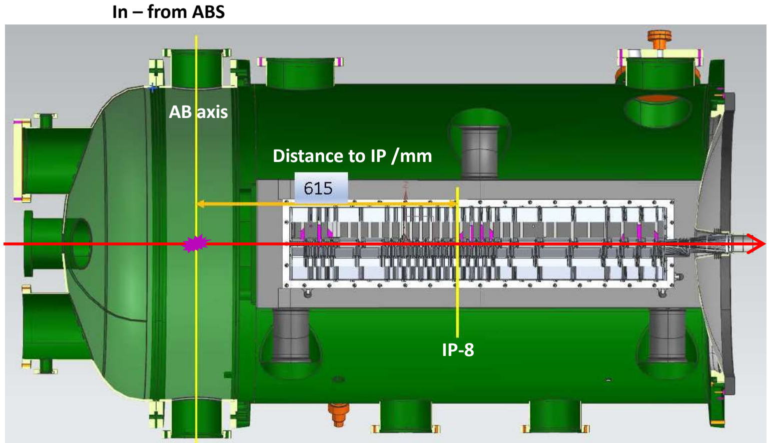
Machine effects
Some basic rules for LHC machine components must be obeyed:

(i) Electron Cloud effect: For positive ion beams as in the LHC, the formation of E-clouds and the resulting transverse instability must be avoided, otherwise beam losses and severe damage may result. Surfaces close to the beam must have low Secondary Emission Yield (SEY).

(ii) RF heating: The RF properties of conducting surfaces have to be such that excitation of Wake Fields are suppressed. All components are analyzed in this respect prior to installation.

(iii) In addition for a PGT: Beam-induced depolarization (BID.) The RF from the bunched beam (f_B = 40.08 MHz) may cause resonant transitions between the energy levels of the polarized H atoms. A strong transverse guide field $B_0 \approx 300$ mT = 6 x B_{Crit} is applied to maximize nuclear polarization. A comparison of the HERA and LHC parameters [6] shows that due to the higher bunch frequency and longer bunches of the LHC beam, BID of a H-target at the LHC will be weaker than at HERA, where it was well under control.

As the search for a suitable coating of the cell surface has not yet yielded a positive result, one may consider a free-beam PGT, employing the free polarized atomic beam. We propose to extend the VELO-vessel (shown in green) in length by means of a short cylindrical chamber with two co-axial flanges for entrance and exit of a polarized atomic beam (AB). The collisions occur at the intercept of Atomic and LHC beam, about 600 mm upstream of the nominal IP, within the VELO acceptance. By means of a focusing Sextupole magnet halfway between entrance flange and LHC axis, the AB is com-pressed at the collision point for maximum luminosity. A holding field of ca. 0.3 T is required at the collision point.



5. Conclusions

The recently installed SMOG2 gas target constitutes the first storage cell target at LHC energies. Its smooth commissioning and performance as expected shows that the design is reliable and safe. It will strongly improve the conditions for Fixed-Target measurements at the LHCb experiment. In parallel, the development of a PGT will continue.

As a minimum-invasive system, ideas towards a Free-Beam PGT have been presented. This avoids the still open coating problem by using a free beam without cell, at the expense of a factor 40 loss in luminosity. A luminosity around $10^{31}/\text{cm}^2$ s could be within reach in this scenario, requiring a strong programme of numerical simulations and tests in the laboratory.

References

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