Physics Beyond Colliders at CERN
Lecture 3/4:
Projects related to the LHC

S. Redaelli, CERN, Beams Department
on behalf on the PBC teams
Acknowledgements

Many thanks to all the supporting teams, from CERN and outside, participating to the working groups within the PBC.

Special thanks for material provided for this lecture:
G. Arduini
M. Ferro-Luzzi
J. Boyd
S. Calatroni, W. Krasny
Focus of this lecture: accelerator aspects of project related to LHC
Physics Beyond Colliders structure

Focus of this lecture: accelerator aspects of project related to LHC
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- Introduction to the LHC
- The LHC fixed-target (FT) studies
- Forward Physics Facilities
- Gamma factory
- Technology
- Conclusions
In addition to the unprecedented beam parameters (see below), some PBC studies were also motivated by the possibility to profit from the **impressive and unique infrastructure** made available to operate a facility like the LHC and its experiments.
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The Large Hadron Collider

**LHC layout**
- 8 arcs (~3 km)
- 8 straight sections (~700 m)
- Two-in-one magnet design
- 4 interaction points (IPs): IP1, IP2, IP5, IP8
- IP2/IP8: beam injection
- IP6: beam dump region
- IP4: RF (acceleration)
- IP3/IP7: beam cleaning

<table>
<thead>
<tr>
<th>Nominal LHC parameters</th>
<th>Design</th>
<th>2018</th>
<th>2023</th>
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<tr>
<td>Beam injection energy (TeV)</td>
<td>0.45</td>
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<td>Beam energy (TeV)</td>
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<td>6.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>1.15 $\times 10^9$</td>
<td>$1.2 \times 10^{11}$</td>
<td>$1.6 \times 10^{11}$</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>2608</td>
<td>2560</td>
<td>~2200</td>
</tr>
<tr>
<td>Max stored beam energy (MJ)</td>
<td>362</td>
<td>300</td>
<td>~430</td>
</tr>
<tr>
<td>Beam current (A)</td>
<td>0.58</td>
<td>0.48</td>
<td>0.56</td>
</tr>
<tr>
<td>Norm transverse emittance (µm)</td>
<td>3.75</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Colliding beam size (µm)</td>
<td>16</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Bunch length at top energy (cm)</td>
<td>7.55</td>
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<td>7.55</td>
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27km underground tunnel
The Large Hadron Collider

**LHC layout**
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**Nominal LHC parameters**

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**HL-LHC project** aims at nearly doubling the beam intensity from the LHC design. Operation to start in 2029 until about 2041.
The LHC beam stored energy

Pre-LHC state-of-the-art
The LHC beam stored energy

Pre-LHC state-of-the-art
The LHC beam stored energy

Clear potential and interest in the LHC beams (energy and intensity frontier), but there are strong constrains on the manipulations of these beams in a superconducting environment.
Beam stored energy challenges

The LHC design parameters at 7 TeV correspond to 362 MJ, or...
Beam stored energy challenges

The LHC design parameters at 7 TeV correspond to 362 MJ, or…

90 kg of TNT
Beam stored energy challenges

The LHC design parameters at 7 TeV correspond to 362 MJ, or…

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The kinetic energy of a 200 m long train at 155 km/hour
Beam stored energy challenges

The LHC design parameters at 7 TeV correspond to 362 MJ, or…

90 kg of TNT

The LHC machine protection and collimation systems are designed to handle safely these energies for all relevant loss operational scenarios and abnormal beam failures!

Any modification and new implementation must be validated to be compatible with a safe operation of the LHC beams!

The LHC has a complex layout — new integrations are often not easy.
The LHC as an ion collider

Achieved and target Pb ion beam parameters

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<td>Beam energy (Z TeV)</td>
<td>7</td>
<td>6.37</td>
<td>6.8</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>100</td>
<td>75</td>
<td>50</td>
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<tr>
<td>Total n.o. bunches</td>
<td>592</td>
<td>733</td>
<td>1240</td>
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<td>Bunch intensity ($10^7$ Pb ions)</td>
<td>7</td>
<td>21</td>
<td>18</td>
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<td>Normalized transverse emittance (μm)</td>
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The LHC as an ion collider

Points of contacts to PBC: ALICE targets and Partially Stripped Ions (PSIs) for \( \gamma \) factory.

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Physics Beyond Collides at the LHC

The availability of LHC beams, running experiments & infrastructure motivated studies for different new opportunities within the PBC effort

- **New experiments directly using the LHC beams**
  - Typically, *parasitic* to main pp and PbPb physics programmes
  - Need nevertheless changes of LHC layouts

- **Dedicated operation modes with novel beam configurations**
  - Future gamma factory, requiring *dedicated* beam operations (PSI beams)

- **Experiments on long-lived particles (LLP) produced at LHC collisions**
  - Typically, installed far from the collision points with no need for LHC layout changes

- **New experiment re-using the existing, unique infrastructure**
  - Some examples of non-accelerator experiments using tunnel / shafts

- **Synergies with CERN technology teams**
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- Introduction to the LHC
- The LHC fixed-target (FT) studies
  - Gaseous target and their polarized future
  - Crystal-based fixed target implementations
- Forward Physics Facilities
- Gamma factory
- Technology
- Conclusions
The PBC LHC fixed-target studies

Accelerators & Technology Domain

The Working Groups in the Accelerators & Technology Domain are coordinated through the PBC Accelerators & Technology Committee, a steering committee which meets around once per month. The steering committee includes the CERN convenors of the various Working Group in the Accelerators & Technology Domain. The Working Group’s core members include accelerator experts and representatives of the projects. Requests from the Working Groups (tests, prototypes, manpower) are discussed by the steering committee.

ACCELERATORS & TECHNOLOGY WORKING GROUPS

- Accelerator Complex Capabilities
- Beam Dump Facility
- Charged particle EDM (cpEDM) measurement
- Conventional Beams
- Forward Physics Facility
- Gamma Factory
- LHC Fixed Target
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- Technology

Focus on proposals supported by experimental teams and compatible with the LHC’s main physics programme! E.g., no dedicated extraction beam lines.

CERN Yellow Report
CERN-2020-004

M. Ferro-Luzzi, S. Redaelli
LHC fixed target (LHC-FT) studies

After initial assessments, the PBC LHC FT focused on two solutions compatible with the LHC stored beam energies and with the main proton physics programme:

Gaseous targets

Crystal-based in-vacuum targets
LHC fixed target (LHC-FT) studies

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- The LHCb SMOG-2 started operation in 2022!
- Future studies are now focused on polarized gases
LHC fixed target (LHC-FT) studies

After initial assessments, the PBC LHC FT focused on two solutions compatible with the LHC stored beam energies and with the main proton physics programme:

- The LHCb SMOG-2 started operation in 2022!
- Future studies are now focused on polarized gases
- Studies for a future experiments on double-crystal setups
- Preparing a machine test for the proof of principle of such setups
Geography of FTs at the LHC

Double-crystal setup:
Proof-of-principle (TWOCRYST) and possible future experiment

Single-crystal setup (now discontinued)

Double-crystal setup:
Proof-of-principle (TWOCRYST) and possible future experiment

SMOG-2: approved

Gaseous targets

Double-crystal setup
Geography of FTs at the LHC

Double-crystal setup:
Proof-of-principle (TWOCRYST) and possible future experiment

Clearly, fundamental when possible to rely on existing LHC experiments!

Gaseous targets

SMOG-2: approved

Double-crystal setup

Single-crystal setup (now discontinued)
Gaseous targets: SMOG-2

Courtesy M. Ferro-Luzzi
Gaseous targets: SMOG-2

Courtesy M. Ferro-Luzzi
SMOG-2 at LHCb

as a result of much work & cooperation (impedance, aperture, SEY/vac)...
SMOG2 Storage Cell successfully attached to LHCb VELO at IP8 (summer 2020)

before and after coating with amorphous carbon

2022: gas-feed system & VELO+SC closing commissioned successfully

Courtesy M. Ferro-Luzzi
SMOG-2 at LHCb

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before

2022: gas-feed system & V

Courtesy M. Ferro-Luzzi
First results in 2022!

The two interaction regions are clearly visible and well separated!

PV distributions consistent with simulations

LHCb is now the first (unique) LHC experiment with two simultaneous interaction regions!

2023 run affected by issues preventing the closure of the VELO — looking forward to a successful proton run in 2024!
Various studies ongoing to use additional gases in SMOG-2:

- $\text{H}_2$ and $\text{D}_2$
  - an excess of hydrogen in the bulk may result in embrittlement (and peel off) of the NEG
- $\text{O}_2$
  - Risk to eventually saturate the NEG, resulting in reduce pumping speed
- Noble gases: Xe, Kr, Ar
  - Not pumped by the NEG
  - Risk to degrade secondary emission yield (SEY)

CERN: experiment to assess saturation and embrittlement of NEG coating by $\text{H}_2$

Beam losses in the machine also to be assessed for heavier gases.
“LHCspin”: polarized gas targets

R&D effort to identify suitable coating for $\bar{H}$

- amorphous carbon has excellent SEY
- very robust, “ages well”, ...
- effect of impurities: hydrogen is bad, nitrogen is good
- does it preserve H nuclear polarization?
- can one apply/control a few H$_2$O monolayers?
- started R&D FZJ, LNF, Ferrara, CERN/TE-VSC

Carbon-coating tests to assess the preservation of polarization: CERN delivered a samples storage cell to FZJ (Jülich), tests ongoing

List compiled by M. Ferro-Luzzi
Crystal based implementations of LHC fixed targets
Planar channeling in bent crystals

Pure crystals with regular lattices

If the protons have $p_T < U_{\text{max}}$

LHC 450 GeV = 9.4 μrad
LHC 6.5 TeV = 2.4 μrad
FCC-hh 50 TeV = 0.9 μrad

Critical angle

Straight crystal: hadron oscillates, “trapped” between planes

Bent crystal: net bending produced

Mechanical crystal bending $\rightarrow$ net kick for particles trapped between planes

Equivalent to very high magnetic fields: e.g., a 4 mm crystal bent to 50μrad corresponds to $\sim$ 300 T at 7 TeV

$\theta_{\text{Chan}} = \sqrt{\frac{2U_{\text{max}}}{pv}}$
Planar channeling in bent crystals

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Does it really work?

Key measurements: crystal angular scans and linear collimator scans

Established in other circular accelerators, in particular: useful operational experience at the SPS (UA9 setup).
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(1) **Angular scan**: strong reduction of local losses in channeling compare to amorphous.

Example: scan at 450GeV

- Beam losses at crystal [ a.u. ]
- Crystal angle [ µrad ]
- Loss rates in amorphous
- Reduced losses in channeling
- ~1/30
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(2) **Linear collimator scan**: measures the profile of the channeled halo.

Example: scan at 6.5TeV
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Example: scan at 450GeV

- Loss rates in amorphous
- Reduced losses in channeling
- ~1/30

(2) **Linear collimator scan**: measures the profile of the channeled halo.

Example: scan at 6.5TeV

- Channeled halo
- Beam core
- Offset at collimator

S. Redaelli, CERN Academic Training Lectures on PBC, 07/11/2023
Example: application to beam collimation

Bent crystals can be used instead of conventional primary collimators to efficiently steer beam halos on collimator absorbers.

Used for ion beam collimation in 2023!
Example: application to beam collimation

- TCP = primary collimator
- TCSG = secondary collimator
- TCLA = shower absorber

Bent crystals can be used instead of conventional primary collimators to efficiently steer beam halos on collimator absorbers.

Used for ion beam collimation in 2023!

Crystal collimation scheme in IR7

TCP = primary collimator
TCSG = secondary collimator
TCLA = shower absorber
Synergy with the LHC collimation studies

Four crystals installed in the LHC: two per beam, one per plane. Provided and validated by the UA9 collaboration. 2 producers: PNPI (3 crystals) and INFN-Fe (1).

IR7 layouts recently upgraded with new crystal assemblies as a part of the HL-LHC upgrade for ion beam collimation.

Crystal-based PBC FTs study were built on the well-established collaborations and know-how developed for LHC collimation.
The double-crystal setup
in circular accelerators

- Charmed baryon MDM/EDM measurements (in part., $\Lambda_c^+$):
  Can probe for physics beyond SM. Not feasible with conventional magnets.
  **Long-crystals behind target can provide sufficient precession!**
- Strong interest from physics community
- Studied in detail in simulation, for different LHC configurations

See proposal by Stocchi and Scandale at PBC kickoff, 2016.
The double-crystal setup in circular accelerators

Using magnetic field for particles decaying within a few cm.

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Possible solutions and open points

Studied to optimise performance and machine aspects; detector to be built

Initial proposal, relying on the LHCb detector (CERN-SPSC-2016-030; SPSC-EOI-012)

Open points calling for a solid experimental validation:
- Need to validate the long-crystal properties in the relevant TeV range
- Reliable operation of the double-crystal scheme to be demonstrated
  Achievable performance with 7 TeV beam is a key input for final experiment design
- Experimental validation of simulation-based performance estimates
  Performance in simulation relies on the complex dynamics of multi-turn collimation halos

Present focus of PBC-FT: proof-of-principle machine experiment in IR3, called “TWOCRYST”

Detailed layout comparisons:
- **Scope of the proof-of-principle:** two crystal assemblies + 1 target + Roman pot for detection of single- and double-channeling
- Layout designed for integration in the LHC IR3 (off-momentum collimation):
  Available longitudinal space and infrastructure (cabling); low radiation levels; existing collimators that can be used in measurements
- Test stand conceived for **low beam intensities**: flexibility vs collimation constraints, simplify impedance considerations
- Compatible with measurements at different beam energies
Status of the forming collaboration

TWOCRYST management status

- **MoU signed** by CERN and 3 collaborating institutes (Dec '22 / Jan '23)
  - INFN (Milano, Milano Bicocca, Padova, Pisa, Ferrara, Legnaro)
  - University of Valencia, Spain
  - IJCLab, Orsay, France

- Other institutes interested in signing

- **Addenda** defining individual contributions by collaborators currently under preparation

- **Work Breakdown Structure (EDMS 2740571)** agreed with CERN teams: final round of GL approval

CERN study leader appointed: Pascal Hermes

Preparation of a letter of intent for an experiment to be integrated in LS3 or beyond is ongoing. Options for IR8 and IR3 still both open.
Crystal goniometer assembly taken from IR7, will be used for IR3

Beam 2 layouts were studied as well: looks more promising because of an easier integration of the required Roman pot.
Recent hardware developments

Crystals for splitting and precession delivered to CERN and tested in the SPS-H8 in August. Preliminary results look very good — data being analysed by the TWOCRYST teams.

- Proceeding with the design of the precession crystal goniometer (impedance aspects)
- Discussion ongoing with ATLAS/ALFA and TOTEM to recuperate existing unused Roman pot
- Effort by INFN/IJCLab Orsay/Valencia to procure LHCb-like sensors and DAQ

Preliminary TCCP design, courtesy SY-STI, CERN

Courtesy A. Mazzolari, INFN
Our goal is to collect results in Run 3 in support for a future experiment in Run 4.
FT studies for ALICE

Potential for extensive data acquisition during proton runs and prospect (to be elaborated) to be used with ions. Layout studies and optics solutions well advanced.

ALICE decided to discontinue because of conflicts with integration.
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Dedicated detectors to record various types of long-lived particles (LLPs) produced from LHC collisions and so far unexploited — *maximise the LHC physics output!*
Dedicated detectors to record various types of long-lived particles (LLPs) produced from LHC collisions and so far unexploited — maximise the LHC physics output!

Convener: J. Boyd

Extensive White Paper submitted to Snowmass (arXiv:2203.05090)
These are cost-effective implementations based on existing tunnels and infrastructures.
Recap. from Claude’s lecture — 2

Idea is to run parasitically to the LHC operation… correct?

- CODEX-b in LHCb hall
- MATHUSLA on CMS surface
- 3 detectors of similar concept: *demonstrators and detailed simulations planned during run3*
- PROPOSED LHC “LARGE ANGLE” LLP FAR DETECTORS
- ANUBIS in ATLAS access shaft
TCL (physics-debris collimators): protect the machine from the pp collision products.

Effect of moving TCL5 — none

Effect of moving TCL6 — millimetre changes change the rates by a factor 2
TCL collimator impact on FASER

TCL (physics-debris collimators): protect the machine from the pp collision products.

A solution was quickly be found thanks to a very good iterations between the FASER and machine teams! Shows that synergy and common studies are important for future implementations.

Various points to be taken into account for present and future implementations:

- Variation of IP optics and crossing angles,
- Access requests for replacing emulsions,
- General running conditions,
- …
FPF for far forward detectors at HL-LHC

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**FPF for far forward detectors at HL-LHC**

: Forward Physics Facility

- Collisions at the LHC produce an enormous number of particles along the beam collision axis line of sight (LOS), which escape existing LHC detectors

\[ \pi, K, D, \nu_e, \nu_\mu, \nu_\tau \]

\[ \Lambda', a, \text{mCPs, } \chi, \ldots \]

- These include **very high energy neutrinos**, and possible **light new particles linked to dark matter**

- The Forward Physics Facility is a proposal to build a new underground cavern to host a suite of far-forward experiments to capture this physics

- During the HL-LHC era, FPF experiments will:
  - Collect $10^5 \nu_e, 10^6 \nu_\mu, 10^4 \nu_\tau$ interactions at TeV energies
  - Be sensitive to LLPs produced in $O(10^{17}) \pi^0/\eta, O(10^{15}) D$–mesons, $O(10^{13}) B$–mesons
    - Huge statistics to search for new particles that could be produced very rarely in the decay of these particles

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*Courtesy J. Boyd*
FPF status

The PBC supports FPF through several technical studies
- **Site investigation for civil engineering works** (1 slide below): assess local geological conditions
  → A 100m deep, 20cm diameter, core drilled at the FPF shaft location
- A very preliminary costing of the facility was done for civil engineering works and services
- **Simulations of muon background**: flux of 0.6Hz/cm² is ok for proposed experiments
  → Considering the possibility to install a “sweeper magnet” to deflect muons
- Simulation shows **radiation level OK** for people to be in the cavern during HL-LHC operation
- **Studied the effect of vibrations during excavation works** on the HL-LHC operation (1 slide)
  → Important for scheduling reasons that works can be done during the HL-LHC operation!

FPF Facility:
- 65m long, 9.7m wide, 7.7m high cavern.
- Connected to surface through an 88m high shaft (9.1m diameter): 617m from IP1.

Civil engineering studies benefit from recent work in point-1 for HL-LHC infrastructure (new shaft and galleries).

FPF teams converged to a **proposal close to the SM18 magnet testing area**, after detailed assessments (including costs): ~100m underground, ~600m west of ATLAS.

Preliminary integration model of the cavern with the proposed experiments

Courtesy J. Boyd
The PBC supports FPF through several technical studies

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Considered experiments

**FLArE**

**FASER2**

**FASERv2**

**AdvSND**

**FORMOSA**
First results include the production of detailed geological study that shows for the moment no showstopper for the excavation.
Vibration studies

CONCLUSION

The optics sensitivity of HL–LHC in the area of the FPF facility excavation works is about a factor of 10 smaller than in the triplet area, and a factor of 3 more than in the SPS optics. Vibration levels and associated impact on orbit stability and luminosity production are expected to be comparable to what was observed during HL–LHC civil engineering works during the LHC 2018 run. In case of excessive vibration levels, road headers might be employed instead of rock breakers. No major tunnel deformations are expected. If any, they could be compensated during the run with orbit correctors (at least for the HL–LHC) followed by re-alignment of the concerned area during a winter shutdown. The general conclusion is that no major disruption of HL–LHC and SPS performance is expected during the FPF excavation works.

No issue seen during site investigation works.
Possible effect of long term slow movement of the tunnel still be evaluated.
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Conveners: Y. Dutheil, W. Krasny, A. Martens (IJCLab Orsay)

Recent workshop: https://indico.cern.ch/event/1205247
The PBC $\gamma$ factory study

Accelerators & Technology Domain

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ACCELERATORS & TECHNOLOGY WORKING GROUPS

- Accelerator Complex Capabilities
- Beam Dump Facility
- Charged particle EDM (cpEDM) measurement

Only focus on some key accelerator aspects for the SPS and the LHC....
Gamma factory in a nutshell

PSI = partially-stripped ion

Principle: matching the laser wave length to the target dimension, excites the electron that than emits a photon.

Large range of gamma ray parameters can be tuned by choosing the PSI energy (SPS or LHC), the atom species and the number of un-stripped electrons.

Promise: generation of high-intensity photon beams for different applications like atomic or nuclear physics, generation of positrons or muons with gammas, photo fission, …

Imminent goal: cooling of ion beams of LHC ion collisions
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W. Krasny, PBC kick-off workshop

CERN as a unique place in the world to host a project, which is capable to increase the intensity of the present \( \gamma \)-ray sources of up to 7 orders of magnitude in the 3 orders of magnitude wide range of the \( \gamma \)-ray energies. New research opportunities in many domains of particle, nuclear and atomic physics could be opened at CERN.
Gamma factory can potentially become a novel research tool that opens up a wide range of experiments and measurements. Part of the PBC effort since the kickoff in 2016.

Key involvements:
- PSI test across the accelerator chain up to LHC (2018)!
- Working on a proof-of-principle at the SPS with $^{208}\text{Pb}^{79+}$
  → Integration of a Fabry Perot Cavity + remote operation of the driving laser in a high intensity hadron machine is a primer!
  → Plan to demonstrate the photon emission with PSIs
  → Observe beam cooling in the SPS

If cooling demonstrated, could be used for the LHC operation as an ion collider to deliver smaller emittance ion beams!
SPS scope

Main goals are to (1) observe X-ray photons and (2) observe fast **cooling** of PSI beams.

See presentation by Y. Dutheil at the last PBC meeting (Nov. 2022).
Goals of initial test in the LHC

- **Inject** new particle “species” in the LHC
  - Well-known Pb-208, but with one remaining electron
- Establish a few **circulating bunches**.
- **Acceleration** and **storage** of partially stripped ions.
  - Study of beam lifetime and beam parameter evolution at injection and top energy
  - Beam loss characterization
PSI beam in the LHC: “LHC atoms”

Goals of initial test in the LHC

12 hours LHC Machine Development (MD) time on 25.07.2018

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*M. Schaumann et al., doi:10.18429/JACoW-IPAC2019-MOPRB055*
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**Injection lifetime (450 Q GeV)**

Figure 3: Fitted intensity lifetimes for all bunches shown in

**Average lifetime of different PSI bunches at 6.5 Q TeV was found to be about 55h!**

M. Schaumann et al., doi:10.18429/JACoW-IPAC2019-MOPRB055
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M. Schaumann et al., doi:10.18429/JACoW-IPAC2019-MOPRB055

**Critical issue: collimation of partially stripped ions!**

S. Redaelli, CERN Academic Training Lectures on PBC, 07/11/2023
PSI beam collimation at 6.5 Q TeV

A. Abramov et al., doi:10.18429/JACoW-IPAC2019-MOPRB058
A. Gorzawski et al., PHYS. REV. ACCEL. BEAMS 23, 101002 (2020)
PSI beam collimation at 6.5 Q TeV

Measured losses with “hydrogen-like Pb atoms”
PSI beam collimation at 6.5 Q TeV

Several exciting issues ahead of us before a high-intensity deployment of PSIs at the LHC!

A. Abramov et al., doi:10.18429/JACoW-IPAC2019-MOPRB058
A. Gorzawski et al., PHYS. REV. ACCEL. BEAMS 23, 101002 (2020)
Table of Contents

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PBC technology working group

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Technological contributions, in particular to non-accelerator experiments, exchanging experience and expertise.
Support the development of new physics experiments.

Link to “PBC technology workshops”: indico category. Already 4 workshops organised so far.

Conveners:
S. Calatroni,
B. Döbrich
Updated list of supported studies

- ALPS-II/Jura -> axion search light-shining-through-wall with lasers
- VMB@CERN -> QED birefringence with lasers
- Grenoble Haloscope (GrAHal): -> axion search with RF cavities
- RADES/HTS -> axion search with HTS RF cavities
- DarkSide -> direct detection of WIMPS with liquid Ar TPC
- Ptolemy -> Carbon Nano Tubes for cosmological neutrino background
- STAX -> axion search light-shining-through-wall with RF cavities
- Advanced-KWISP -> search for Short Range Interactions
- New: Axion Heterodyne Detection -> axion search with two-mode RF cavities
- New: AION-100 @ CERN -> vertical atom interferometer
- Now independent: babylAXO -> axion search from the sun

Impressive!
AION-100 at CERN

AION is a vertical Atom Interferometer Observatory and Network for mid-frequency gravitational waves and ultra-light Dark Matter detection
- Proof-of-Principle (10m) being built in UK
- Possible siting of a 100m setup in an LHC shaft (PX46) under investigation in PBC (Integration, RP & general safety, evaluation of EM interference - RF zone- and seismic noise/vibrations)

Detailed scoped of CERN PBC activities (list by S. Calatroni)

- Identify location for a vertical AI ~100 m deep at CERN
  (Site to be already part of a large international laboratory and experimental facility)
- Assess technical feasibility and impact from presence of LHC machine
- Based on AION-100 technical requirements as guideline
  - “A Long-Baseline Atom Interferometer at CERN: Conceptual Feasibility Study”
  - CERN-PBC-REPORT-2023-002, https://cds.cern.ch/record/2851946
Study for integration in LHC P4

Selected location: PX46
Study for integration in LHC P4

Selected location: PX46
Assessment of compatibility

- Compatibility with technical requirements for an AI – influence of the LHC
  - Vibrations, seismic noise and local geology
  - EM noise
  - Radiation protection
  - Fire safety
  - He release hazards
  - Access control

- Available infrastructure
  - Electrical supply, network, etc.
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Conclusions

The LHC is a collider and it offers unique and interesting opportunities for physics beyond colliders!

— At the frontier of stored beam energy for protons and ion beams
— Well established and unique underground infrastructures
— Part of a laboratory that plays centre role in the worldwide physics community

Various opportunities have been studied since the PBC kick-off in 2016 and are now at different stages of maturity

— From approved experiments taking data, to new proposal that are still coming in!
— From shift-lived baryons (~ cm) to long-lived particles (measured at hundreds of m)

Some examples were reviewed, with focus on LHC oriented project

— LHC fixed-target plans, FPF, gamma factories, examples of non-accelerator experiments for gravitational waves, …

Thank you very much for your attention.
1232 NbTi superconducting dipole magnets – each 15 m long
Magnetic field of 8.3 T (current of 11.8 kA) @ 1.9 K (super-fluid Helium)
Complex layouts and configurations...

\[ \Delta L = 116 \text{ meter} \]
Complex layouts and configurations...

\[ \sigma^* \propto \sqrt{\beta^*} \]

\( \sigma^* \): colliding-beam size (RMS)
\( \beta^* \): betatron function

<table>
<thead>
<tr>
<th>( \beta_{\text{triplet}} )</th>
<th>Sigma triplet</th>
<th>( \beta^* )</th>
<th>Sigma*</th>
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<tbody>
<tr>
<td>~4.5 km</td>
<td>1.5 mm</td>
<td>55 cm</td>
<td>17 um</td>
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</tbody>
</table>
Crystal bending

LHC design parameters for *Silicon crystals*

Bending 50µrad
Crystal collimation for heavy ion beam will be used in Run 3
- Our test stand in IR7 (betatron collimation) has being upgraded with the installation of 4 new crystal primary collimators to become an operational system
- Good results obtained already in 2018 for special forward-physics runs!

LHC-FT studies will profit from the strong synergy with this program!
- Already explored beam tests relevant for LHC-FT using the “collimation” crystals
- Important know-how on key hardware and software solutions, and on operation
- Built competence in CERN teams for crystal validation and characterization.

Latest design of the crystal primary collimator: starting point for CRY-1

One new unit installed in IR7 for HL-LHC

Courtesy HL-LHC WP5 teams
Crystal collimation for HL-LHC

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