Implementation of fixed target experiments at the LHC: proposals and challenges

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with help from Stefano Redaelli
and material obtained from many contributors of the PBC LHC Fixed-Target WG

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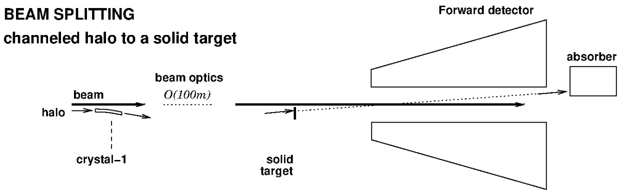
Outline

- Currently studied LHC fixed-target proposals
  1. beam halo deflected by crystal channeling and directed onto a solid target (IP2)
  2. beam halo deflected by crystal channeling and directed onto a solid target followed by a 2nd crystal for precession of baryon dipole moments (IP8 or IR3)
  3. unpolarized gas injected into a storage cell (IP8)
  4. nuclear-polarized gas injected into a storage cell (IP8)
- Framework to explore the technical feasibility
  - Physics Beyond Colliders, working groups...
- Achieved so far (2017-now)
- Main work topics for the few years to come

Currently studied LHC fixed-target proposals



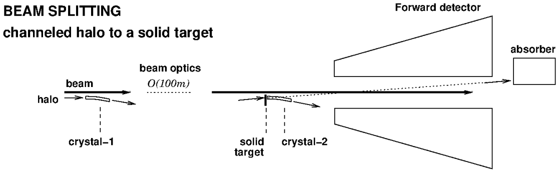
- Beam halo deflected by crystal channeling
- beam and deflected halo transported through machine optics.
- Deflected halo hits an off-axis solid target (Be, W, ...) near the IP
- Measure cross-sections and distributions
  $\rightarrow$ QCD, phases of strongly interacting matter
  $\rightarrow$ improve physics simulations (also for astroparticle physics)

Experiment at IP2 (ALICE) is under study.

See in this workshop:
- Charlotte Van Hulse, "Impact studies of fixed-target system on FoCal in ALICE"
- Rihan Haque, "Simulation of TPC performance for the ALICE fixed target program"
- Marcin Patecki, "Status of the crystal based ALICE fixed target layout"
- Kevin Pressard, "Solid target design for ALICE"
- Barbara Trzeciak, "Heavy-flavour projections for pA collisions and flow decorrelation predictions ..."
- Alexey Kurepin, "Antiproton production with fixed target and search for superheavy particles in ALICE"

also CERN-PBC-Notes-2019-004 and Ref [9].

Currently studied LHC fixed-target proposals



see:

L. Burmistrov et al., CERN-SPSC-2016-030,

A.S. Fomin et al., JHEP 2017 (2017) 120,

F.J. Botella et al., Eur. Phys. J. C 77 (2017) 181,

E. Bagli et al., Eur. Phys. J. C 77 (2017) 828

- Beam halo deflected by crystal channeling
- Beam and deflected halo transported through machine optics.
- Deflected halo hits an offset solid target near the Interaction Point.
- Produced (polarized) baryons channeled in a 2nd crystal behind the target
  $\rightarrow$ measure magnetic or electric dipole moment through precession
  $\rightarrow$ soft QCD, BSM physics (large EDM ?)

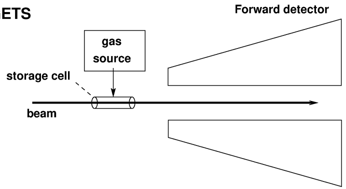
Experiment at IP8 (LHCb) or IR3 (momentum cleaning) under study.

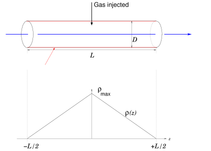
See in this workshop:
- Alex Fomin, "Considerations for Double-Crystal setups at the LHC"
- Federico De Benedetti, "Goniometer for long bent crystal for charm baryon dipole moments experiment"
- Andrea Merli, "Progress towards the charm baryon dipole moments with bent crystals"
- Elisabeth Niel, "Lambda_c polarisation with SMOG"

Currently studied LHC fixed-target proposals

UNPOLARIZED GAS TARGETS

H_2 , D_2 , He , N_2, O_2, Ne , Ar ...





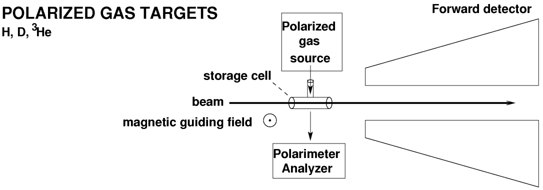
$$\int \mathcal{L}\,dt \approx \rho_{max}\,\frac{L}{2}\,n\,N\,f\,T \approx 1\ \text{pb}^{-1}\,\frac{\rho_{max}}{10^{12}\ \text{cm}^{-3}}\,\frac{n}{2500}\,\frac{N}{10^{11}}\,\frac{T}{10\ \text{h}}$$

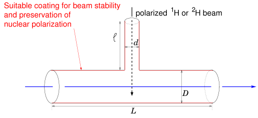
$(L = 20\ \text{cm},\ f = 11245\ \text{Hz})$

- LHC beams through thin gas target, produce beam-gas interactions
- Already used at IP8 / LHC in Runs 1+2: SMOG. (He, Ne, Ar)
- Now doing SMOG upgrade = SMOG2. Implementation of a Storage Cell just before the IP to boost the density. New gas-feed system, more gas types.
- SMOG2 SC studied, approved, installed. To be commissioned soon.
  - NB: new gas injection scenarios are not yet approved. Individual assessment of impact for each one. Under study.
- Measure cross-sections and distributions
  → QCD, phases of strongly interacting matter
  → improve physics simulations (also for astroparticle physics)

See in this workshop:
- Felipe Garcia Rosales, "Tracking in LHCb in high multiplicity events and LHCb Phase II"
- Benjamin Audurier, "Highlights from fixed target at the LHC: SMOG results"
- Pasquale Di Nezza, "SMOG2",
- Edoardo Franzoso, "Study of cold nuclear matter with SMOG2"
- Elisabeth Niel, "Lambda_c polarisation with SMOG"

see also in CERN-LHCb-PUB-2018-015





- Experiment at IP8 (LHCb). Requires a sophisticated apparatus to feed polarized gas into the SC, preserve, and measure the nuclear polarization.
- Guide B field needed at the target.
- Interesting R&D needed, in particular on the SC coating!
- Farther in future.
- Measure spin-dependent cross-sections (asymmetries) with transverse polarization
  $\rightarrow$ QCD, Generalized Parton Distrib., Transv. Momentum Dependent factoris.

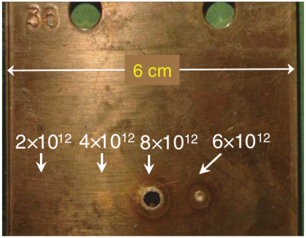
See in this workshop:
- Marco Santimaria, "LHCspin"

see also in arXiv:1901.08002 [hep-ex]

Are these technically feasible ?

Remember:

- in normal operation, each LHC beam carries ~ 0.5 GJ.
  - $E \approx 6.5$ TeV, $n \approx 2800$ bunches, with population $N \approx 1.7 \cdot 10^{11}$
- Enough to heat and melt about about 700 kg of copper.



Damage with a "modest" 450 GeV p beam (from R. Schmidt et al., 2006, New J. Phys. 8 290)

Thus, any near-beam device must respect strict rules

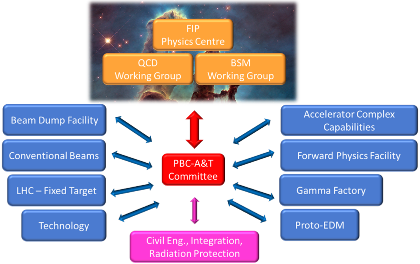
- machine and experiment protection strategy (aperture, failure scenarios, etc)
- LHC impedance compatibility
- vacuum compatibility
- experimental background constraints

$\Rightarrow$ it is crucial to review the proposals with the LHC machine experts.

Framework to explore the technical feasibility

The PBC forum

- http://pbc.web.cern.ch/
- (web pages being refurbished for phase 2, soon online)



- exploratory forum set up at Cern in 2016 to
  - exploit full science potential of Cern's accel. complex / infrastructure through projects complementary to the LHC, HL-LHC and other future colliders.
  - aimed at fundamental physics questions, similar to those addressed by HEP colliders, but requiring different types of beams / experiments.
  - NB: it also includes "add-on" experiments which use LHC in collider mode
    - "Forward physics facility", FASER, Codex-B, SND@LHC...
  - Phase 1: from 2016 to ESU update (roughly 2016 - 2020)
  - Phase 2: extension, from now to ...

Framework to explore the technical feasibility

LHC Fixed-target Working Group:

Conveners: Stefano Redaelli (CERN) and MFL, scientific secretary: Cynthia Hadjidakis (IJCLab)

Several proposals for fixed-target (FT) physics experiments at the LHC have been actively studied by interested communities. The use of splitting of beam halos from the core with bent crystals for internal targets and the use of internal gas (possibly polarised), or solid targets, were considered. Following the first PBC-FT report to the update of the European Strategy for Particle Physics (ESPP) and the subsequent recommendations, the working group will continue investigating FT proposals and conduct the relevant R&D to provide, as much as possible, the necessary support towards the evaluation of their technical feasibility.

- Open WG, participation of proponents of experiments, LHC experts, LHC experiments, etc
- Resources:
  - So far based mostly on "best effort" of a few people
  - 2021-2023: some Cern resources will be created for this scope
- NB: Several proposals mention LHCb/ALICE as a possible place to perform their experiment. This does **not** imply that LHCb/ALICE have approved these proposals.
  - Notable exception: SMOG2 storage cell approved and installed last year.

Framework to explore the technical feasibility

A biased selection of recently published documents relevant to the PBC LHC Fixed-Target WG (not an exhaustive list, but may give you some hooks to other Refs):

[1] C. Barschel, et al., *"LHC fixed target experiments: Report from the LHC Fixed Target Working Group of the Cern Physics Beyond Colliders Forum"*, Cern Yellow Report, Vol. 4 (2020), DOI:10.23731/CYRM-2020-004.

[2] D. Mirarchi, et al., *"Layouts for fixed-target experiments and dipole moment measurements of short-lived baryons using bent crystals at the LHC"*, Eur. Phys. J. C 80, 929 (2020), DOI:10.1140/epjc/s10052-020-08466-x.

[3] A.S. Fomin, et al., *"The prospect of charm quark magnetic moment determination"*, Eur. Phys. J. C 80, 358 (2020) DOI:10.1140/epjc/s10052-020-7891-0.

[4] W. Scandale, et al., *"The UA9 setup for the double-crystal experiment in CERN-SPS"*, Nucl. Instrum. Meth. A 975 (2020), 164175, DOI:10.1016/j.nima.2020.164175.

[5] Caterina Boscolo Meneguolo, *"Study of beam-gas interaction at the LHC for the Physics Beyond Collider Fixed-Target study"*, Master Thesis, Padova Univ., CERN-THESIS-2020-120.

[6] D. Marangotto, *"Amplitude analysis and polarisation measurement of the Λ_c^+ baryon in $pK^-\pi^+$ final state for electromagnetic dipole moment experiment"*, PhD thesis, Milan Univ., CERN-THESIS-2020-015.

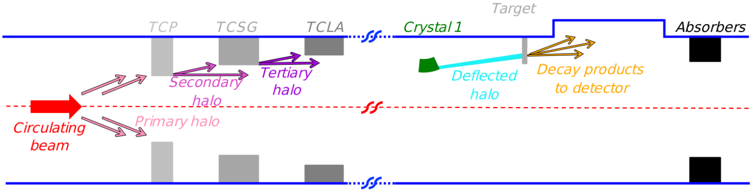
[7] E. Bagli, et al., *"Erratum to: Electromagnetic dipole moments of charged baryons with bent crystals at the LHC"*, Eur. Phys. J. C 80, 680 (2020), DOI:10.1140/epjc/s10052-020-8180-7.

[8] S. Aiola, et al., *"Progress towards the first measurement of charm baryon dipole moments"*, Phys. Rev. D 103, 072003 (2021), DOI: 10.1103/PhysRevD.103.072003.

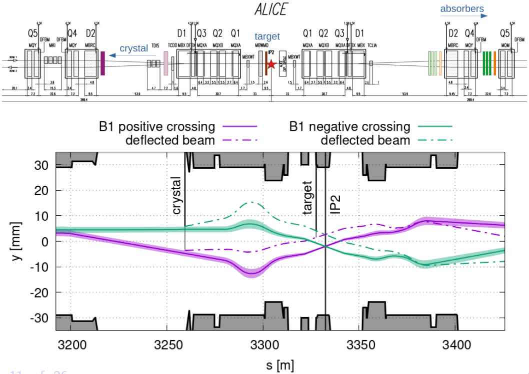
[9] C. Hadjidakis, et al., *"A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies "*, Phys. Rep. 911, 1 (2021), DOI: 10.1016/j.physrep.2021.01.002.

1-Crystal Setup at IP2

see talk by Marcin Patecki



- LHC tracing simulations performed, first machine layout defined
  Francesca Galluccio, Alex Fomin
- Now optimizing the layout, continue with detailed study
  Marcin Patecki



1-Crystal Setup at IP2

PoT = protons on target

Challenges / tasks:

- explore crystal+target+absorber layout to optimize PoT while maintaning operability
  - constraint: deflect preferably in V plane (beam dump in H)
  - longitudinal/transverse position and bending angle of crystal
  - position of target, position of absorber
  - two crossing angles, p and ion beams, possibly different beam energies

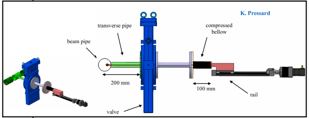
  → agreed with ALICE to focus LHC studies on layout optimisation and multi-turn simulations (SixTrack) for proton beam1 (later also Pb beam1)
- explore design of a movable target, evaluate performance and (minimize) impact on ALICE & LHC
  - demonstrate physics feasibility with Run3+4 ALICE detector conditions using just the TPC — see talk by Rihan Haque
  - background to specific detectors in ALICE (FoCal) — see talk by Charlotte van Hulse
  - design of target system (with help from Cern) — see talk by Kevin Pressard
    - beryllium beam pipe!
    - machine interface issues (impedance, vacuum, ALICE wants $< 10^{-11}$ mbar!!)
    - movable device, machine/experiment protection

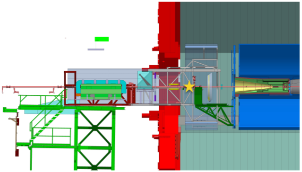
1-Crystal Setup at IP2

Fixed-Target WG has taken onboard this proposal and will support the associated activities

Solid target system

- Solid target design and implementation in ALICE:
  - possible integration at z~-4.8 m from IP2 before an existing valve (inside L3 magnet)
  - insertable target with step motor (linear movement) with motorisation outside of L3
  - aim: installation in LS3





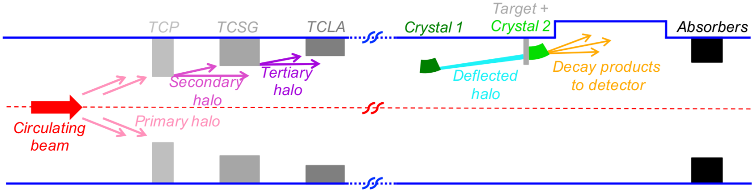
- Ongoing work / todo list
  - Target design study: thermal study, geometry and motion system
  - Study of target integration and impact on FoCal detector (both projects target LS3 and in similar location)
  - Study of ALICE TPC tracking performances for displaced vertices and realistic simulation
  - Preparation of SPS test beam with UA9: particle production and expected signal on available detector (timepix)
  - Not started: target system vacuum studies (~2 years for the target)
  - Not started: target system impedance studies (~6 months, end of 2022 by M. Patecki)

ALICE IJCLab université PARIS-SACLAY Cynthia Hadjidakis PBC-FT December 16th 2020 4

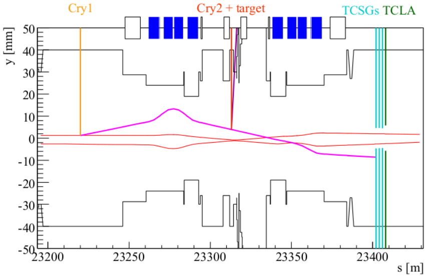
actions started with Cern teams:

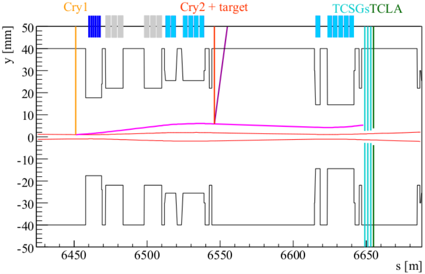
- target, mechanics (SY/STI)
- controls (BE/CEM)
- vacuum (TE/VSC)
- layout optimization (BE/ABP)

2-Crystal setup IP8/IR3



- LHC tracing simulations performed, IP8 machine layout defined and optimized, then, explored also IR3 D. Mirarchi, A. Fomin
  $\rightarrow$ at least 10^6 PoT/s achievable
- NB: *long* crys2, *large* bend ! $\sim 13 - 15$ mrad for IP8, ~ 7 mrad for IR3





2-Crystal setup IP8/IR3

see talks by Andrea Merli, Federico De Benedetti, Alex Fomin

Challenges / tasks:

- constraint: deflect preferably in V plane (beam dump in H)
- optimal long./transv. positions and bending angle of crys1,
- position/length of target and crys2 parameters
  - gain factor Ge vs Si, length, bending radius, T°, new ideas...
- validation of crystal simulation
  - long crystals, large bending, $E \sim \mathcal{O}(1\ \mathrm{TeV})$ → measurements needed!
- validation of physics simulation
  - Λ_c spectrum, polarization → measurements needed!
- Impact of IR8 bumps on operation
  - two crossing angles, p beam at top energy
  - luminosity levelling, VELO aperture
- Explore operational scenarios to maximize the flux, PoT
  - Excitation of bunches (work started, not yet presented to WG)
- Mechanical design for movable target+crys2 holder
- Absorber design

2-Crystal setup IP8/IR3

How to go about IR3 versus IP8 ?

Advantages:

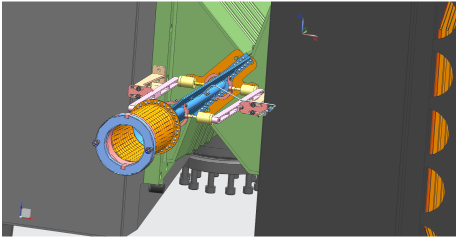
1. single-beam vacuum pipe
2. collimation region
   - "robust" region, no LHC experiment, detector can be designed ad hoc
   - may come closer to primary collimator position ? (more PoT ?)
3. parasitic operational scenario, no bkg to host experiment
4. no lower limit on bending angle linked to LHCb acceptance
5. no interference/competition from other usptream devices of LHCb

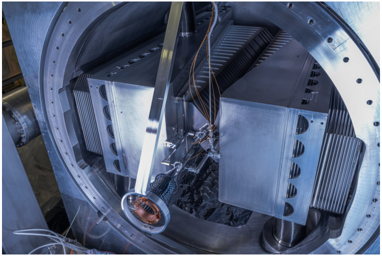
Disadvantage: must build a completely new detector (a jump in cost)

(see talk by Pasquale di Nezza)

SMOG2: Storage Cell attached to LHCb VELO at IP8 (fall 2020)

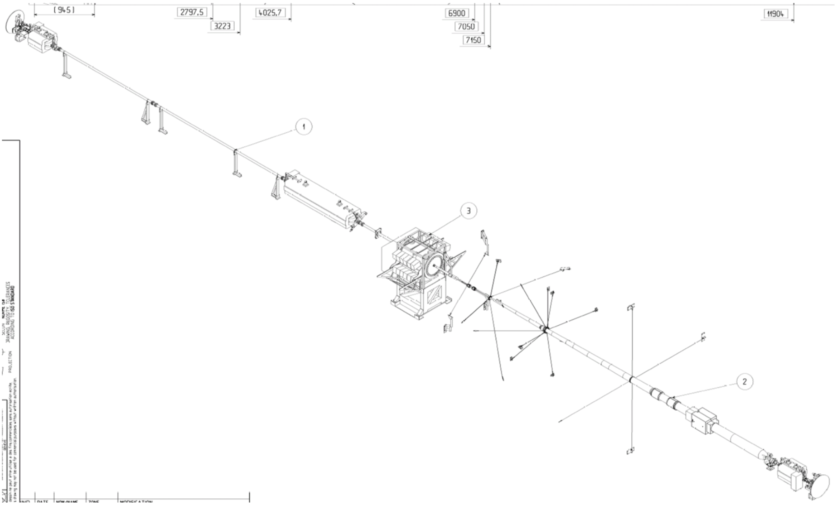
before and after coating with amorphous carbon



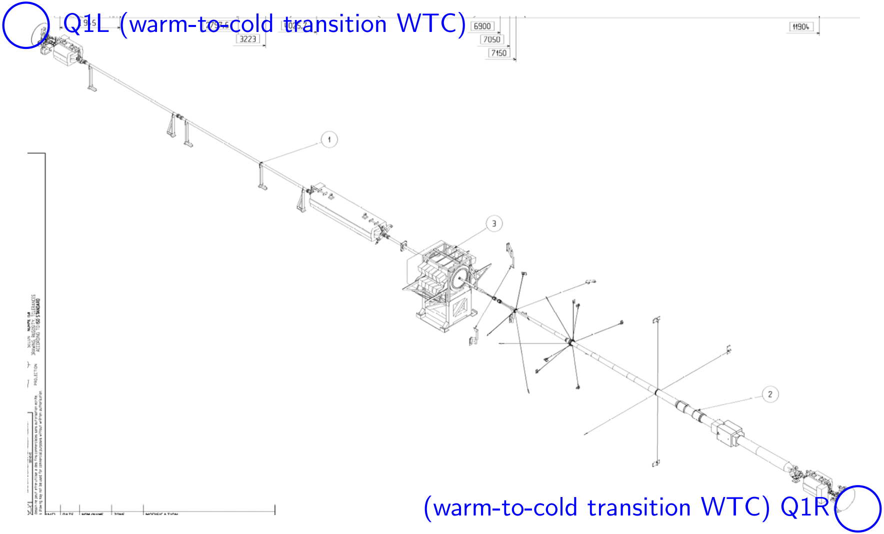


Next: gas-feed system, controls, validation/calibration, define injection scenarios, run scenarios, etc.

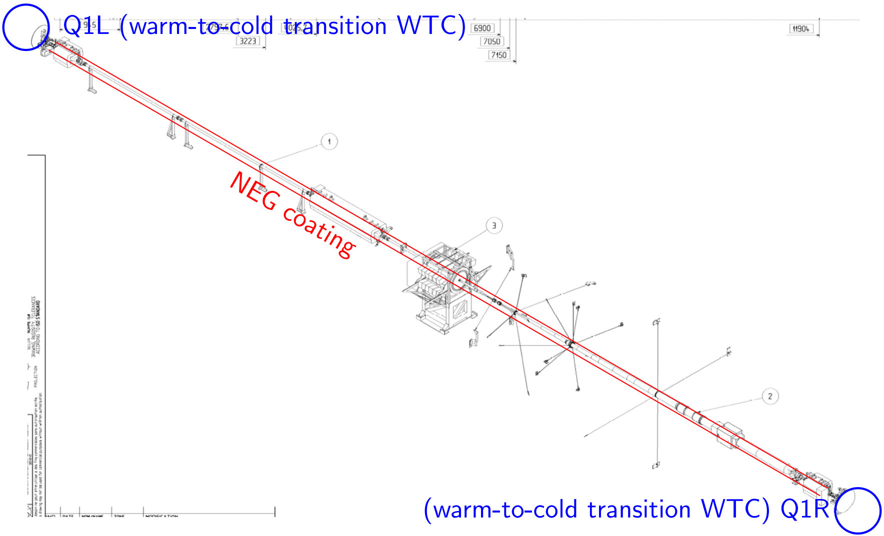
Unpolarized gas targets at IP8



Unpolarized gas targets at IP8



Unpolarized gas targets at IP8

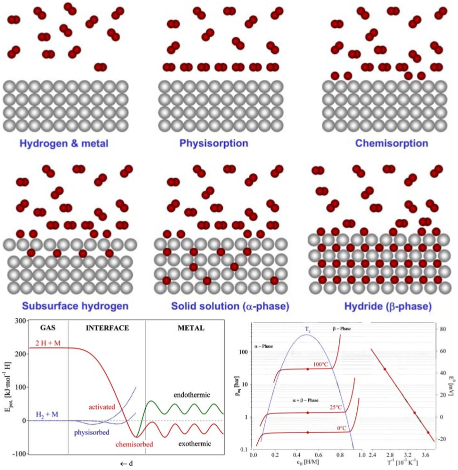


Unpolarized gas targets at IP8

The case of hydrogen (H_2 or D_2):

figs. from A. Züttel, Mitig Adapt Strat Glob Change 12 (2007) 343

- molecular hydrogen on the surface of TiZrV (LHC low-T° NEG): sticks and dissociates or is re-emitted
- atomic hydrogen diffuses in the bulk of TiZrV ($\sim 1\ \mu$m thick)
- results in a pressure equilibrium between hydrogen in the bulk and hydrogen in the gas volume
- an excess of hydrogen in the bulk may result in embrittlement (and peel off) of the NEG
  - R&D needed to quantify this in SMOG2@LHC conditions
- Most exposed NEG is on the VELO RF foil, 3.5 mm from the beam axis



What gas flux results in what presssure equilibrium at the VELO RF foil ?

Possible mitigation ?

Unpolarized gas targets at IP8

The case of oxygen (O_2):

quotes from P. Chiggiato, P. Costa Pinto, Thin Solid Films 515 (2006) 382

- molecular oxygen is pumped on the surface of TiZrV (LHC low-T° NEG)
- sticking coefficient depends on available pumping sites
- continuous gas flow will saturates progressively the NEG surfaces, from the SC vicinity to farther away
- results in less pumping speed for getterable gases ('ok' for LHCb)
- but also in an increase of the SEY ?
  → to be quantified!
  (data available ? M. Taborelli et al.)

3.5. Performance deterioration: ageing of Ti–Zr–V films

In many applications, vacuum chambers are frequently exposed to air and, as a consequence, Ti–Zr–V coatings undergo several venting–activation cycles. Since the film thickness is typically about 1 μm and the maximum quantity of oxygen that can be dissolved in the film is limited, a deterioration of the film performances is expected [11]. The

The experimental results can be interpreted by using both thermodynamic and kinetic considerations. Each cycle dissolves into the film an identical quantity of oxygen; hence the maximum possible number of cycles is reached when the oxygen solubility limit is attained. If an oxygen solubility limit similar to that of the elements of the fourth group is considered, full saturation after about 100 cycles is expected for each μm of film thickness [47]. However, heating at temperatures lower than 250 °C does not allow a uniform oxygen concentration to be reached in the film and, as a consequence, oxygen atoms are settled in the film to form a concentration profile with the maximum close to the surface, which finally leads to accelerated performance degradation. These conclusions are not peculiar to films but rather they apply to NEG materials of any nature.

Possible mitigation:

- re-activation ? (beam pipe bake-out, heavy operation)
- limited number of re-activations ?

The case of heavy noble gases Xe, Kr, (Ar):

- not pumped by NEG!
- part of the noble gas flows from VELO vacuum vessel into beam pipe
- around ± 20 m from IP8, gas reaches transition (WTC) from room to cryogenic temperature ($\mathcal{O}(10\ \mathrm{K})$ in the quadrupole Q1)
- noble gas is cryosorbed on the cold surfaces
- due to its high SEY, cryosorbed layer can provoke beam instabilities
  $\rightarrow$ more specific data needed

What gas flux results in what coverage at the WTCs ?

Possible mitigation:

- For Ne or Ar, a cryo/vacuum operation (local partial warm-up) may be used to force the cryosorbed gas to "migrate" towards the cold bore (behind the beam screen). It seems impossible to apply this method to Kr and Xe due to their thermodynamic properties.
- longer term: upgrade/adapt pumping scheme L/R of IP8 ?

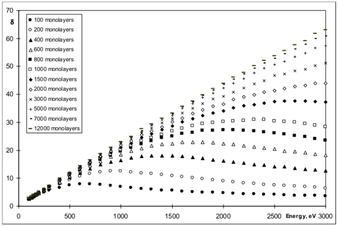


Fig. 14. "Secondary electron yield - incident energy" plane for neon.

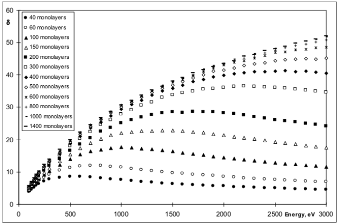


Fig. 20. "Secondary electron yield - incident energy" plane for xenon.

NB: data taken at 4.2 K

plots from plots from
Y. Bozhko et al., arXiv:1302.2334 [physics.acc-ph]

Unpolarized gas targets at IP8

Challenges / tasks:

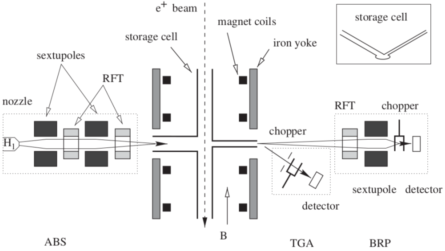
- Commisisioning with beam and gas
  - image storage cell aperture with tracks
  - verify local beam losses
  - check beam-induced effects vs increasing target density and beam intensity
    - non linear dependence as a sign of beam-induced effects
- New gas types, issues to tackle:
  - H_2, D_2: NEG saturation, embrittlement ?
  - O_2: NEG saturation, SEY
  - Kr, Xe: cryo-accumulation at WTC surface, local beam-induced effects
- R&D on NEG behaviour/evolution (saturation, pumping speed, SEY, surface microstructure imaging) under different gas exposures
- R&D on Kr, Xe properties (SEY), handling strategies
- Much of this will also build on detailed molecular flow simulations

SEY = Secondary electron yield, WTC = warm-to-cold transition

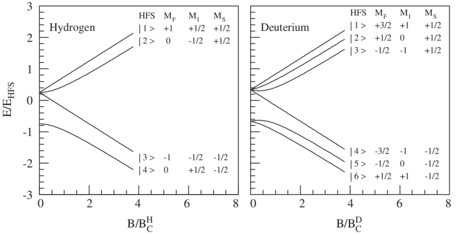
Polarized gas targets at IP8

From A. Airapetian et al., NIM A540 (2005) 68

Sketch of HERMES pol. H/D target



Hyperfine levels of atomic H and D



$$\mathrm{B_C^{H/D}} = 50.7 \; / \; 11.7 \text{ mT}$$

Nuclear polarization of the target in the storage cell:

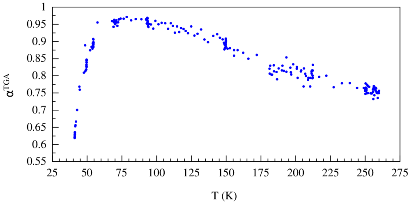
$$P = \underbrace{\alpha_0\,\alpha_r P_a}_{\text{atoms}} + \underbrace{\alpha_0\,(1-\alpha_r)\,\beta\,P_a}_{\text{molecules}}$$

α_0 = injected dissociation fraction

α_r = non-recombined fraction

$\beta = P_m/P_a$

$P_{a,m}$ = avg nucl. pol. of molec./atoms



atomic fraction sampled from SC

Polarized gas targets at IP8

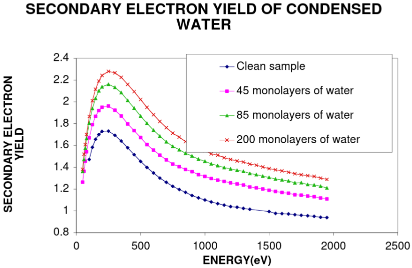
HERMES used a think layer of ice (H_2O) on a (Drifilm-coated) Al storace cell surface in order to prevent recombination and nuclear depolarization

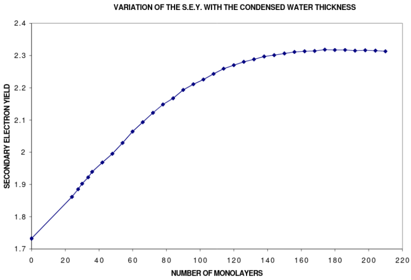
Applicable to LHC ? not so obvious... R&D needed!

Polarized gas targets at IP8

HERMES used a think layer of ice (H_2O) on a (Drifilm-coated) Al storace cell surface in order to prevent recombination and nuclear depolarization

Applicable to LHC ? not so obvious... R&D needed!



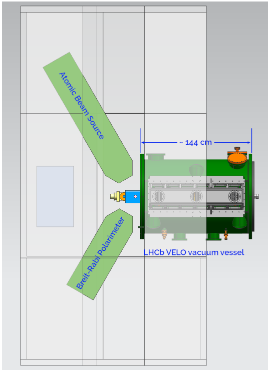


From Baglin et al., Proceedings of EPAC 2000, Vienna, Austria

Polarized gas targets at IP8

HERMES setup at DESY / Hera
(picture from Pasquale Di Nezza)

Top view sketch at IP8 / LHCb
(V. Carassiti, Ferrara)



Main challenges: (my bias)

- demonstrate a suitable SC coating.(Cooling needed ? was $\sim$ 80 K at HERMES)
- ABS/BRP compactness / interfacing to VELO system (also timewise!)

Outlook

Main subjects for the PBC LHC FixT WG in 2021 (and further)

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- assess impact of O_2 on IP8 NEG and possible mitigation
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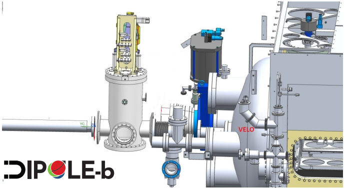
Crystals

- Finalize comparison of target + crystal simulation models
  - Crystal orientation, new ideas to reduce nuclear interactions
- PoT optimization / operational scenarios
  - Dedicated beam excitations
  - Explore further how to exploit IR3
  - Run3 optics, reversal, levelling
- Develop mechanical designs and machine interfaces of insertable crystal / target arms (impedance, vacuum) for IP8/IR3 and IP2



- propose beam tests (LHC/SPS/NA) during Run3, to address most critical aspects.