Perspectives for a polarized internal gas target at LHC

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Motivation

- AFTER@LHC: *A Fixed-Target ExpeRiment for hadron, heavy ions and spin-physics at LHC*.

- Physics goals:
  - Large-x gluon, antiquark and heavy-quark content in the nucleon and nucleus.
  - Dynamics and spin of gluons in (un)polarised nucleons
  - Heavy-ion collisions towards large rapidities

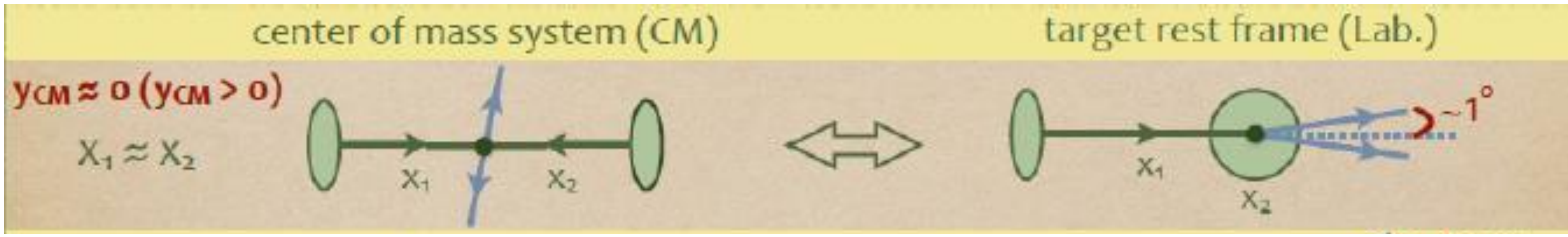
Kinematics for a fixed target at LHC

7 TeV proton beam on a fixed target

CMS energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115\ \text{GeV}$	**Rapidity shift:** $y_{CM} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_p) \approx 60$	

2.76 TeV Pb beam on a fixed target

CMS energy:	$\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72\ \text{GeV}$	**Rapidity shift:** $y_{CM} = 0 \rightarrow y_{lab} = 4.3$
Boost:	$\gamma \approx 40$	



Novel testing ground for QCD in the high x frontier: x = [0.3-1]

Fixed target mode at LHC

Advantages of the fixed-target mode (wrt to collider):

- Access high Feynman x_F domain ($x_F = p_z/p_{zmax}$)
- High luminosities (dense targets)
- Easy change target type
- Possibility to polarize the target
    - Spin physics program

-> D. Kikola plenary talk on Thursday at 09:00

No effect on the LHC performance:

Two options possible:

- Bent crystal in the halo of the LHC beam + solid target.
- Internal gas target

Fixed target experiment at LHC
Storage cell internal gas target

History

- Storage Cell part of the hydrogen MASER (Ramsey 1965): .

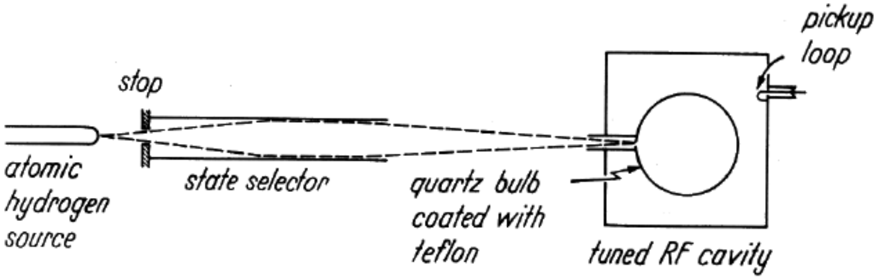


Fig. 1. Schematic diagram of atomic hydrogen maser

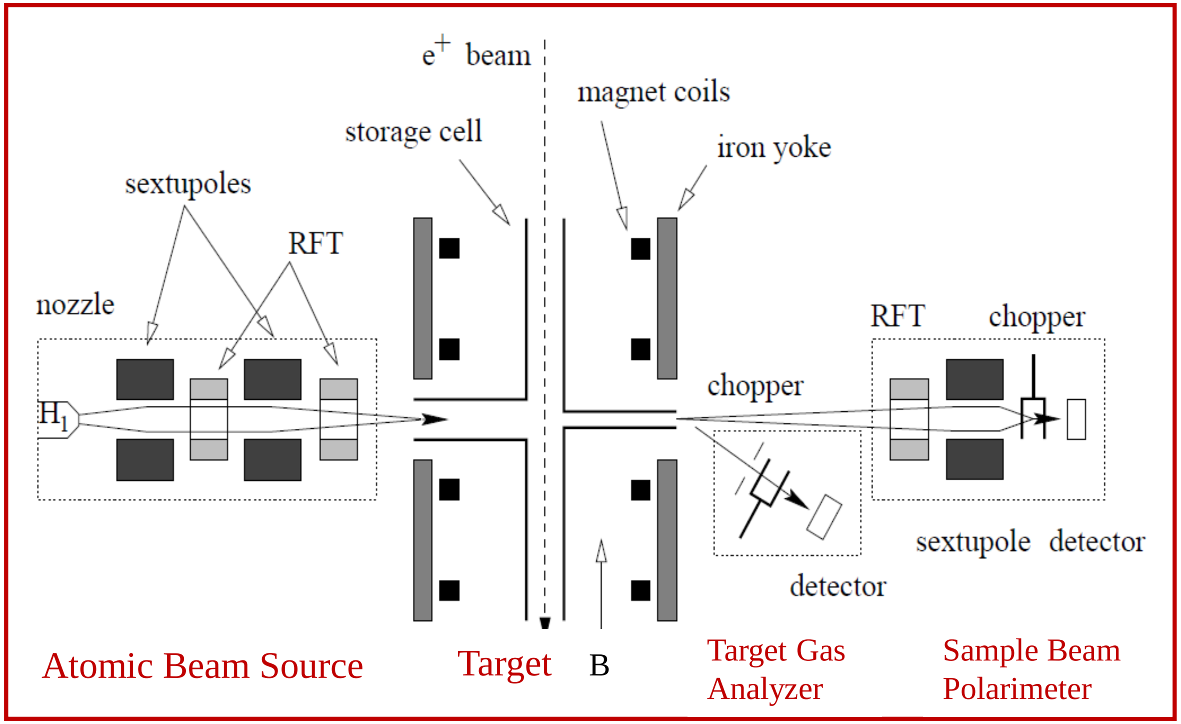
- Teflon-coated storage cell filled with polarized H from an ABS as target for Scattering Experiments first proposed by W. Haeberly in 1965

- First experimental test of in Madison, Wisconsin (1980)

- Experimentally used with:
  - Proton beams (< 2 GeV): PINTEX@IUCF, ANKE/PAX@COSY
  - Electron/positron beam (27 GeV): HERMES@HERA (1995-2005)

The HERMES polarized internal gas target @ HERA

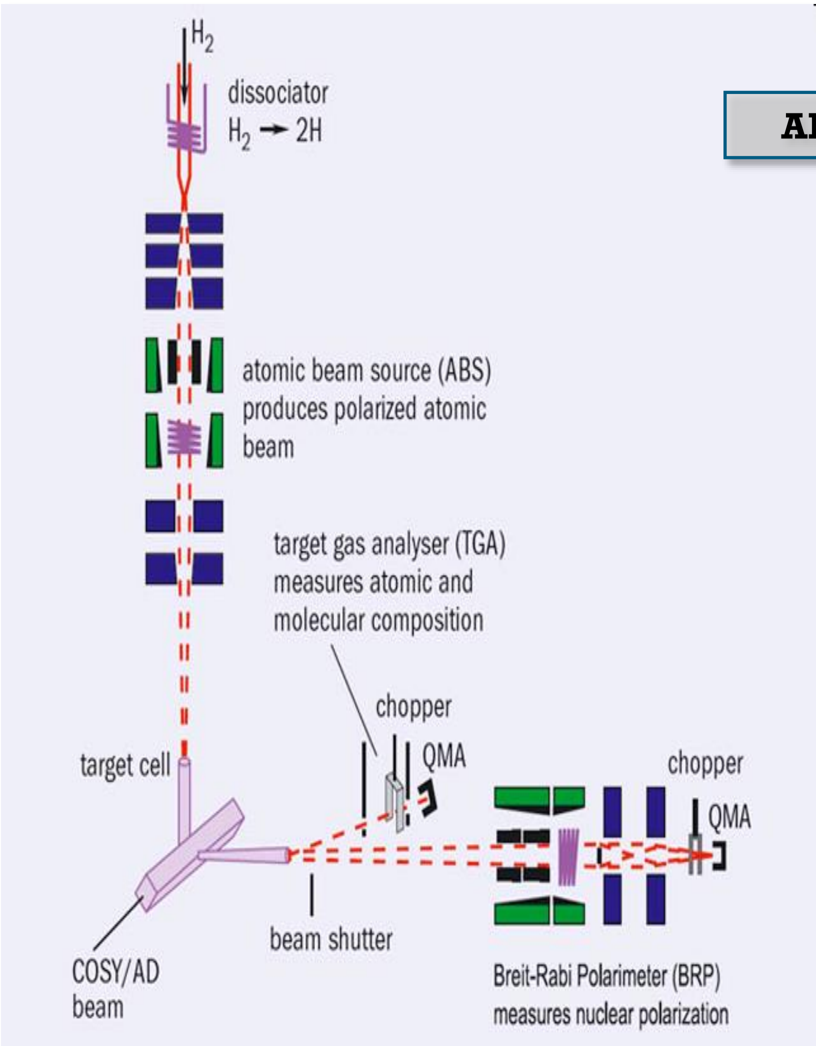
- Polarized atomic beam injected from left
- Sample beam:
  - QMS (α = molecular fraction).
  - Polarimeter (P = atomic polarization).
- *Sampling corrections* to compute polarization seen by beam.

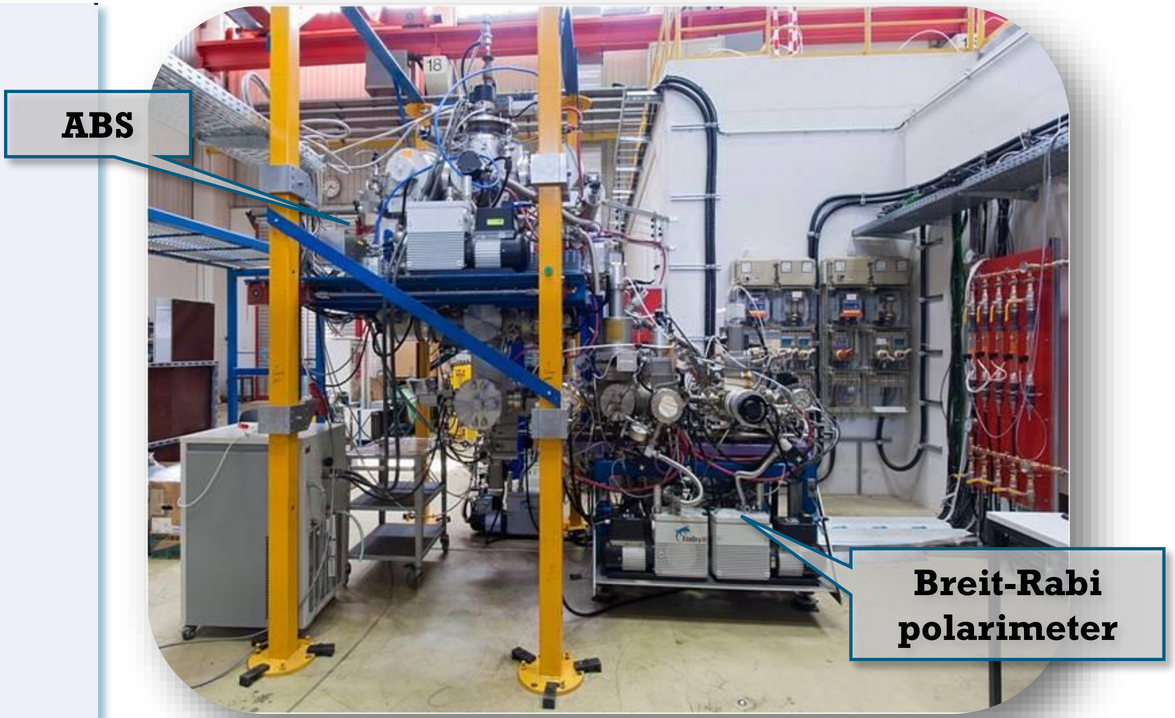


HERMES H&D target

p 920 GeV   e 27.6 GeV

The HERMES target now: PAX @ COSY



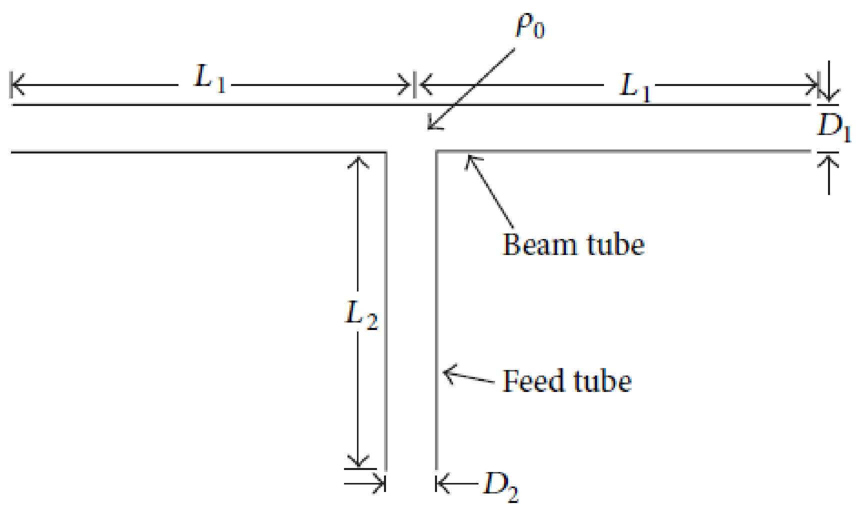


- Last achievement
  - Target compatible for H and D running
    (Without vacuum breaks!)

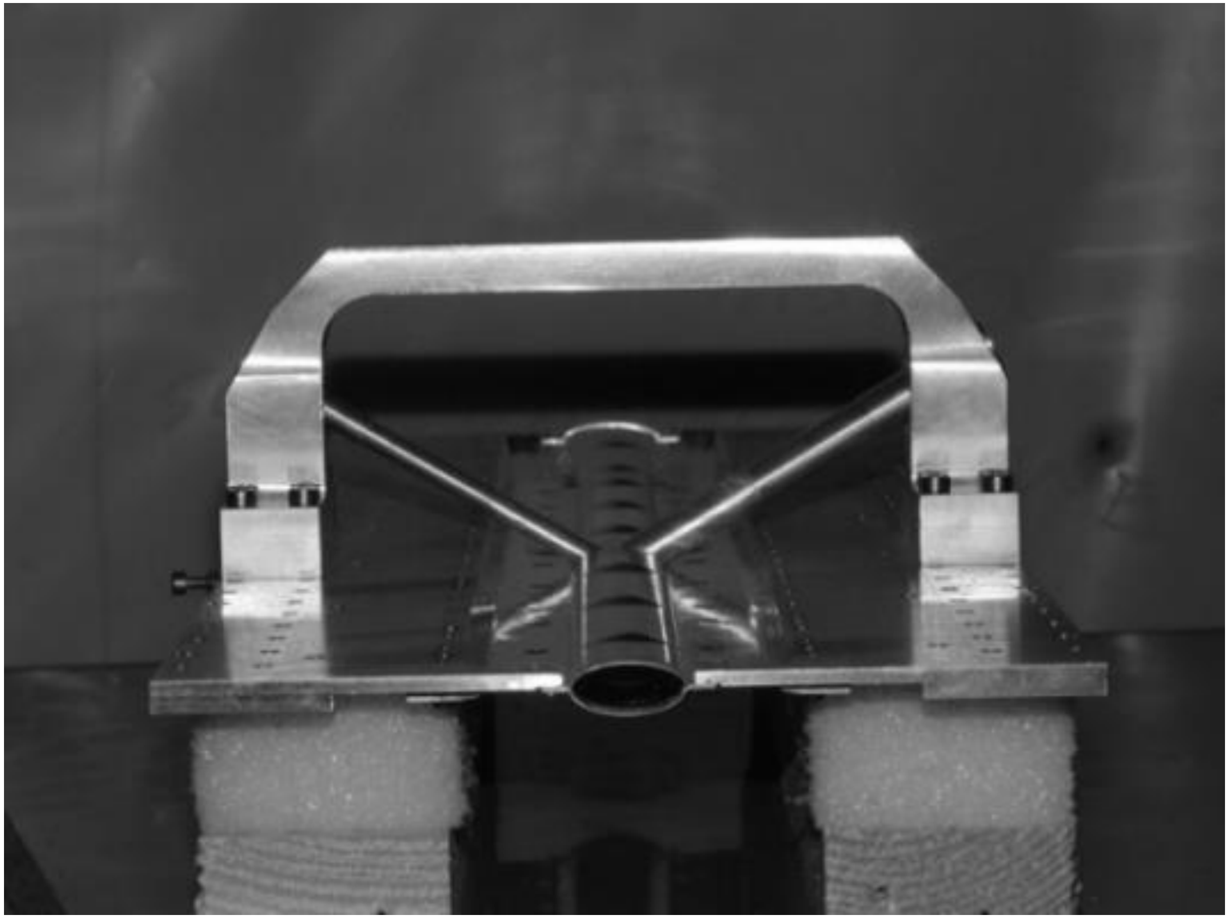
The HERMES (at DESY) target (1995-2005)

- Low-β section @ 30 GeV HERA e^+/e^-
- Polarized ^3He, ^1H, ^2D and unpolarized gas H_2 to Xe *[NIM **A540** (2005) 68]*.
- T-shaped Al-storage cell (75 μm thick)
  - 400 mm long
  - Elliptical cross section $r_{x,y} \approx 15\, \sigma_{x,y} + 1$ mm
  - Feed tube: 100 mm long, 10 mm (plus capillary for gas feed system).
  - Cell temperature $T_c = 100 - 300$ K.

- Density ρ_0 at cell center: $\rho_0 = I / C_{tot}$
- Narrow tube gives high density, but space for the beam needed!
- Additional requirements:
  - wall properties for low recombination and depolarization;
  - strong guide field.



The storage cell



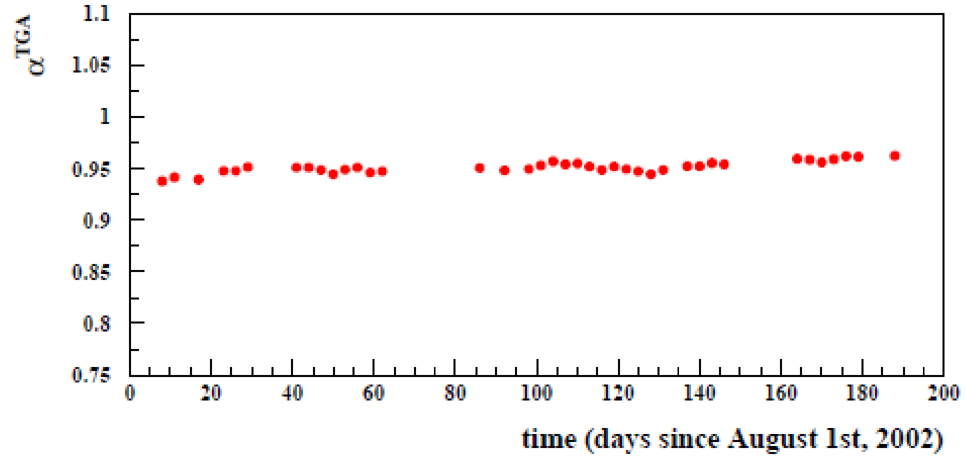
Material:	75 μm Al with Drifilm coating
Size: length:	400mm, elliptical cross section (21 mm x 8.9 mm)
Temperature:	100 K (variable 35 K – 300 K)

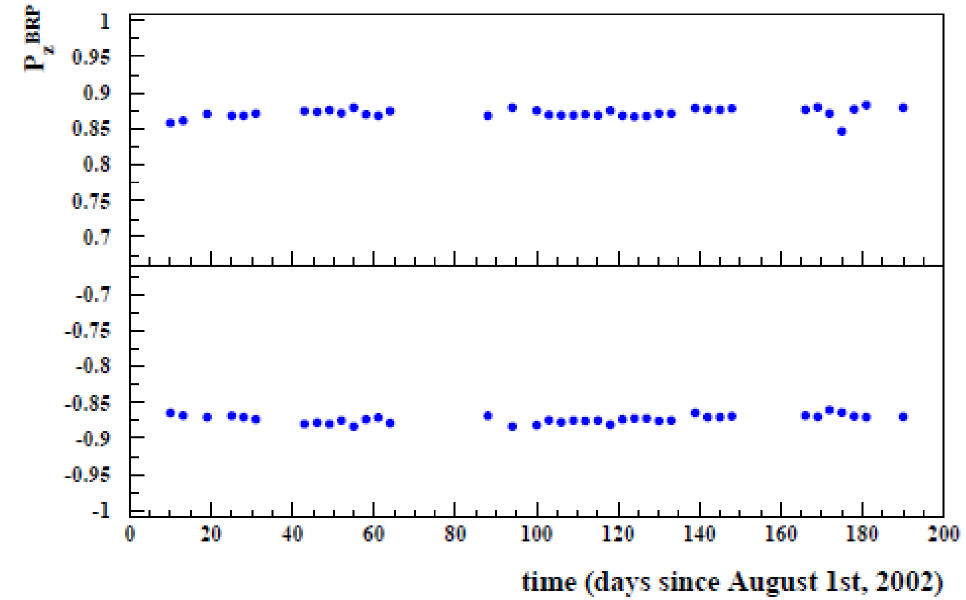
Performance for H (2002/03)

HERMES 2002/03 data taking with transverse proton polarization

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

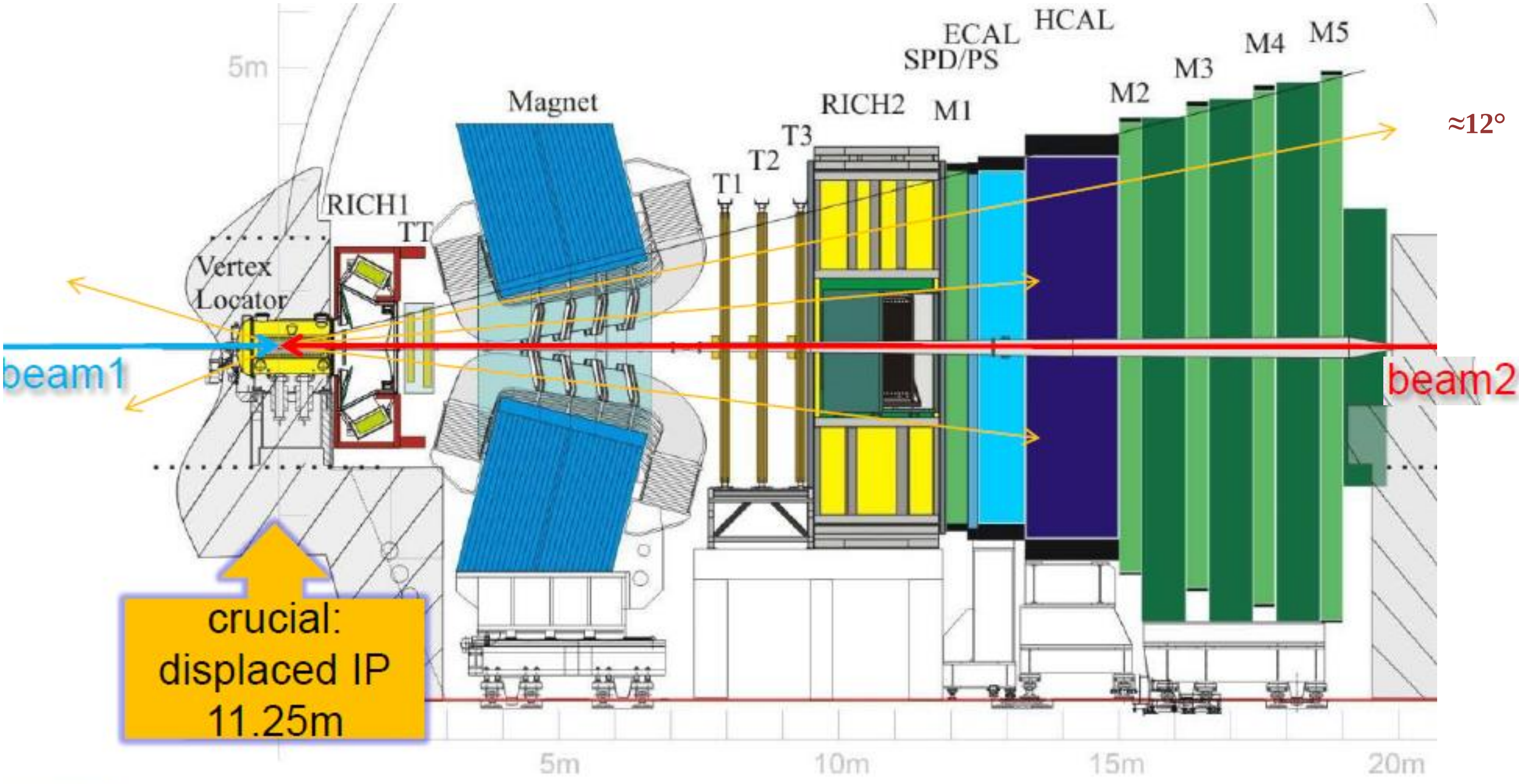
Bottom: Vector polarization P_z measured by Breit-Rabi-Polarimeter.





The SMOG gas target @ LHCb
for diagnostic purposes (vertex locator)

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



The SMOG internal gas target @ LHC

- **AFTER@LHC** M. Ferro-Luzzi (CERN):

- Originally: pure residual gas (10^{-9} mbar).
  - Switching off the pumps, pressure up to $5\cdot10^{-9}$ mbar used as target.

- Since 2012: Ne injected up to $p \approx 1.5\cdot10^{-7}$ mbar
  - At T=293K corresponds to $\rho = 4\cdot10^{12}$ /cm^3.
  - Pressure bump 10 m long areal density θ is $4\cdot10^{15}$/cm^2.
  - Beam losses negligible (τ >>10^8 s).

- Si-strip detector (VELO): two halves positioned near beam axis.
  - Closed position: detectors-distance to beam: 8 mm, Al housing: 5 mm.
  - Opened position: free space of ≈ 50 mm.

Conclusions:

- "LHCb has pioneered the use of gaseous "fixed target" in the LHC …"
- "Extensions involving target polarization require bigger investments and long studies (!) …."

LHC beams

p and Pb beams intensities @ LHC

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

Beam half-life: ≈ 10 h

- Parasitic operation requires small reduction of half-life (< 10%)

1σ-radius at IP (full energy): < 0.02 mm

- Negligible compared with the cell radius (> 5 mm)

Safety radius at injection (450 GeV for p): > 25 mm

- "Openable" cell required.

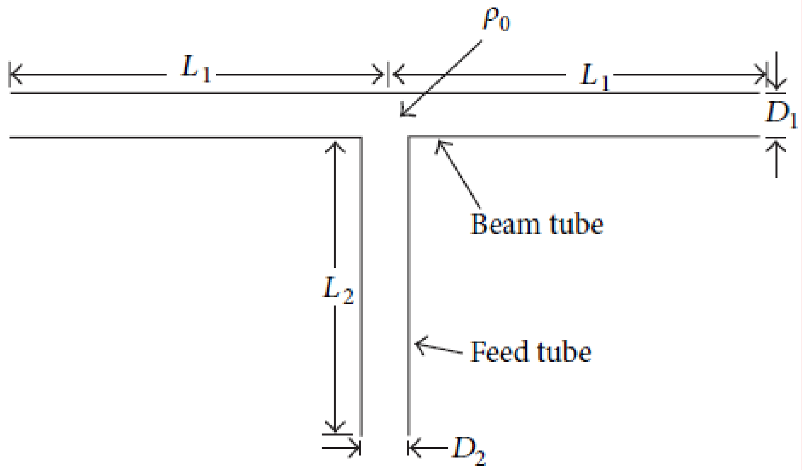
Openable storage cell development in Ferrara

(Storage cell for 2 GeV p/d beam at COSY (FZ-Juelich)

Geometry for a LHC storage cell

LHC Requirements:

- Beam tube
  - Length: 1000 mm (L_1 = 500 mm)
  - Closed: D_1 = 14 mm (> D_{VELO} = 10 mm).
  - Opened: D_1 = 50 mm
- Feed tube:
  - D_2 = 10 mm and L_2 = 100 mm
- Cell temperature: T = 300 K.



Conductance: C_i [l/s] = 3.81 √(T/M)· D_i^3 / (L_i + 1.33 D_i) (M = molecular weight)

Density: $\rho_0 = I / C_{tot}$ with $C_{tot} = C_1 + C_2 + \dots$ (I [part/s] gas flow-rate)

Example: H, $C_{tot} = 2\,C_1 + C_2$ = 12.81 l/s, $I = 6.5\cdot10^{16}$/s (HERMES):

$\rho_0 = 5.07\cdot10^{12}/cm^3$

*areal density $\theta = L_1\cdot\rho_0$ = **$2.54\cdot10^{14}/cm^2$***

Polarized ^{1}H gas target performance

Polarized H injected into storage cell

- Areal density: $\theta = 2.54 \cdot 10^{14}$ H/ cm^2
- Proton current $I_p = 3.63 \cdot 10^{18}$/s *(similar @ TeV)*

Total luminosity: $p\vec{p}$ **L_{pp} = $0.92 \cdot 10^{33}$/ cm^2 s**

- (About 10% of the collider luminosity)
- (x20 RHIC p↑-p↑ luminosity)
- Possibility to cool down the cell to 100 K (θ increase by $\sqrt{(300/100)} = \sqrt{3} = 1.73$)

σ_{pp} @ $\sqrt{s} = \sqrt{2M_n E_p} \approx 100$ GeV = 50 mb = $5 \cdot 10^{-26}$ cm^2

- Loss rate dN/dt: $4.5 \cdot 10^7$/ s
- Stored protons: $N = 3.2 \cdot 10^{14}$

Max. *relative* loss rate: $(dN/dt)/N = 1.4 \cdot 10^{-7}$/ s.

The H target does not affect the life time of the 7 TeV proton beam.

Polarized ^{2}D and ^{3}He gas targets

- Polarized ^{2}D target produced with densities comparable ^{1}H.
- HERMES: ^{3}He target operated at HERA in 1995.
    - ^{3}He gas polarized by Metastability Exchange Optical Pumping (1083 nm laser).
    - Modern lasers make a ^{3}He source (much) more intense than an ABS

Choice of the best target has to be made in an early phase of the project!

Unpolarized gas targets (H_2, ^{20}Ne, ^{84}Kr, ^{131}Xe,...)

- LHC enables collisions of beams of same rigidity
  - i.e. p-p collisions @ E_{max}= 2x7 TeV and Pb-Pb @ E_{max} = 2x2.76 TeV/nucleon.
  - (Other ions than p or Pb not used for experiments so far).

- *Parallel operation of heavy-Ion Fixed-Target program possible:*
  - Storage cell target fed with unpolarized gas:
    - Different combinations of masses could be studied (e.g. Pb on Xe or Ne).

Pb on Xe target
(with Pb-beam loss rate limited to 10%)

- Pb lifetime in Pb-Pb collider: τ_c = 10 h/ 0.693 = 14.4 h
  - Max Induced target life time: τ_t = 10·14.4 h = 144 h
  - Loss rate dN/dt = $N^{\cdot}$ (N = number Pb ions = $4 \cdot 10^{10}$):

    $N^{\cdot}/N = 1/144$ h -> $N^{\cdot} = N/5.18 \cdot 10^5$ s = $7.72 \cdot 10^4$/s = $\mathbf{L}_{Pb\text{-}Xe} \cdot \sigma_{tot}$ (Pb-Xe)
- $\sigma_{hadronic}$: 7.65 barn -> scaling with nuclear radii: σ_{tot} (Pb-Xe) = 6.6 barn

Max. Pb-Xe lumi: $\mathbf{L}_{Pb\text{-}Xe} = 1.17 \cdot 10^{28}/\ cm^2s$

- (*10 x Pb-Pb collider design luminosity ($10^{27}/\ cm^2\ s$)*)
- Xe density θ: $2.52 \cdot 10^{13}/cm^2$
- Xe flow rate at 300 K: $2.1 \cdot 10^{-5}$ mbar l/s

Conclusions

- **Interesting physics perspectives for a fixed target at LHC.**
- **Storage cell target** provides highest areal density at minimum gas input.
  - **Solid technology** tested at the HERA - 27.6 GeV e^+/e^- at I = 40 mA
- **Polarized H gas target:**
  - Cell with L=1 m and ϕ = 14 mm assumed (as SMOG/VELO @ LHCb)
  - $10^{33}/cm^2$ s accessible (16% of collider lumi)
- **Unpolarized target:**
  - p-A and Pb-A collisions with H_2, He, Ne, Ar, Kr and Xe
  - Max. Pb-Xe lumi: $\mathbf{L}_{Pb\text{-}Xe} = 1.17 \cdot 10^{28}/\ cm^2 s$ (10 x higher than collider lumi)

- **Locations at LHC to be identified for realistic planning and design!**

Further reading…

Advances in High Energy Physics

Physics at a Fixed-Target Experiment Using the LHC Beams

http://www.hindawi.com/journals/ahep/si/354953/

Thank you !

Extracted beam by bent-crystal

AFTER@LHC (Phys. Part. and Nucl.(2014) p. 336):

- LHC beam halo (p)extraction by bent-crystal onto polarized proton target.
  - Exp beam intensity: $i_p = 5 \cdot 10^8$/s.

- COMPASS type frozen spin target too large for LHC tunnel.
- UVa-type NH_3 DNP target with smaller target set-up considered:
  - $n_t = 1.5\ 10^{23}/cm^2$, $P_p = 0.85$, dilution $f = 0.17$.
  - $FoM = n_t\ P^2 f^2 = 3.1 \cdot 10^{21}/cm^2$.
  - Beam intensity i_p also enters the measurement quality:
    - $FoM^* = i_p \cdot FoM = P^2 \cdot f^2 \cdot i_p \cdot n_t = P^2 \cdot f^2 \cdot \mathbf{L}$

Comparison:

UVa-target and bent-crystal extr. beam: $FoM^* = 1.57 \cdot 10^{30}/cm^2\ s$

'COMPASS-target " " " $FoM^* = 1.87 \cdot 10^{32}/cm^2\ s$

'HERMES' target and full LHC beam: $FoM^* = 0.60/1.04 \cdot 10^{33}/cm^2\ s$
($T = 300/100$ K, $P = 0.85$, $\alpha = 0.95$)