High luminosity Fixed Target ExpeRiment at the LHC (AFTER@LHC)

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Outline

• A fixed-target experiment with LHC proton and lead beams: main kinematic features and advantages

• Possible technical implementations

• Achievable luminosities in ALICE and LHCb and ongoing investigations/projects

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To be submitted to Physics Report

A Fixed-Target Programme at the LHC:
Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies

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Physics cases and projected performances presented by:
Aleksander Kusina Probing the high-x content of the nuclei in the fixed-target mode at the LHC
Jean-Philippe Lansberg Future heavy-ion facilities: fixed-target at LHC (AFTER)
Antonio Uras Heavy-flavour-production studies in a new energy and rapidity domain with the nuclear LHC beams in the fixed-target mode
Nodoka Yamanaka Ultra-peripheral collision studies in the fixed-target mode with the proton and lead LHC beams
A fixed-target experiment at the LHC

Main kinematic features:

Energy range
- 7 TeV proton / 2.76 TeV Pb beam on a fixed target

<table>
<thead>
<tr>
<th>beam type</th>
<th>CM energy $\sqrt{s_{(NN)}}$</th>
<th>boost $\gamma=\sqrt{s/2m}$</th>
<th>rapidity shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton (E = 7 TeV)</td>
<td>115 GeV</td>
<td>61</td>
<td>4.8</td>
</tr>
<tr>
<td>lead (E = 2.76 TeV)</td>
<td>72 GeV</td>
<td>38</td>
<td>4.2</td>
</tr>
</tbody>
</table>

→ center-of-mass energy in-between SPS at CERN and nominal RHIC

Rapidity range
- Entire center-of-mass forward hemisphere ($y_{CM} > 0$) within 1 degree
- Easy access to (very) large backward rapidity range ($y_{CM} < 0$) and large parton momentum fraction in the target ($x_2$)
A fixed-target experiment at the LHC

• Several advantages of fixed-target mode:
  – Accessing **high-x frontier** \(y_{CM} < 0\) and parton momentum fraction \(x > 0.5\)
  – Achieving **high luminosity**
  – Varying **atomic mass number** of the target
  – **Polarising** the target

• This can be realized at LHC in a parasitic mode!

• Fixed-target mode started at LHCb with a low density gas-target (by using SMOG)
Physics motivations

- Advance our understanding of the high-$x$ gluon, antiquark and heavy-quark content in the nucleon and nucleus and its connection to astroparticles
- Unravel the spin of the nucleon: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
- Study the quark-gluon plasma between SPS and RHIC energies over a broad rapidity domain
Possible fixed-target implementations

– **Internal gas target similar to SMOG at LHCb / inspired by HERMES at HERA, RHIC polarimeter**
  • Full LHC proton flux: $3.4 \times 10^{18}$ p/s and Pb flux: $3.6 \times 10^{14}$ Pb/s on internal gas target
    → high intensity beam on gas target

– **Internal wire/foil target as in HERA-B, STAR**
  • Beam halo is recycled directly on internal solid targets

– **Beam line extracted with a bent crystal**
  • Beam halo is deflected by a bent crystal
  • Expected proton flux $\sim 5 \times 10^8$ p/s, Pb flux $\sim 2 \times 10^5$ Pb/s
  • Provides a new facility with 7 TeV proton and 2.76 lead beams
  • Civil engineering required

– **Beam “split” by a bent crystal**
  • Beam halo is deflected on a solid target internal to the LHC beam pipe
  • Similar fluxes as for beam extraction
    → beam halo on dense target

**Internal gas and solid target can be coupled with an existing LHC detector**

Technical implementations currently discussed within the Physics Beyond Collider working group ([http://pbc.web.cern.ch/](http://pbc.web.cern.ch/)) with a fixed-target working group evaluating the effect on the LHC beams

*S.Redaelli et al. Proceedings of IPAC2018*

*Physics Beyond Collider Working Group meeting June 2018: https://indico.cern.ch/event/706741/*
SMOG in LHCb: a gas-target demonstrator

**SMOG/LHCb (System for Measuring the Overlap with Gas)**

- Gas injecting into Vertex Locator (VELO) vacuum chamber: P $\sim 1.5 \times 10^{-7}$ mbar
- LHC vacuum ion pump stations located ±20m on both sides
- Use full intensity of the LHC proton and lead beam without decrease of the beam lifetime
- Limited to noble gases. Already injected: He, Ne, Ar
- Limited luminosities (density, running time, …), no p-H baseline, no heavy nuclei

**Luminosity**

- Maximum obtained luminosity so far: $\mathcal{L}_{p-Ne@68\text{GeV}} = 100$ nb
Internal gas target: gas-jet

**Polarised H-jet polarimeter at RHIC-BNL**  *Zelenski et al. NIM A 536 (2005) 248*
- Used to measure the proton beam polarisation at RHIC
- Polarised gas: free atomic beam source (ABS) crossing the RHIC beam: H, D and ³He possible
- 9 vacuum chambers: 9 stages of differential pumping
- Holding field in the target vacuum chamber
- Diagnostic system: Breit-Rabi polarimeter

**Density**
- Polarised inlet H↑ flux: 1.3 \(10^{17}\) H/s
- Areal density \(\vartheta_{H↑} = 1.2 \times 10^{12}\) atoms/cm² (10 × SMOG)
- Much higher density can be obtained for H₂
- Gas target profile at interaction point: gaussian with a full width of ~6 mm

**Typical luminosity**
- Using nominal LHC bunch number [2808 bunches for proton and 592 for lead] and for 1 LHC year [\(10^{7}\) s proton beam and \(10^{6}\) s lead beam]
- \(\mathcal{L}_{p-H↑} = 4.5 \times 10^{30}\) cm²s⁻¹ \(t = 10^{7}\) s: \(\mathcal{L}_{p-H↑} = 45/pb\)
- \(\mathcal{L}_{p-H2} = 10^{33}-10^{34}\) cm²s⁻¹ \(t = 10^{7}\) s: \(\mathcal{L}_{p-H2} = 10-100/fb\)
- Other possible gases: D↑, ³He↑
Internal gas target: storage cell

HERMES/DESY T-shape internal storage cell target:
- Vacuum chamber target ~ 72 cm x 50 cm and pumping system
- Polarised gas: atomic beam source
- Holding field in the target chamber
- Diagnostic systems: target gas analyzer and polarimeter
- Unpolarized gas via capillary

Density
- Polarised inlet H↑ flux: 6.5 \times 10^{16} \text{ H↑/s}
- Areal density \( \vartheta_{\text{H↑}} = 2.5 \times 10^{14} \text{ atoms/cm}^2 \) (~100 \times gas jet)
- Unpolarised gas pressure limited by beam lifetime

Typical luminosity
- \( \mathcal{L}_{\text{p-H↑}} = 0.9 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) [t = 10^7s: \( \mathcal{L}_{\text{p-H↑}} = 9/\text{fb} \)]
- \( \mathcal{L}_{\text{p-H2}} = 5.8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) [t = 10^7s: \( \mathcal{L}_{\text{p-H2}} = 58/\text{fb} \)]
- \( \mathcal{L}_{\text{Pb-H↑}} = 1.2 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1} \) [t = 10^6s: \( \mathcal{L}_{\text{Pb-H↑}} = 100/\text{nb} \)]
- \( \mathcal{L}_{\text{Pb-Xe}} = 3 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1} \) [t = 10^6s: \( \mathcal{L}_{\text{Pb-Xe}} = 30/\text{nb} \)]
- Other possible gases: D↑, \(^3\)He↑, all noble gases
Beam split by using a bent crystal

**Bent crystals**
- Studied by UA9 for collimation purpose at the LHC
- Channelled particles of the beam halo are deflected
- Beam split by a bent crystal:
  - Crystal located ~100 m upstream the target
  - Solid target internal to the beam pipe close to an existing experimental apparatus
  - Absorber ~100 m downstream the target

**Extracted proton and lead flux**
- Proton flux ~5 x 10^8 p/s (LHC beam loss: ~10^9 p/s)
- Lead flux ~2 x 10^5 Pb/s

**Typical luminosity**
- Assuming 5 mm target length
  - $\mathcal{L}_{\text{p-W}} = 1.6 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ [t = 10^7s: $\mathcal{L}_{\text{p-W}} = 160$/pb]
  - $\mathcal{L}_{\text{Pb-W}} = 3 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ [t = 10^6s: $\mathcal{L}_{\text{Pb-W}} = 3$/nb]
- Target type: Be, C, W, …
Detector requirements for a LHC fixed-target programme

- **Wide rapidity coverage** (rapidity shift: $\Delta y = 4.8$ with proton beam and 4.2 with lead beam) with PID and vertexing capabilities
- Readout **rate similar as LHC** collider: up to 40 MHz in pp, 300 MHz in pA and 200 kHz in PbA
- Heavy-ion: good detector performance in **high-multiplicity events**, up to 600 charged tracks per unit of rapidity at $\eta_{\text{lab}} \sim 4$

LHCb as a fixed-target experiment

• Forward detector (2 < \( \eta \) < 5) with full PID
• Limitation in high-multiplicity event reconstruction (up to \(~50\%\) less central events in Pb-Pb collider mode)
• Upgrade LS2:
  • New Vertex Locator
  • New Tracker
  • Readout rate: 40 MHz

Achievable luminosities with gas target (storage cell):

- \( \mathcal{L} \) \(_{p-H}@115\text{GeV}\) = 10/fb, \( \mathcal{L} \) \(_{p-Xe}@115\text{GeV}\) = 300/pb \([t = 10^7\text{s}]\)
- \( \mathcal{L} \) \(_{Pb-Xe}@72\text{GeV}\) = 30/nb, \( \mathcal{L} \) \(_{Pb-H}@72\text{GeV}\) = 100/nb \([t = 10^6\text{s}]\)

With beam splitting and 5 mm solid target:

- \( \mathcal{L} \) \(_{p-W}@115\text{GeV}\) = 160/pb \([t = 10^7\text{s}]\)
- \( \mathcal{L} \) \(_{Pb-W}@72\text{GeV}\) = 3/nb \([t = 10^6\text{s}]\)
Projects under investigation in LHCb

Several investigations/projects:
- Beam splitting and internal W solid target (with a second crystal) for Electromagnetic Dipole Moment of charmed baryons
- Polarized storage cell gas target for spin physics
- Unpolarized storage cell gas target (SMOG2)

SMOG2 internal storage cell target:
- Openable storage cell of 20 cm long attached to the VELO
- Unpolarized gas via capillary: gas feed tube in the cell center

Density
- Gas pressure up to $100 \times$ SMOG: $P \sim 10^{-5}$ mbar

Possible systems and luminosities (not approved by LHCb)
- $p$-$H$, $p$-$D$, $p$-$Ar$, $Pb$-$Ar$, …
- $\mathcal{L}_{p-H@115GeV} = 10/pb$
- $\mathcal{L}_{p-D@115GeV} = 10/pb$
- $\mathcal{L}_{Pb-Ar@72GeV} = 5/nb$ (+ $\mathcal{L}_{p-Ar@72GeV} = 1/pb$)
- Discussion ongoing on target types, parallel / dedicated running, possible vacuum issue, …

Formal approval of SMOG2 this Fall and installation foreseen in LS2
ALICE in a fixed-target mode

- Central Barrel ($|\eta| < 0.9$) with full PID
- Muon Spectrometer ($2.5 < \eta < 4$)
- No limitation in high-multiplicity event reconstruction
- Upgrade LS2:
  - New Silicon Tracker
  - A Muon Forward Tracker
  - Readout rate: 50 kHz in PbPb and possibly up to 1 MHz in pp and pA

Achievable luminosities with gas target:
- $\mathcal{L}_{p-H_2/\text{H}}@115\text{GeV} = 260/\text{pb}$, $\mathcal{L}_{p-Xe@115\text{GeV}} = 8/\text{pb}$
- $\mathcal{L}_{\text{Pb-Xe}@72\text{GeV}} = 8/\text{nb}$

With beam splitting and at most 5 mm solid target:
- $\mathcal{L}_{p-W@115\text{GeV}} = 6/\text{pb}$
- $\mathcal{L}_{\text{Pb-W}@72\text{GeV}} = 3/\text{nb}$
Fixed-target investigation in ALICE

Current investigation:
• Beam splitting and internal solid target

**Internal solid target:**
- Inside the L3 solenoid
- Pneumatic motion system with two positions IN and OUT of the beam pipe

*C.H. Annual Workshop PBC, June 2018*

**Detector acceptance vs \( z_{\text{target}} \)**

Convention: \( z \)-direction positive on C-side

The rapidity coverage is shifted towards larger rapidities (mid-rapidity in the c.m.s) if the vertex is located few meters upstream the I.P.
Acceptance in center-of-mass rapidity

In a fixed-target mode:
- ALICE Central Barrel covers very backward rapidity and Muon Spectrometer covers rapidity interval towards mid-rapidity
- LHCb: wide rapidity range starting from $y_{\text{cms}} \sim 0$

With $z_{\text{target}} = z_{\text{IP}}$ and a 7 TeV proton beam
Summary

• Three main physics motivations for a high-luminosity fixed-target program at the LHC:
  – **High-x frontier**: nucleon and nuclear structure and connections with astroparticles
  – **Nucleon spin** and the transverse dynamics of partons
  – **Quark Gluon Plasma** over a broad rapidity domain

• Two promising technical implementations with large luminosities:
  – **an internal gas-target (gas-jet or storage cell)**
  – a slow beam extraction with **a bent crystal on an internal solid target**

• Investigations/projects in **ALICE** and **LHCb** ongoing for the implementation of fixed-target setup
back-up slides
Achievable luminosities in ALICE

<table>
<thead>
<tr>
<th>Target</th>
<th>proton beam ($\sqrt{s_{NN}} = 115$ GeV)</th>
<th>Pb beam ($\sqrt{s_{NN}} = 72$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L$ [cm$^{-2}$s$^{-1}$]</td>
<td>$\sigma_{inel}$ [mb]</td>
</tr>
<tr>
<td>Gas-Jet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^1$H</td>
<td>$4.3 \times 10^{30}$</td>
<td>39</td>
</tr>
<tr>
<td>$^2$H</td>
<td>$2.6 \times 10^{31}$</td>
<td>39</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$4.3 \times 10^{30}$</td>
<td>72</td>
</tr>
<tr>
<td>$^3$He$^+$</td>
<td>$8.5 \times 10^{30}$</td>
<td>117</td>
</tr>
<tr>
<td>Storage Cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^1$H</td>
<td>$2.6 \times 10^{31}$</td>
<td>39</td>
</tr>
<tr>
<td>$^2$H</td>
<td>$2.6 \times 10^{31}$</td>
<td>39</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$1.4 \times 10^{31}$</td>
<td>72</td>
</tr>
<tr>
<td>$^3$He$^+$</td>
<td>$8.5 \times 10^{30}$</td>
<td>117</td>
</tr>
<tr>
<td>$^7$Xe</td>
<td>$7.8 \times 10^{39}$</td>
<td>1.3</td>
</tr>
<tr>
<td>Wire Target</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (500 $\mu$m)</td>
<td>$2.8 \times 10^{30}$</td>
<td>271</td>
</tr>
<tr>
<td>Ti (500 $\mu$m)</td>
<td>$1.4 \times 10^{30}$</td>
<td>694</td>
</tr>
<tr>
<td>W (184 $\mu$m / 500 $\mu$m)</td>
<td>$5.9 \times 10^{29}$</td>
<td>1.7</td>
</tr>
<tr>
<td>Beam splitting</td>
<td></td>
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</tr>
<tr>
<td>E1039</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^4$He</td>
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<td>39</td>
</tr>
<tr>
<td>$^4$He$^+$</td>
<td>$1.4 \times 10^{31}$</td>
<td>72</td>
</tr>
<tr>
<td>Unpolarised solid target</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (658 $\mu$m / 50000 $\mu$m)</td>
<td>$3.7 \times 10^{30}$</td>
<td>271</td>
</tr>
<tr>
<td>Ti (515 $\mu$m / 50000 $\mu$m)</td>
<td>$1.4 \times 10^{30}$</td>
<td>694</td>
</tr>
<tr>
<td>W (184 $\mu$m / 50000 $\mu$m)</td>
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<td>1.7</td>
</tr>
</tbody>
</table>

Table 11: Summary table of the achievable integrated luminosities with the ALICE detector accounting for the data-taking-rate capabilities in the collider mode and by considering the luminosities of Table 9. As detailed in the text, a higher rate depending on the collision system could be envisioned. The inelastic cross sections are taken from EPOS [97, 132].
Achievable luminosities in LHCb

<table>
<thead>
<tr>
<th>Target</th>
<th>LHCb proton beam ($\sqrt{s_NN} = 115$ GeV)</th>
<th>Pb beam ($\sqrt{s_NN} = 72$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mathcal{L}$ [cm$^{-2}$s$^{-1}$]</td>
<td>$\sigma_{inel}$</td>
</tr>
<tr>
<td><strong>Gas-Jet</strong></td>
<td></td>
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</tr>
<tr>
<td>$H_1$</td>
<td>$4.3 \times 10^{30}$</td>
<td>$39$ mb</td>
</tr>
<tr>
<td>$H_2$</td>
<td>$1.0 \times 10^{33}$</td>
<td>$39$ mb</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$4.3 \times 10^{30}$</td>
<td>$72$ mb</td>
</tr>
<tr>
<td>$^3$He$^+$</td>
<td>$3.4 \times 10^{32}$</td>
<td>$117$ mb</td>
</tr>
<tr>
<td><strong>Storage Cell</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_1$</td>
<td>$0.92 \times 10^{33}$</td>
<td>$39$ mb</td>
</tr>
<tr>
<td>$H_2$</td>
<td>$1.0 \times 10^{33}$</td>
<td>$39$ mb</td>
</tr>
<tr>
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<td>$117$ mb</td>
</tr>
<tr>
<td>$Xe$</td>
<td>$3.1 \times 10^{31}$</td>
<td>$1.3$ b</td>
</tr>
<tr>
<td><strong>Internal solid target with the beam halo</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wise Target</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C ($500$ $\mu$m)</td>
<td>$2.8 \times 10^{30}$</td>
<td>$271$ mb</td>
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<td>$1.7$ b</td>
</tr>
<tr>
<td><strong>E1039</strong></td>
<td></td>
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</tr>
<tr>
<td>$^{16}$O$^+$</td>
<td>$7.2 \times 10^{31}$</td>
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<td>$7.2 \times 10^{31}$</td>
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<tr>
<td><strong>Unpolarised solid target</strong></td>
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<td>$1.7$ b</td>
</tr>
</tbody>
</table>
Internal solid target (beam splitting)

- First sketch of the target system: pneumatic motion system with three target types
- Size of the target: diameter approximately 5mm, thickness 0.1-5mm
- Target holder: titanium alloy
- Parking position out of the pipe and 2 positions: In/Out
- One valve on each side

- Compatibility of proposed target types (Be, C, Ti, W, …) with LHC conditions to be studied
- Compatibility of the target system with the operation of ALICE forward detectors to be verified