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

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1. Motivation

**AFTER@LHC initiative** for A Fixed-Target Experiment at the LHC

see talk by Jean-Philippe Lansberg (Orsay)

Fixed-Target experiments have led to the discovery of many new phenomena. Due to their potentially high luminosity and different kinematical range, they may be valuable additions to colliders (e.g. HERA, RHIC).

Regular AFTER@LHC meetings at CERN → Special issue of the open journal *Advances in High Energy Physics*, entitled *Physics at a Fixed-Target Experiment Using the LHC Beams*, will appear in fall 2015.

Accepted paper C. Barschel (LHCb), P. Lenisa (Ferrara), A. Nass (FZJ) and E.St. (Erlangen): *A Gas Target Internal to the LHC for the Study of pp Single-Spin Asymmetries and Heavy Ion Collisions* devoted to Prof. W. Haeberli on the occasion of his 90th birthday on June 17, 2015!

Basic ideas and estimations presented here!
...and a bit of history

A Storage Cell was part of the hydrogen MASER (Ramsey 1965, NP 1989), consisting of a dissociator with nozzle, a ‘state selector’ (sextupole magnet) injecting into the storage cell (‘bulb’) coated with Teflon in homogenous B-field and inside an rf-cavity used as sensitive microwave amplifier.

The idea of a Teflon-coated storage cell filled with polarized hydrogen from an ABS as target for Scattering Experiments was proposed at the 2nd Polarization Symposium (Karlsruhe 1965 – fifty years ago!) by Prof. Willy Haeberli.

Much later, he did a first experimental test of this idea with his group in Madison (Wisconsin). The results were reported at the 5th Int. Symp. on Pol. Phenomena in Nuclear Physics, Santa Fe 1980, p. 931.
First storage cell employed in a nuclear scattering experiment

- Teflon-coated storage vessel filled with polarized H-atoms from an Atomic Beam Source (left)
- 12 MeV $\alpha$ beam passing the cell by means of entrance and exit tube
- Scattered $\alpha$'s were detected left and right behind exit windows

Results:
(i) despite about 900 wall collisions and after background subtraction, no significant depolarisation!
(ii) Areal density of the target from the volume seen by the detectors: $1.1\cdot10^{12}/\text{cm}^2$
(iii) Similar results for deuterium
2. Characteristics of the HERMES storage cell target

Installed at the 30 GeV HERA electron ring in a low-β section (1995 – 2005); operated with polarized $^3$He, $^1$H and $^2$D and unpolarized gas $\text{H}_2$ to Xe [see HERMES H&D target paper NIM A540 (2005) 68].

T-shaped storage cell from thin Al, straight Beam tube 400 mm long of elliptical cross section $r_x \approx 15 \sigma_x + 1$ mm ($x = \text{hor, vert}$), Feed tube from the side 100 mm long, 10 mm i.d., additional capillary for a gas feed system. Cell temperature $T_c = 100 – 300$ K.

Maximum density $\rho_0$ at the cell center given by $\rho_0 = I / C_{\text{tot}}$

with $C_{\text{tot}} = C_1 + C_2 + ...$, resulting in an areal density $\theta = \rho_0 \cdot L/2$

Narrow beam tube results in high density, but one has to provide sufficient space for the beam!

Additional requirements: (i) wall properties for low recombination, (ii) ‘strong’ guide field at the cell.
Schematic of the HERMES H&D target
(top view)

Fig. taken from HERMES H&D target paper NIM A 540 (2005) 68

• Polarized atomic beam injected from left into cell of elliptic cross section, traversed by the lepton beam ($B = \text{guide field}$)
• A sample beam is extracted from a tube and analyzed by a QMS ($\alpha = \text{molecule fraction}$) and a Polarimeter ($P = \text{polarization of atoms}$)
• By means of simulations, Sampling corrections are deduced which allow to compute from $\alpha$ and $P$ the average polarization of protons (or deuterons) as seen by the beam.
Performance for H (2002/03)

Results of the target analysis for the HERMES 2002/03 data taking period with transverse proton polarization as function of the number of days, since August 1, 2002 - taken from HERMES target paper (2005);

Top: Degree of dissociation $\alpha$ measured by the TGA ($\alpha = 1$: no molecules);

Bottom: Positive and negative vector polarization $P_z$ as measured by the Breit-Rabi-Polarimeter.
HERMES H&D target (running 1996 – 2005)
HERMES H&D target: more details...

- Operated 1996 – 2005 in the HERMES e-ring (E = 27.6 GeV, I_e ≤ 40 mA) parallel to ZEUS and H1. Scheduled access was about 1x per month, plus in emergency, e.g. a broken dissociator tube. The vacuum system involved pumps of a total pumping speed of about 10,000 l/s.

- A system of narrow Tungsten collimators served to shield the cell from synchrotron radiation produced by upstream bending and focusing magnets. A central X-ray beam traversed the cell on axis with an estimated power of a couple of hundred Watt (as the power scales with $\gamma^4$ and beam current, the corresponding X-ray power for a 7 TeV proton beam is less than 1 W – calculations for the LHC lattice required).

- Essential for high P and low $\alpha$ was a stable running at about T = 100 K which allowed for the build-up of a layer of frozen water inside the storage cell with low recombination for atomic hydrogen. A cell at 100 K produces a $\sqrt{3}$ higher areal density, compared with 300 K.

- A B-field of about 0.3 T served to decouple electron and nucleon spins, enabling high polarization of all substates (‘strong-field’ case). It was chosen such that bunch-field depolarization is suppressed.

All these and more effects have to be studied for LHC conditions before such a target can be proposed for AFTER@LHC.
3. **SMOG gas target @ LHCb**

for diagnostic purposes (vertex locator)

from talk by M. Ferro-Luzzi (CERN) workshop **AFTER@LHC** on 17-Nov-2014

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**Diagram:**
- **Beam 1** and **Beam 2** indicated.
- **Vertex Locator** crucial: displaced IP 11.25m.
- **Magnet** and various detector components labeled (RICH1, RICH2, ECAL, HCAL).
- Angle ≈12° indicated.
SMOG gas target @ LHCb

Workshop AFTER@LHC on 17-Nov-2014: talk by M. Ferro-Luzzi (CERN) on the SMOG gas target as a monitor for the LHCb IP (Vertex Locator).

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 min. distance of the detectors to the beam axis is 8 mm, and that of the Al housing 5 mm. At injection, a free space of ≈ 50 mm in diameter is required.

Originally, pure residual gas has been used (10^{-9} mbar). By switching off the ion pumps, a pressure rise up to 5\cdot10^{-9} mbar occurs which was used as target. Since 2012, Neon gas is injected up to a pressure of p \approx 1.5\cdot10^{-7} mbar resulting in much higher rates.

Such a pressure at room temperature corresponds to a volume density of \rho = 4\cdot10^{12} /\text{cm}^3. For a pressure bump 10 m long, the areal density \theta is 4\cdot10^{15}/\text{cm}^2. The beam losses are negligible (\tau >> 10^8 s).

In his summary, M. Ferro-Luzzi concludes:

• LHCb has pioneered the use of gaseous “fixed target” in the LHC for beam-gas imaging, luminosity calibration, ghost and bunch charge measurements

• Extensions involving target polarization would require much bigger investments and long studies (!)
4. LHC beams and geometry of a LHC storage cell

We consider a proton and a lead beam at nominal values ($f_R = 11.25$ kHz)

- **Protons:** $I_p = 3.63 \cdot 10^{18}$ p/s at 7 TeV
- **Lead:** $I_{Pb} = 4.64 \cdot 10^{14}$ Pb/s at 2.76 TeV/u

The $1\sigma$-beam radius at IP (full energy) is $< 0.02$ mm, i.e negligible compared with the cell radius of $> 5$ mm. At injection energy (450 GeV for protons), a much bigger safety radius of the order of 25 mm has to be provided, i.e. a cell for opening is required.

The lumi half-life is about 10 h. For parallel/parasitic operation the reduction of the half-life should be a small fraction of it, e.g. 10% or less.
**Geometry of a LHC storage cell**

**LHC Requirements:** Beam tube for opening to 50 mm with diameter $D_1$ in closed position and half length $L_1$. We assume $D_1 = 14$ mm $> D_{VELO} = 10$ mm, and $L_1 = 500$ mm. As Feed tube we assume the standard size $D_2 = 10$ mm and $L_2 = 100$ mm and a Cell temperature of $T = 300$ K.

The Gas Conductance $C_i$ of a tube of diameter $D_i$ and length $L_i$ is

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

with $M =$ molecular weight.

If gas at a flow rate $I \ [part./s]$ is injected via feed tube, then a maximum density $\rho_0$ builds up at the cell center, decreasing linearly to the ends, and given by

$$\rho_0 = I / C_{tot} \quad \text{with} \quad C_{tot} = C_1 + C_2 + ...$$

**Example**

Atomic hydrogen ($M = 1$) and LHC target cell: $C_{tot} = 2 \ C_1 + C_2 = 12.81 \ l/s$

With $I = 6.5 \cdot 10^{16}/s$ (HERMES) we obtain

$$\rho_0 = 5.07 \cdot 10^{12}/cm^3$$

and an areal density $\theta$ of the target of

$$\theta = L_1 \cdot \rho_0 = 2.54 \cdot 10^{14}/cm^2$$
5. Estimation: Polarized gas target \((^1\text{H}, ^2\text{D}, ^3\text{He})\)
for the study of Single-Spin-Asymmetries

We assume that polarized H gas is injected ballistically into a T-shaped storage cell \(2L_1 = 1000\) mm long with inner diameter \(D_1 = 14\) mm, at 300 K via a standard feed tube by a HERMES-type Atomic-Beam Source (ABS) of intensity \(I = 6.5\cdot10^{16}\) H/ s. (previous slide →) The resulting areal density is

\[
\theta = 2.54\cdot10^{14} \text{ H/ cm}^2
\]

limited by the available source intensity. With \(I_p = 3.63\cdot10^{18}\) / s as proton current we have a \(p\bar{p}\) luminosity

\[
\mathcal{L}_{pp} = 0.92\cdot10^{33} / \text{ cm}^2 \text{ s}
\]

At \(\sqrt{s} \approx 100\) GeV the total pp cross section is about 50 mb = \(5\cdot10^{-26}\) cm\(^2\). This gives a loss rate \(dN/dt\) of \(4.5\cdot10^7\) / s or, with the number of stored protons \(N\) of \(3.2\cdot10^{14}\), a max. relative loss rate \((dN/dt)/N = 1.4\cdot10^{-7}\) / s.

We conclude that the H target does not affect the life time of the 7 TeV proton beam.
Polarized gas target ($^1$H, $^2$D, $^3$He) for the study of Single-Spin-Asymmetries

In the same way by using an ABS, a polarized deuterium target could be produced. Densities are comparable to hydrogen.

At the HERMES H&D target, the cell was run at about 100 K for obtaining a frozen-water layer with low recombination rate, and for boosting the density by a factor $\sqrt{(300/100)} = \sqrt{3} = 1.73$. This would increase the maximum luminosity to

$$L_{pp} (100 \text{ K}) = 1.59 \cdot 10^{33}/ \text{cm}^2 \text{ s}$$

which is 16% of the pp collider design luminosity.

At HERMES, a polarized $^3$He target has been operated during in1995 for the measurement of the spin structure function of the neutron. $^3$He gas was polarized by Metastability Exchange Optical Pumping with 1083 nm infrared light. Modern lasers are capable of delivering photons at an even higher rate than in the 1990’s, thus making a $^3$He source much more intense than an ABS for the stable hydrogen isotopes.

A choice of the best target source (or combination of target sources?) by physics arguments must be made in an early phase of the project.
Basic requirements for a polarized gas target in the LHC tunnel

For the performance parameters discussed so far, a few essentials must be enabled:

- A high gas flow of about $10^{17}$ atoms/s corresponding to $Q'(H_2) = 1.9 \cdot 10^{-3}$ mbar l/s into the target section must be accommodated which requires a powerful differential pumping system requiring some space.
HERMES H&D target (running 1996 – 2005)
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- A high gas flow of about $10^{17}$ atoms/s corresponding to $Q(H_2) = 1.9 \cdot 10^{-3} \text{ mbar l/s}$ into the target section must be accommodated which requires a powerful differential pumping system requiring some space. Out of the total flow accepted by the feed tube, 46% exits from the feed tube, 2 x 27% through both ends of the beam tubes, forming a directed beam along the beam axis.

Example: to pump the ‘target section’ to $10^{-7}$ mbar, a pumping speed of $S = 2 \cdot 10^4 \text{ l/s}$ is needed! This could probably be realized by modern adsorption pumps (Cryo, NEG) of high capacity, e.g. 0.2 bar·l of $H_2$ per day.

- In case of a failure of the target source and/or the polarimeter, the valves to the target section will be closed by the Interlock. In this case, the option to feed the cell with unpolarized gas for a different physics program is possible. Access to the target area for fixing the polarized target should be enabled 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: (i) on-axis of the storage cell, or (ii) with a Chicane of moderate deflection angle sideways by the cell.
Comparison with Bent-Crystal Proposal


Extract the LHC beam halo (p) by a bent-crystal onto a polarized proton target. Here, based on exp. studies, a beam intensity of \( i_p = 5 \cdot 10^8/s \) is expected.

The authors claim that the COMPASS type frozen spin target machinery takes too much space in the LHC tunnel. Instead, a UVa-type NH\(_3\) DNP target* with smaller target set-up may be considered for this comparison with parameters§:

\[
\begin{align*}
    n_t &= 1.5 \times 10^{23}/cm^2, \quad P_p = 0.85, \quad \text{dilution } f = 0.17.
\end{align*}
\]

This results in a \( \text{FoM} = n_t \cdot P^2 \cdot f^2 = 3.1 \cdot 10^{21}/cm^2 \). As the beam intensity \( i_p \) also enters the measurement quality, we define

\[
\text{FoM}^* = i_p \cdot \text{FoM} = P^2 \cdot f^2 \cdot i_p \cdot n_t = P^2 \cdot f^2 \cdot L
\]

**Results:**

- UVa-target and bent-crystal extr. beam
  - ‘COMPASS-target’
  - ‘HERMES’ target and full LHC beam

  \( T = 300/100 \text{ K}, \ P = 0.85, \ \alpha = 0.95 \)

\[
\begin{align*}
    \text{FoM}^* &= 1.57 \cdot 10^{30}/cm^2 \text{ s} \\
    \text{FoM}^* &= 1.87 \cdot 10^{32}/cm^2 \text{ s} \\
    \text{FoM}^* &= 0.60/1.04 \cdot 10^{33}/cm^2 \text{ s}
\end{align*}
\]

*) from talk N. Doshita − AFTER@LHC 2014

§) note that \( n_t \) = density of target nucleons; then \( f \cdot n_t \) is the number of polarizable nucleons
6. Estimation: Unpolarized gas target ($^{1}\text{H}_2$, $^{20}\text{Ne}$, $^{84}\text{Kr}$, $^{131}\text{Xe}$, ... ) for the study of Heavy-Ion collisions, e.g. $^{208}\text{Pb}$ on $^{131}\text{Xe}$

The ideas presented here are motivated by the fact that 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 the same rigidity, i.e. $p$-$p$ collisions at a maximum energy of $2 \times 7$ TeV and $\text{Pb}$-$\text{Pb}$ collisions at a maximum energy of $2 \times 2.76$ TeV nucleon. Different beams of equal rigidity $|B \cdot \rho| = c \cdot p / q \approx E / q$ can be collided as well. A run of $p$ (3.50 TeV) on $\text{Pb}$ (1.38 TeV/A) for the ALICE experiment has been provided in 2013. Other ions than $p$ or $\text{Pb}$ 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. $\text{Pb}$ on $\text{Xe}$ or on $\text{Ne}$. This would open up a different kinematical range, together with flexibility in the choice of the target gas. For the $\text{Pb}$ beam, the nucleon-nucleon CM energy is $\sqrt{s} = 71.9$ GeV, above the values of the CERN SPS Heavy Ion program (about 20 GeV) and the FAIR CBM program (4 – 9 GeV).
Pb on Xe target with increase in Pb-beam loss rate limited to 10%

- Assume that Pb beams in Pb-Pb collider mode have a beam life time $\tau_c$ of 10 h/0.693 = 14.4 h

- From the hadronic cross section of 7.65 barn we estimate for Pb-Xe by scaling with the nuclear radii $a_{\text{tot}}$ (Pb-Xe) of 6.6 barn

- Require that the additional target life time* $\tau_t = 10 \cdot 14.4 \text{ h} = 144 \text{ h}$ is related to the loss rate $dN/dt = N'$ ($N$ = number of stored Pb ions = $4 \cdot 10^{10}$) by:

\[
N' / N = 1 / 144 \text{ h}, \quad \text{i.e. } N' = N / 5.18 \cdot 10^5 \text{ s} = \frac{L_{\text{Pb-Xe}}}{a_{\text{tot}} (\text{Pb-Xe})} 
\]

- This results in a maximum Pb-Xe lumi of $L_{\text{Pb-Xe}} = 1.17 \cdot 10^{28}$ / cm$^2$ s and a max. density of Xe atoms $\theta = 2.52 \cdot 10^{13}$ / cm$^2$. The corresponding Xe flow rate into the cell target 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. This 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 smaller.

*) note: total beam life time of collider $c$ plus gas target $t$ is $\tau_{\text{tot}} = \frac{1}{\tau_c} + \frac{1}{\tau_t}$
Conclusions

➤ **Storage cell target** gives highest areal density at minimum gas input. Good performance over many months experienced at the HERA 27.6 GeV electron storage ring in 1996 – 2005 at $e^\pm$ currents up to 40 mA. A cell of 1 m in length and 14 mm i.d. has been assumed for the estimates which is in accordance with the aperture requirements at the SMOG/VELO detector of LHCb.

➤ **Polarized H gas target:** (i) $p\bar{p}$ luminosities of $10^{33}$/cm$^2$ s seem accessible – about 662 x higher* than a Bent-Crystal beam and a UVa-type target used at JLab and 10% of the collider lumi; (ii) practically no background i.e. better systematics; (iii) sign of P switchable at 1/min or faster.

➤ **Cell filled with unpolarized gas:** p-A and Pb-A collisions could be studied with gases like H$_2$, He, Ne, Ar, Kr and Xe at $\sqrt{s_{NN}} = 72$ GeV and high luminosity.

➤ Possible locations at the LHC have to be identified in order to perform a realistic planning and design!

*) Note added in proof: In my presentation, I gave a factor 28 which is too low.

Thank you!