Fixed-target opportunities at LHCb

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On behalf of the LHCb Collaboration
LHCb detector

Single-arm forward spectrometer, optimized for b- and c-hadron physics.
The only LHC experiment fully instrumented at large $\eta$ (2<\eta<5)

A fixed-target like geometry!
SMOG comes…

- Inject gas in the VELO tank, primarily done to perform luminosity measurement by measuring the beam images with beam-gas vertices (1.2% precision)

**Noble gas only**
(very low chemical reactivity)

He Ne Ar
A = 4 20 40

**Gas pressure:**
From nominal $10^{-9}$ (LHC vacuum) to few×$10^{-7}$ mbar (for beam safety)

**Allows p-gas and ion-gas interactions**
SMOG comes…

- Inject gas in the VELO tank, primarily done to perform luminosity measurement by measuring the beam images with beam-gas vertices (1.2% precision)

- Can be used as an internal gas system and operate in fixed-target mode

- Fixed-target physics at LHC via SMOG is already yielding results, e.g.

\[ p \text{ He} \rightarrow \bar{p} \ X \@ \sqrt{S_{NN}} = 110 \text{ GeV}, \]

important and well recognized input for cosmic rays physics

\[ J/\psi \text{ and } D^{0} \text{ production cross-sections and yields in } p \text{ He} \@ \sqrt{S_{NN}} = 86.6 \text{ GeV} \]

\[ \text{and } Ar \@ 110 \text{ GeV} \]

Noble gas only
(very low chemical reactivity)

\[
\begin{array}{ccc}
\text{He} & \text{Ne} & \text{Ar} \\
A = 4 & 20 & 40 \\
\end{array}
\]

Gas pressure:
From nominal \( 10^{-9} \) (LHC vacuum) to few\( \times 10^{-7} \) mbar (for beam safety)

Allows p-gas and ion-gas interactions

Reconstructed beam-gas vertices inside VELO
...and opens new horizons

- These results motivate continued exploitation of SMOG and upgrade of the current system with the introduction of a gas storage cell (SC) inside VELO tank (aka SMOG2)

- And other, more ambitious ideas…
  - Polarised gas target, to perform spin-physics measurements
  - Tungsten target paired to bent crystal to access magnetic (MDM) and electric (EDM) dipole moments of heavy flavoured baryons
  - Solid (metal) wire target, to extend SMOG2 heavy-ion program

- Discussions ongoing with...

Disclaimer

- None of these proposals has been yet approved by LHCb.
- Moreover, they will have to be approved by relevant machine committees, as they rely on the LHC machine and/or could have some interference with it.
Tentative LHCb fixed-target program schedule

LHC Era
- 2011-2012: Run 1
- 2015-2018: Run 2
- Current LHCb

LS2
- 2021-2023: LHCb Upgrade I
- SMOG

LS3
- 2026-2029: LHCb LS3 Consolidation
- SMOG2?

LS4
- 2031-...
- Polarised gas?

Metal wires?

Bent crystals?

HLLHC Era
- 50 fb-1
- 300 fb-1
- Run 4
- Run 5...

Tentative start of operation
- Today

F. Martinez Vidal, LHCP Bologna, 4-9 June 2018
Fixed-target physics with LHC beams

**Wide Physics Goals**

- **Drell-Yan processes**
- **Heavy flavour states**
- **Jets**
- **Direct/isolated photons**
- **Z and W bosons, near threshold**

**QCD and QGP**

- **Nuclear partonic structure:** PDFs for gluons, antiquarks and heavy quarks (EMC effect, anti-shadowing, Fermi motion,...)
- **Particle production in soft QCD regime,** of particular relevance for cosmic-ray physics
- **Probes of QGP formation and deconfinement,** e.g. suppression of charmonium
- **TMD functions, nucleon spin puzzle,** Soft Collinear Effective Theory (gg→H)
- **Ultra-peripheral and diffractive reactions**

**High x (>0.5), including exotic x>1**

Copious production (up to ~0.1 fb⁻¹/year) opens many novel possibilities

**√s_{NN} ≈ 115 GeV (pA) and ≈ 72 GeV (PbA), intermediate between SPS (~20 GeV) and RHIC (~200 GeV)**

**~1 TeV secondary beams**

- **Heavy baryons,** e.g. \( \Lambda_c^+ \)
  to be channelled in a bent crystal for **magnetic and electric dipole moments**
- **D⁰ and B⁰ mesons,** e.g. for oscillations in matter (amorphous bent crystal)
- **Other flavour physics,** complementary to LHCb core physics program...

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Additional vacuum sector upstream VELO

- In order to allow installation/maintenance of required instrumentation without breaking the VELO beam vacuum, a new vacuum valve will be installed in LS2.

Credit: Courtesy of Josef Sestak, CERN

Approximately 1250 mm
Principle of gas targets and storage cells (SC)

- Cylindrical open-ended tube located around the beam

- Gas injected in the middle of the tube, $\approx$ triangular density
- Enhanced target thickness as compared to gas injected directly in the beam pipe

[Image of diagrams showing the principle of gas targets and storage cells]
SMOG upgrade: SMOG2

- Install a gas SC inside VELO tank, upstream the sensors
- Many benefits:

  Increase of target density up to two orders of magnitude for the same gas flow
  (e.g. from $\approx 5 \times 10^9$ He/cm$^3$ for $\approx 4 \times 10^{15}$ He/s to $\rho_{\text{max}} \approx 10^{12}$ He/cm$^3$)

Better known density (luminosity)

Goal to inject other gasses, eg. H$_2$, D$_2$, besides He, Ne, Ar,…

Update of Gas Feed System, HERMES-like: 1% or better gas flow uncertainty and remote control for gas change

VELO pump activated, lower residual gas pressure

Fixed-target IP upstream proton-proton IP

"SMOG" [-200, +200]
Center: $z = 0$
IP Region selected for SMOG analyses

SMOG2 cell [-500, -300]
Center: $z = -400$ mm
Length: 20 cm
SMOG2

- No overlap with pp collisions: reduced backgrounds and possibility for parallel running with pp collisions
- Better acceptance at high $\eta$
- Lower PV reconstruction performances
  - Can be compensated by the higher (and better known) gas density
- First technical design of the SC: two halves, supported to VELO box and retractable along with sensors
- Further studies to assess the interaction of the SC with the beams (impedance and wakefields, dynamic vacuum,…) and impact of target density on detector performance

R&D on SC at NIKHEF, INFN-Ferrara, INFN-Frascati
Polarised gas

- Polarised gas target similar to the one used in HERMES [1]
- Requires compact gas chamber, centered at \(-1.6\) m from pp IP
- Acceptance and tracking in the upstream configuration worst but still acceptable
  - Can be improved adding detector layers
- Gas atoms or molecules undergo large number of wall collisions \(\Rightarrow\) depolarisation
  - R&D on coating materials compatible with both LHC and target requirements. Also interesting for FCC
- More studies needed to assess physics case, interaction with beams (magnetic fields, beam RF depolarisation,…) and detector performance

The high electric field between the crystallographic planes makes the heavy baryon spin precess, giving access to the MDM/EDM.
Bent crystals

- Proof-of-principle by E761: MDM of $\Sigma^+$ from 800 GeV protons on Cu target
- Compatibility with LHC collimation scheme seems feasible according to preliminary studies, but detailed studies are required

Machine operation
(parasitic vs dedicated, primary/secondary/tertiary halos)

Achievable proton flux

Collimation system (absorber)
for disposal of the split beam and other products

- Channeling with 6.5 TeV LHC protons demonstrated in 2016
- First test of double-crystal scheme at SPS on 18 Sep 2017
  very encouraging

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Proceedings of IPAC2018, Vancouver
Bent crystals

- R&D ongoing at INFN-Ferrara & PNPI/IHEP for large bending angle, \( \approx 15 \text{ mrad} \) (\( \approx 10 \text{ cm long} \)), mainly determined by detector acceptance
  - Cannot use anticlastic deformation
  - Need special bending techniques with very precisely machined (\( \approx 100 \text{ nm} \)) holder to maintain uniform deformation
  - First prototypes produced. First test beam results will be available soon

Sample tested on May 22, 2018 at H8 external line of the SPS in the frame of the UA9 Collaboration.

Bending angle is \( \approx 12 \text{ mrad} \)

Courtesy of A. Mazzolari, INFN-Ferrara
Bent crystals

- Setup at $\approx 0.4$ cm from beam center, installed on retractable goniometer ($\approx 20$ $\mu$rad) upstream the VELO tank, $\approx -1.2$ m from pp IP (W)
- Crystals rotated for optimal acceptance
- Clean signal signature mostly based on precise kinematical information, compensates low vertex resolution
- $\approx 2 \times 10^{14}$ protons on 2.0 cm thick W target could be reached in 3 years of
  - parallel running with pp collisions (no overlap with pp), at maximum of $\sim 10^7$ p/s
  - dedicated running, 2 weeks/year, at flux $10^8$ p/s
- $\sim 10^{-3} - 10^{-2}$ $\mu_N$ for charm MDM. Very valuable for low-energy QCD
- $\sim 10^{-17}$ e cm for charm EDM. Improve indirect limits and sensitivity to new physics at EW scale. Also proof-of-principle for future experiments
- Setup can also be used as a standard fixed (gas) target
Solid wire target

- Wire metal target in the LHC ion beam halo
- Wires are target and sensors, vertices precisely located
- To avoid breaking the principle of magnet safety, current proposal uses super-thin wires (STW, \( \sim 1 \, \mu \text{m} \)) also in the beam core at low luminosity dedicated runs
- Installation inside VELO box mounted on a movable up & down platform
- Can use many different materials
- Proof-of-principle at HERA-B, but LHC conditions are completely different
- Need to assess impact on detector & machine and physics reach wrt SMOG2
Conclusion

- LHCb success in Fixed Target (gas) has open new horizons

- **New ideas**, more ambitious, very challenging, but no showstoppers so far

- New realms that would expand the LHC physics potential

- Priority of the experiment is the **Upgrade I** and **Flavour Physics core program**, but **significant R&D** towards making these ideas a realm