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Estimation of the Performance of a HERMES-type Gas Target Internal to the LHC

Erhard Steffens
Physikalisches Institut, Physics Dept., FAU Erlangen-Nürnberg
Erwin-Rommel-Str. 1, 91085 Erlangen, Germany
E-mail: Erhard.Steffens@fau.de

A storage cell target is capable of producing a high areal density at minimum gas flow into a vacuum system. At the LHC, such a target with polarized hydrogen atoms might be employed for the study of single-spin asymmetries in ultra-relativistic fixed-target pp collisions, or similar light-ion reactions with spin. Another application could be to inject heavy noble gases like Xe (M ≈ 131) in conjunction with a Pb beam to investigate Heavy Ion collisions. A storage cell target with polarized hydrogen or deuterium atoms has been operated successfully in the HERA 27.6 GeV electron beam by the HERMES collaboration. In a recent study by C. Barschel et al, the performance of a HERMES-type storage cell target combined with the full LHC beams has been estimated. In the present talk, the estimates and underlying assumptions are presented in detail. The luminosities obtained are for pp collisions of the order 10^{33}/cm^{2}s, and for HI collisions of the order of or above the Pb-Pb collider design value of 10^{27}/cm^{2}s. An alternative scheme to extract the LHC beam halo by Bent Crystals and to direct it onto a solid polarized target is discussed and the figure of merit (FoM) for both methods is presented. It appears that the polarized storage cell target offers a much higher FoM as compared with the bent-crystal scheme.

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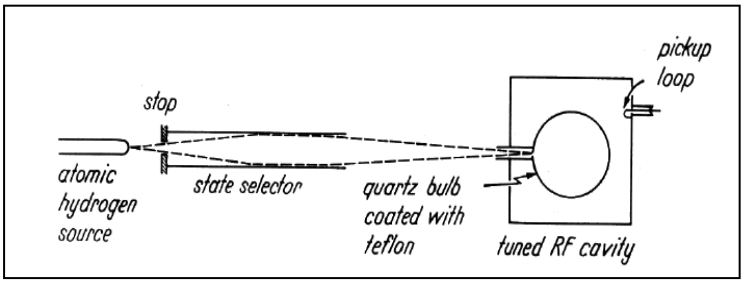
1. Motivation and History

The study presented here was motivated by the AFTER@LHC initiative [1] for a Fixed Target Experiment using the LHC beams, i.e. 7 TeV protons or 2.76 TeV/u Pb ions. Due to its potentially high luminosity and different kinematical range, a fixed target experiment could provide valuable data in addition to colliders like HERA or RHIC. The application of a HERMES-type gas target at the LHC was first discussed by C. Barschel et al [2]. The present talk gives a short description of the HERMES storage cell target and of the diagnostic SMOG device at LHCb which is providing first data from a gas target internal to the LHC. In addition to [2], more details on the performance estimates are provided, completed by a comparison of the Figure of Merit of the internal gas target and the bent-crystal extracted beams onto an external solid polarized target.

The history of the Storage Cell targets starts in the 1960's with Ramsey's Hydrogen Maser [3] shown in Fig.1, which was invented as sensitive resonant microwave amplifier.

__Fig.1__ Schematic representation of the Hydrogen Maser (picture taken from ref. [3]). A sextupole magnet as State Selector focuses H-atoms with electron spin up into a Teflon-coated quartz storage bulb inside a tuned μ-wave cavity.



The idea of a Teflon-coated storage cell fed with polarized hydrogen from an Atomic Beam Source (ABS) [4] as target for scattering experiments was proposed at the 2nd Polarization Symposium (Karlsruhe 1965 – 50 years ago!) by Prof. Willy Haeberli (Wisconsin). About 15 years later, he and his group conducted a first test experiment of this idea, reported at the 5th Polarization Symposium (Proc. Santa Fe 1980, p. 931). Polarized H-atoms from an ABS were injected into the storage cell traversed by a beam of 12 MeV α particles. The scattered α's were detected by two detector telescopes left and right behind exit windows. The results were quite exciting: (i) Despite about 900 wall collisions in the average, and after background subtraction, no significant depolarization of the stored H-atoms could be detected; (ii) the areal density of the fiducial target volume seen by the detectors was $1.1\cdot10^{12}/\mathrm{cm}^2$; (iii) similar results were obtained on deuterium. - Later, a number of high-density storage cell targets were applied at various storage rings (see Table 3 in ref. [4]).

2. Characteristics of the HERMES H&D Storage Cell Target

2.1 Overview of the target system (see Fig.2)

A polarized atomic beam of hydrogen or deuterium atoms (H, D) is produced by an ABS[1] (see above), consisting of a dissociator with nozzle, a differential pumping system and a system of sextupole magnets and RF transitions to select the required hyperfine states [5]. In this way, vector- and for D also tensor-polarized beams can be obtained and switched between opposite signs.

This beam is injected ballistically via feed tube of the T-shaped storage cell (see Sect. 2.2) into the center of the long narrow beam tube along the electron beam axis. The cell is located

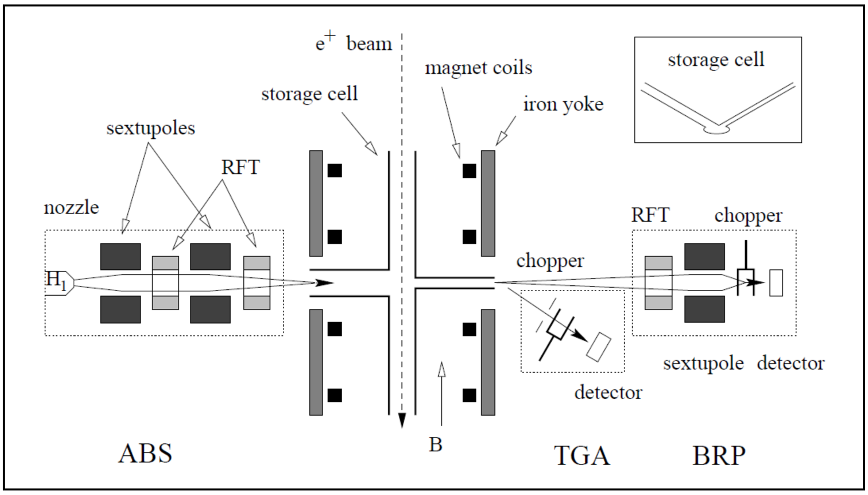


Fig.2 *Overview of the HERMES target systems (taken from ref. [5]). For details see text.*

in a target chamber with homogeneous longitudinal or transverse holding field and high pumping power. A triangular density distribution of the target gas is assumed with its maximum in the center.

A narrow 'sample' tube at the cell center serves to form a sample beam of target atoms and molecules which are analyzed by a diagnostic system, consisting of the Target Gas Analyzer (TGA) for the measurement of the fraction α of H-atoms in H_2-molecules[2], and a Breit-Rabi-Polarimeter (BRP) measuring the substate population, from which the polarization P of the atoms is deduced. For more details, the reader is referred to [5] and references therein.

By means of Monte Carlo simulations of the molecular flow, sampling corrections are deduced which allow to compute from α and P the average polarization of protons (deuterons) as seen by the beam. As an example, the results of the 2002 run with transverse proton target are given here (ref. [5], Table 8): $P_{BRP} = \pm (0.86 \pm 0.03)$, $\alpha = 0.90 \pm 0.03$, density-averaged corrected target polarization $P^T = \pm (0.78 \pm 0.04)$.

2.2 Operation of the HERMES target

The target was installed in 1996 at the HERA electron storage ring and operated until 2005 with polarized ^1H, ^2D and unpolarized gas in the mass range H_2 to Xe [5] at an electron energy of E = 27.6 GeV and beam currents of $I_e \leq 40$ mA in parallel to the experiments ZEUS and H1. Regular access was scheduled for about once per month. The vacuum system of the target involved pumps of a total pumping speed of about 10^4 l/s.

The target was located in a low-β section and a system of narrow fixed and movable Tungsten collimators served to shield the cell from Synchrotron radiation produced by the upstream bending and focusing magnets. A central X-ray beam traversed the cell on axis with an estimated power of 200 – 300 W (as the power scales with γ^4 and beam current, the corresponding X-ray power for a 7 TeV proton beam is less than 1 W and thus negligible).

It appeared essential for high polarization and low fraction of molecules to run the target at a temperature of 100 K or below in order to build-up a layer of frozen water at the inner walls of the cell, resulting in a surface with low recombination of the atomic hydrogen gas. In addition, the cell at 100 K produces a √3 higher areal density than at 300 K.

A B field of about 300 mT served to decouple the electron and nucleon spins, enabling high polarization of all substates in the so-called Strong Field case [4]. It was chosen such that Bunch-Field depolarization is suppressed [6].

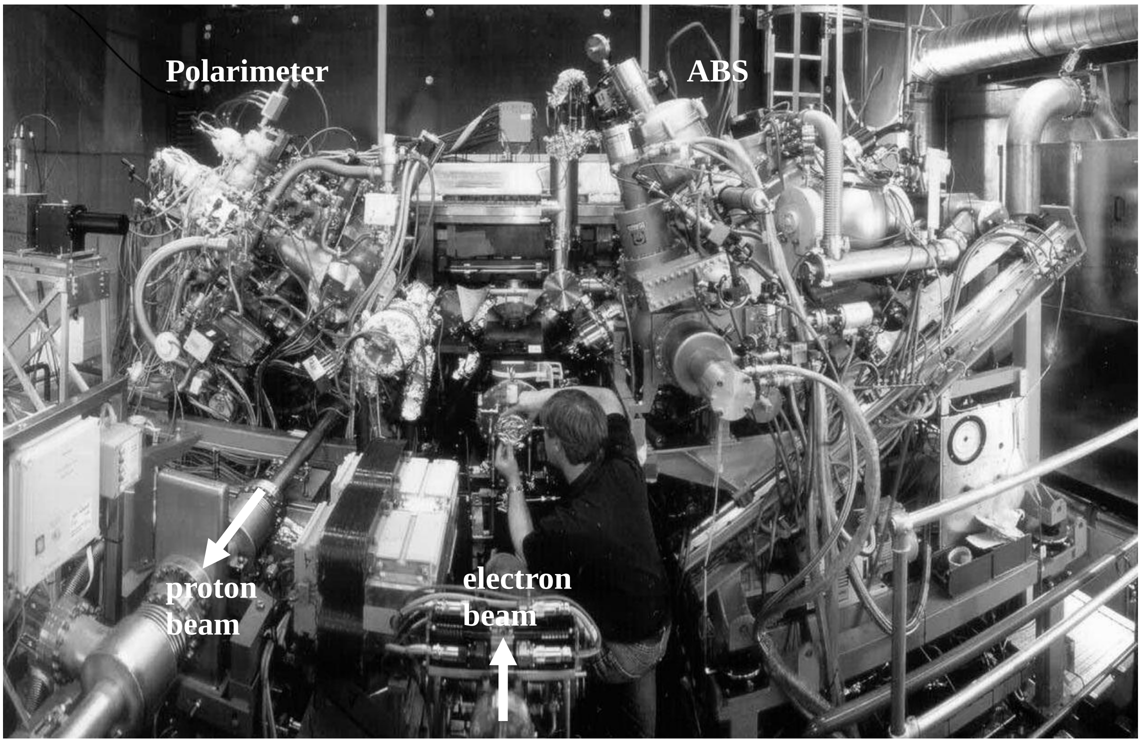


Fig.3 *Photograph of the HERMES-target in the HERA tunnel. The 920 GeV proton beam passes the experiment via a tube on the left without interaction. The 27.6 GeV electron beam moves into the plane of paper via the target chamber to the gap of the spectrometer magnet.*

3. The SMOG Gas Target @ LHCb for Diagnostic Purposes

First experience of the effect of a gas target in the LHC comes from the SMOG system which serves as a monitor for the LHCb vertex location [7]. The Si-strip detector of this device, called VELO, is enclosed in a chamber consisting of two halves which can be positioned near the beam axis. In the closed position, the minimum distance to the beam axis is 8 mm, and that of the Al housing with its half-cylindrical gap 5 mm. This means that a well-tuned and stable LHC beam can run within a cylindrical tube of 10 mm inner diameter. At injection, a free space of about 50 mm in diameter has to be provided.

Originally, residual gas in the pressure range of 10^{-9} mbar has been employed as scattering target. By switching off the ion pumps, a pressure rise up to $5 \cdot 10^{-9}$ mbar occurs which is used as target. Since 2012, Neon gas can be injected up to a pressure of $p \approx 1.5 \cdot 10^{-7}$ mbar resulting in much higher rates. Such a pressure at room temperature corresponds to a volume density of $\rho = 4 \cdot 10^{12}/\text{cm}^3$. For a pressure bump 10 m long, the areal density θ is $4 \cdot 10^{15}/\text{cm}^2$. The beam losses are negligible ($\tau >> 10^8$ s). In his talk at the AFTER@LHC workshop on Nov. 17, 2014, Ferro-Luzzi concludes: (i) LHCb has pioneered the use of gaseous fixed targets in the LHC for beam-gas imaging, luminosity calibrations, ghost and bunch charge measurements; (ii) Extensions involving target polarization would require much bigger investments and long studies.

4. Estmations for a Proposed Polarized LHC Storage Cell Target

We consider proton and Lead beams of nominal value (f_R = 11.25 kHz)

Protons: $I_p = 3.63\cdot10^{18}$ p/s

Lead ions: $I_{Pb} = 4.64\cdot10^{14}$ Pb/s

The 1σ-beam radius at the Interaction Point (IP) at full energy is < 0.02 mm, i.e. negligible compared with the cell radius of the order of 5 mm (see Sec. 3). At injection energy (450 GeV for protons), a much bigger safety radius of the order of 25 mm has to be provided, i.e. an openable storage cell is required.

The luminosity half-life is about 10 h. For parallel/parasitic operation the reduction of the half-life should be limited. We assume a 10% reduction as a reasonable value.

4.1 Geometry proposed for a LHC storage cell

The storage cell itself consists of a straight beam tube of length $2L_1$ = 1000 mm and diameter $2\ r_1 = D_1$ = 14 mm > D_{VELO} = 10 mm, and a feed tube L_2 = 100 mm long and D_2 = 10 mm inner diameter. An additional capillary (not shown) enables injection of unpolarized gas from a gas handling system into the cell center.

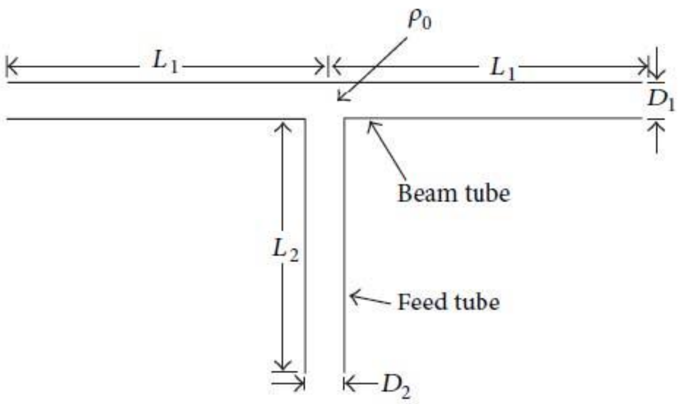


Fig.4 *Schematic representation of the T-shaped storage cell with straight beam tube of length 2 L_1 and feed tube of length L_2 connecting to the center where the maximum volume density ρ_0 arises.*

The gas conductance C_i of a tube of diameter D_i and length L_i (in cm) at temperature T in K and molecular weight of the gas M is given by

$$C_i\ [\mathrm{l/s}] = 3.81\ \sqrt{(T/M)}\cdot D_i^3 / (L_i + 1.33\ D_i)$$

The maximum density ρ_0 arises in the cell center and is given by $\rho_0 = I / C_{tot}$, I being the flux of injected atoms [s^{-1}] and $C_{tot} = 2\ C_1 + C_2$ the total gas conductance [l/ s] of all tubes from the center outwards. The areal density of the target θ [cm^{-2}] is then $\theta = \rho_0 \cdot L_1$.

Example: Atomic hydrogen (M =1) and LHC target cell (L_1 = 500 mm, D1 = 14 mm) at 300 K. With the HERMES flow rate $I = 6.5\cdot10^{16}$/s we obtain $\rho_0 = 5.07\cdot10^{12}/cm^3$ and an areal density $\theta = L_1\cdot\rho_0 = 2.54\cdot10^{14}/cm^2$.

A narrow beam tube gives low conductance and thus a high density, but sufficient space for the beam has to be provided. Additional requirements are (i) cell wall with low recombination, and (ii) a strong guide field over the cell volume [4, 5].

4.2 Estimate of a polarized gas target (^{1}H, ^{2}D) for the study of Single-Spin asymmetries

We assume a cell of LHC geometry mentioned before, fed by a HERMES-type ABS[1] with nominal flow rate, and obtain the areal density of hydrogen atoms $\theta = 2.54 \cdot 10^{14}$ H/cm^2, limited by the available source intensity. With proton beam intensity $I_p = 3.63 \cdot 10^{18}$/s we have a pp luminosity of

$$\mathcal{L}_{pp} = 0.92 \cdot 10^{33} / \text{cm}^2\,\text{s}$$

At $\sqrt{s} \approx 100$ GeV the total pp cross section is about 50 mb = $5 \cdot 10^{-26}$ cm^2. This results in a loss rate dN/dt of $4.5 \cdot 10^7$/s or, with the number N of stored protons of $N = 3.2 \cdot 10^{14}$, a maximum relative loss rate

$$(dN/dt) / N = 1.4 \cdot 10^{-7}/\text{s}$$

We conclude that the polarized H target does not affect the life time of the 7 TeV proton beam. In the same way by using an ABS, a vector and tensor polarized deuterium target can be produced. The densities are comparable to hydrogen.

At the HERMES H&D target, the cell was run at about 100 K for obtaining a layer of frozen water with low recombination, and for boosting the density by a factor $\sqrt{(300/100)} = \sqrt{3} = 1.73$. This increases the maximum luminosity to $\mathcal{L}_{pp}$ (100 K) = $1.59 \cdot 10^{33}$/ cm^2 s which is 16% of the pp collider design value.

In 1995, prior to the H&D target, a polarized ^{3}He target has been operated at HERMES for the study of the neutron spin structure [8]. ^{3}He gas was polarized by Optical Pumping with infrared light. With a modern *state of the art* ^{3}He target source a very dense target could be built. A choice of the best target species by physics arguments must be made in an early phase of a possible polarized gaseous fixed target at the LHC.

4.3 Basic requirements for a polarized HERMES-type gas target in the LHC tunnel

The high gas flow of 10^{17} H-atoms/s corresponding to a H_2-gas flow of $1.9 \cdot 10^{-3}$ mbar l/s into the target section must be accommodated by means of a powerful differential pumping system for which the necessary space must be provided. Out of the total flow accepted by the feed tube, 46% flows back via the feed tube and 2 x 27% through both ends of the beam tubes, forming a directed beam along the ion beam axis.

In case of a failure of the target source (ABS) and/or the polarimeter, the valves to the target chamber will be closed by the Interlock. In this case, the option to feed the cell with unpolarized gas for a different physics program should exist. Access to the target area for fixing the target should be provided in due time.

The experimental area for the AFTER@LHC experiment must be designed such that it can run in parallel to the Collider experiments. The cell should be located close to a beam waist. The counter-rotating beam has to be guided through the experiment, either (i) on-axis of the storage cell, or (ii) by means of a Chicane of moderate deflection angle sideways by the cell.

4.4 Comparison with the Bent-Crystal proposal

It has been proposed [9] to extract the halo of the LHC beam by a bent-crystal deflector onto a solid polarized proton target. Based on experimental studies, a beam intensity of $I_p = 5 \cdot 10^8$/s is expected. The authors [9] claim that machinery of a COMPASS-type Frozen-Spin target can not be accommodated in the LHC tunnel. Instead, a UVa-type NH_3 DNP target[3] with smaller target set-up may be considered for this comparison with parameters [10]

$$n_t = 1.5 \cdot 10^{23}/\mathrm{cm}^2,\ \ P_p = 0.85,\ \ \text{dilution factor } f = 0.17$$ [4]

This results in a Figure of Merit as defined in [10] of $FoM = n_t\, P_p^2\, f^2 = 3.1 \cdot 10^{21}/\mathrm{cm}^2\,\mathrm{s}$. As the beam intensity I_p enters the quality of the measurement, too, we define

$$FoM^* = I_p \cdot FoM = P_p^2 \cdot f^2 \cdot \mathcal{L}_{pp}$$

Table 1 *Comparison of the Figure of Merit FoM* as defined above, for the different experimental schemes*

Target and beam technology	FoM* [$cm^{-2}\, s^{-1}$]
UVa target and bent-crystal extracted beam	$1.57 \cdot 10^{30}$
COMPASS target " " "	$1.87 \cdot 10^{32}$
HERMES-type target and full LHC beam (T = 300/100 K, P = 0.85, α = 0.95)	$0.60/1.04 \cdot 10^{33}$

As a result of this comparison we conclude that the proposed HERMES-type polarized gas target for the LHC gives at T = 100 K a FoM* which is 660 x, i.e. nearly three orders of magnitude higher than for the Bent-Crystal scenario. Even with the present COMPASS target, the gas target approach is more than 5 x better in measurement quality.

5. LHC Storage Cell Target Fed with Unpolarized Gas

5.1 Opportunity for the study of Heavy-Ion collisions, e.g. ^{208}Pb on $^{\approx 131}$Xe

Like at HERMES the program could easily be extended by running the storage cell target with unpolarized gas in a broad mass range. In this way, an additional Heavy-Ion Fixed-Target program in parallel to the operation of the collider could be initiated at moderate costs compared with a new machine.

The LHC is a collider with two-in-one main dipoles which enable collisions between beams of equal rigidity, e.g p-p collisions at a maximum energy of 2 x 7 TeV and Pb-Pb collisions at 2 x 2.76 TeV/nucleon. Different beams of equal rigidity $|B \cdot \rho| = c \cdot p\,/q \approx E\,/q$ could be collided as well. A run p (3.50 TeV) on Pb (1.38 TeV/u) for the ALICE experiment has been provided in 2013. Other ions than protons or Pb have not been used for experiments so far.

By means of the storage cell target fed with unpolarized gas, different combinations of masses could be studied, e.g. Pb on Xe or on Ne. This would open up a different kinematical range, together with a flexible choice of the target gas. For the Pb beam, the nucleon-nucleon CM energy is $\sqrt{s} = 71.9$ GeV, above the values of the SPS Heavy Ion program (about 20 GeV) and the FAIR CBM program (4 – 9 GeV).

5.2 Estimations for a Xe target and possible luminosities of Pb-Xe collisions

For the Pb beams in Pb-Pb collider mode we assume a beam life time τ_C of 10 h/ ln2 = 14.4 h. From the Pb-Pb hadronic cross section of 7.65 barn we estimate for Pb-Xe by scaling with the nuclear radii a σ_{tot} (Pb-Xe) of 6.6 barn. We require that the <u>additional</u> target life time[5] $\tau_t = 10 \cdot 14.4\ \mathrm{h} = 5.18 \cdot 10^5\mathrm{s}$ is related to the loss rate $dN/dt = \dot{N}$ (N = number of stored Pb ions = $4 \cdot 10^{10}$) by $\dot{N}/N = \{5.18 \cdot 10^5 \mathrm{s}\}^{-1}$, i.e. $\dot{N} = 7.72 \cdot 10^4/\mathrm{s} = \mathcal{L}_{Pb\text{-}Xe} \cdot \sigma_{tot}(Pb\text{-}Xe)$. This results in a maximum Pb-Xe luminosity of $\mathcal{L}_{Pb\text{-}Xe} = 1.17 \cdot 10^{28}/cm^2s$ and a maximum density of Xe atoms of $\theta = 2.52 \cdot 10^{13}/\ cm^2$. The corresponding Xe flow rate into the target cell at 300 K is $2.1 \cdot 10^{-5}$ mbar l/ s. The result shows that a high luminosity for heavy ion collisions can be achieved by the storage cell technique. The predicted value is one order of magnitude higher than the Pb-Pb collider design luminosity of $10^{-27}/\ cm^2\ s$.

For the Bent-Crystal case, the luminosities for medium A targets are comparable, for hydrogen they are considerably lower.

6. Conclusions

The Storage Cell target gives a high areal density at minimum gas input. Such a target has been operated at the HERA 27.6 GeV electron storage ring in 1996 to 2005 at $e^{\pm}$ currents up to 40 mA with excellent performance over many months of continuous running. For the LHC, a cell 1000 mm in length and 14 mm i.d. has been assumed for the estimates presented here, which is in accordance with the aperture requirements of the SMOG/VELO detector at LHCb.

The estimates for a polarized hydrogen target based on a HERMES-type target source indicate that pp↑ luminosities of $10^{33}/cm^2\ s$ seem accessible, nearly three orders of magnitude higher than a Bent-Crystal extracted beam and a UVa-type DNP target used at JLab. In addition, there is no unpolarized background, and the sign of the polarization is switchable at 1/min or faster, both resulting in a better systematic error.

If the storage cell is filled with unpolarized gas e.g. from a gas handling system, then p-A or Pb-A collisions could be be studied with gases like H_2, He, Ne, Ar, Kr, Xe at $\sqrt{s_{NN}} = 72$ GeV and high luminosity.

Possible locations of an AFTER@LHC experiment with HERMES-type gas target at the LHC have to be identified in due time in order to perform a realistic planning and design!

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[1] Atomic Beam Source [4].

[2] (1-α) is the fraction of protons in H_2-molecules with lower polarization.

[3] UVa = Univ. of Virginia target group; NH_3 = frozen Ammonia target; DNP = Dynamical Nuclear Polarization.

[4] We define n_t = areal density of target nucleons and P_p = polarization of target protons; then $f \cdot n_t$ is the density of polarizable nucleons and $f \cdot P_p$ the average polarization of target nucleons.

[5] Note: total beam life time of the collider c plus target t is $\tau_{tot} = \{1/\tau_c + 1/\tau_t\}^{-1}$.