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Efficiency of Differential Pumping in the LHC Polarized Gas Target (PGT)

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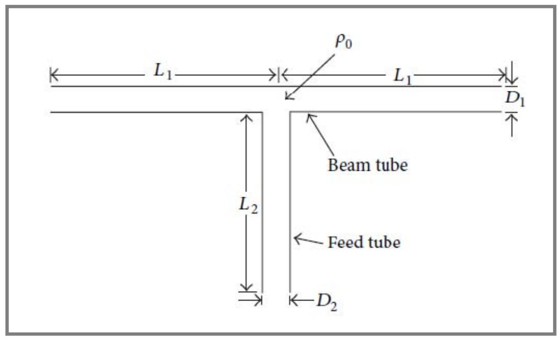
Abstract: For a sufficient density of a window-less gas target based on a storage cell, a substantial gas flow rate is required, exceeding that of UHV vacuum systems. Therefore, differential pumping has to be applied in order to limit the gas flow into neighbouring sections. Applying analytical formulae valid in the molecular flow regime, the on-axis flow – which can not be collimated – from the downstream end of the target tube towards the VELO vessel is estimated. It has been shown that the existing vacuum systems can cope with the flow.



I. Introduction The concept of the PGT for the LHC upstream of the LHCb experiment has been described recently for the first time in a SPIN2018 conference paper [1]. The T-shaped target cell (see **Figure 1** to the right, [2]) consists of a straight beam tube and a feed tube, by which a 'ballistic' flow from the ABS is injected directly into its center [2]. In the present design (L_1 = 150 mm, L_2 = 100 mm, $D_{1,2}$ = 10 mm), an at an ABS flow rate of 6.5 10^{16} H/s, a maximum density $\rho_0 = 8.1 \cdot 10^{12}$ H/cm^3 can be produced at a cell temperature of T = 100 K. In this case, about 42 % of the flow is emitted back towards the ABS, and about 29% each is emitted as a peaked flow from the upstream and the downstream end of the beam tube. The upstream flow has to be pumped by the LHC beam tube and eventually by the cold mass starting at about 20 m upstream. The downstream flow may partially enter the Vertex Locator (VELO) vessel and put a significant load on the VELO vacuum system.

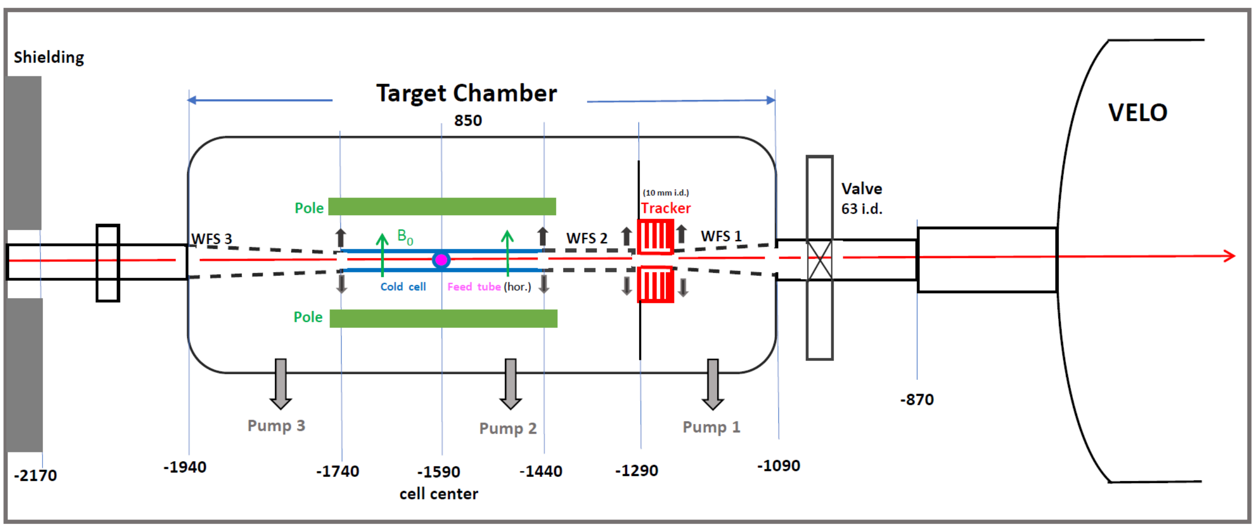


Figure 2: Sketch of the PGT arrangement upstream of the VELO detector. The Run3 configuration of the beam line with a new sector valve is shown. The dimensions are preliminary. The z values are given relative to the IP8 at z = 0. The LHC beam used for fixed target measurements moves from left to right. The 300 mm long storage cell (blue) is centered at z = -1590 mm. The opening of the horizontal feed tube is shown in pink color. Downstream of the cell, a gridded Wake Field Suppressor WFS2 150 mm long connects to the 10 mm opening of the tracker, which acts also as a restriction of the differential pumping system (pump 1- 3). The system of cell and the three WFS's 1 – 3 incl. tracker is openable during injection and beam tuning.

In the present conceptual PGT layout [1] (see Fig.2), there is a 10 mm-diaphragm foreseen as part of a differential pumping system at the position of the Tracker, 300 mm downstream of the cell center, corresponding to an opening angle of about 1.0°. A safe estimate of the flow from the beam tube passing through the diaphragm and entering the VELO vessel is important for a lay-out of the vacuum system. By multiplying the maximum value I_0 of the peaked flow on axis with the solid angle of the diaphragm as seen from the cell center should result in a reliable estimate of the VELO gas load by the PGT. Unfortunately, a working molecular flow simulation program was not available within the study group for the estimation of the effusive flow. Therefore, first estimates are done analytically.

II. Estimate of the intensity of the near-axis flow by an analytical approach: For the molecular flow from a narrow tube of diameter D and length L [3], two regimes can be distinguished: **(i)** $\theta < \theta_0$ and **(ii)** $\theta > \theta_0$, with $\theta_0 = \arctan \Gamma^{-1}$ and $\Gamma = L/D$; $\theta = 0$ corresponds to the tube axis. For our conditions with $\Gamma = 15$ it results in $\theta_0 = 3.8°$, i.e. significant peaking.

In regime **(i)**, a narrow peak is produced by particles directly emitted from the high-density region at the cell center without further collision, plus a background from particles which have undergone wall collisions. Regime **(ii)** contains particle with wall collisions, only. According to Clausing (ref.3, equ. 2.9), the intensity ($dI/d\omega$) of the central peak I_0 around $\theta = 0$ is given by that of an source of the tube's cross section and volume density ρ_0 . Any background from particles having performed wall bounces is low and neglected here. This leads to a peak flow intensity [3] of

$$dI_0 / d\omega = (1/4\pi \text{ sr}) \cdot \rho_0 \cdot v(100 \text{ K}) \cdot A_{source}$$

$$= (1/4\pi \text{ sr}) \cdot 8.1 \cdot 10^{12}/\text{cm}^3 \cdot 1.455 \cdot 10^5 \text{ cm/s} \cdot 0.785 \text{ cm}^2 = \underline{7.37 \cdot 10^{16} \text{ H/sr s}}.$$

The full half-width FHW of the flow distribution can be estimated by (ref. 3, equ. 9.9):

FHW (in deg.) = 0.0962 L (in mm) /D (in 10−3 mm), resulting in H = 6.1°.

A cone with full opening angle $2 \cdot \Delta\phi = 6.1°$ has a solid angle of $\Delta\omega = \pi \Delta\phi^2 = 0.052$ ster. The flow rate into $\Delta\omega$ is then $\Delta I = 3.8\ 10^{15}$ H/s. - We may calculate the flow rate into an orifice of 10 mm inner diameter, 300 mm downstream of the cell's center. Such an orifice, e.g the opening of the tracker in Fig. 2, may be employed to perform differential pumping. From the cell's center, it appears under a solid angle of $\Delta\omega = 8.73 \cdot 10^{-4}$ sr. The flow rate through that orifice is $6.43 \cdot 10^{13}$ H/s, about 0.34% of the total flow leaving the beam tube on either side, corresponding to $2.43 \cdot 10^{-6}$ mbar l/s of H_1, and $1.22\ 10^{-6}$ mbar l/s of H_2 after recombination. In a typical run time of 10^6 s, a quantity of 1 mbar·l of molecular hydrogen is to be pumped.

III Summary: The properties of the flow of target gas (atomic hydrogen at 100 K) out of the cell's beam tube have been estimated using an analytic approach assuming molecular flow. The following results have been obtained:

1. About 29% of the total ABS flow exits at each of the two ends of the beam tube;
2. The half-width of the effusive beam is FHW = $2\theta = 6.1°$;
3. **(a)** Only about 0.34% of the flow emitted downstream towards the VELO vessel passes a 10 mm-orifice which indicates that efficient differential pumping could be implemented in a future PGT. **(b)** During a run of 10^6 s (12 d's) and if no other gas components would enter the VELO vessel, the VELO vacuum system would be loaded by a quantity as low as 1 mbar l of hydrogen (H_2).

Statements (1, 2, 3a) are independent of T_{cell}, and (3b) is for $T_{cell} = 100$K.

Molecular flow simulations are in progress to obtain more precise estimations of the flows to the PGT's neighbouring sections.

IV References:

[1] E. Steffens et al.: *Design Consideration on a Polarized Gas Target for the LHC*. Preprint available at: https://arxiv.org/abs/1901.06361

[2] E. Steffens and W. Haeberli: *Polarized gas targets*, Rep. Progr. Phys. **66** (2003), 1887.

[3] C.B. Lucas: *Atomic and Molecular Beams*. CRC Press (2017).