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STUDIES FOR FUTURE FIXED-TARGET EXPERIMENTS AT THE LHC IN THE FRAMEWORK OF THE CERN PHYSICS BEYOND COLLIDERS STUDY

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Abstract

A study on prospects for Physics Beyond Colliders at CERN was launched in September 2016 to assess the capabilities of the existing accelerators complex. Among several other working groups, this initiative triggered the creation of a working group with the scope of studying a few specific proposals to perform fixed-target physics experiments at the Large Hadron Collider (LHC). This includes for example physics experiments with solid or gaseous internal targets, polarized gas targets, and experiments using bent-crystals for halo splitting from beam core for internal targets. The focus of the working group's activities is on the technical feasibility and on implications to the LHC ring. In this paper, the current status of the studies is presented and future plans are discussed.

INTRODUCTION

The European Organization for Nuclear Research (CERN) offers a unique accelerator complex that covers beam energies up to the 7 TeV at the Large Hadron Collider (LHC) [1], with a variety of beam types (protons, ions). As a part of the Physics Beyond Colliders study at CERN (PBC) [2], a working group on fixed target physics at the LHC was launched in 2017 to collect concrete proposals from the physics community and evaluate their impact on the LHC. Several proposals have been presented, e.g. the use of bent crystals for separating the beam halo from the core and directing it to an internal target with a second channeling crystal [3,4] to measure magnetic [5, 6] and electric [7, 8] dipole moment of charged baryons, or the use of internal gas targets (possibly polarized) and solid targets for studying the nucleon and nuclear partonic structure [9], the quark-gluon plasma and also to produce unique hadronic cross section data sets useful for cosmic ray physics models (see for example [10] or [11]). The working group is currently addressing the technical feasibility and impact, principally from the perspective of the LHC accelerator, with the aim of producing a report that will serve as input to the approaching update of the European Strategy for Particle Physics (ESPP). This paper summarizes the present status of the working group's studies.

Some of the proposed fixed target experiments build on the experience accumulated in past years in other colliders, such as HERA [12,13], the Tevatron [14] and RHIC [15,16]. While studying these cases is certainly pertinent to guide future choices, it is important to highlight aspects specific to the operation of the high intensity beams at the LHC. With a design stored energy of 362 MJ [1], that will nearly be doubled for the High-Luminosity upgrade of the LHC [17]

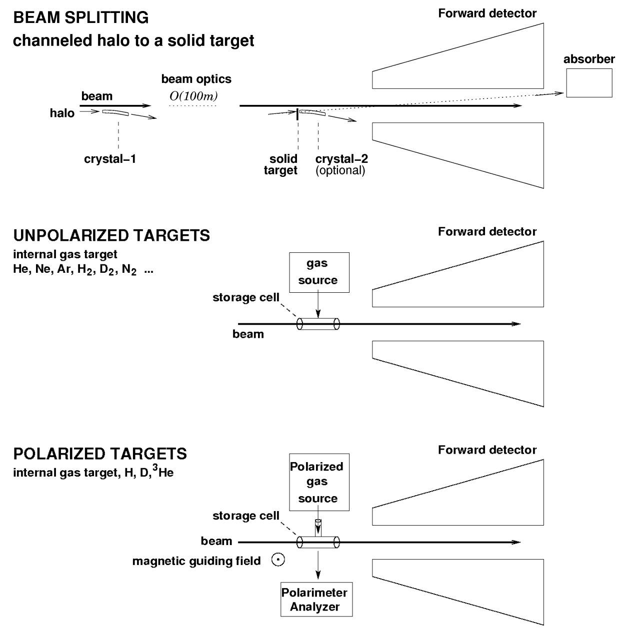

Figure 1: Sketches of three fixed target setups: crystal beam splitting for a double-crystal setup (top) and unpolarized (middle) and polarized (bottom) gaseous targets.

(HL-LHC), collimation and machine or experiment protection constraints, which were less of a concern in previous colliders, must be taken into account early on.

Most fixed target proposals would greatly benefit from re-using an existing detector at the LHC, as this reduces the cost of implementation. The implications for such a hypothetical "host" experiment must be carefully evaluated (operational risks, experiment protection, induced background rates, compatibility of simultaneous operation or sharing of beam time, etc). Some of the proposed scenarios may also have a global effect on all existing LHC experiments, for example in terms of integrated luminosity or induced background. The working group tries to identify possible implications and interferences.

OVERVIEW OF PRESENT PROPOSALS

Three types of fixed target implementations are being considered by the working group. Sketches of these implementations are shown in Fig. 1. The top sketch shows how the beam halo is extracted from the beam core by use of a channeling bent crystal (crystal-1) and directed towards a solid target located upstream of a forward detector. It can be used for a solid target physics program or, in conjunction with a second bent crystal (crystal-2), for measuring

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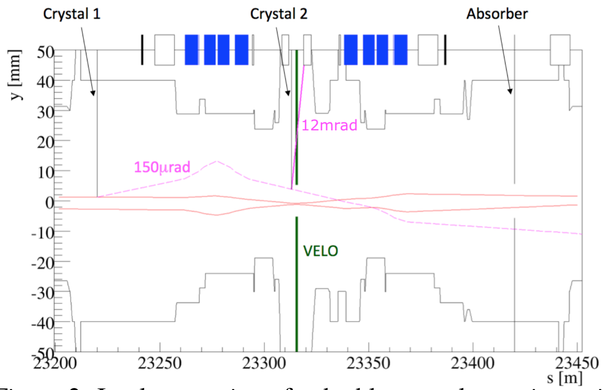

Figure 2: Implementation of a double-crystal experiment in LHCb, as presented in [3]. *Courtesy of D. Mirarchi, CERN.*

the dipole moment of charged baryons (see below). The middle (unpolarized) and bottom (polarized) sketches show how gaseous targets would be used in front of a forward detector for a fixed target physics programme. In the case of a polarized target, additional instrumentation is needed to produce, guide and measure the nuclear polarization.

Crystal Channeling for Beam Splitting and Fixed-Target Experiments

In this concept (Fig. 1, top), a bent crystal, similar to the ones presently used for hadron-beam collimation at the LHC [4, 18, 19], separates from the circulating beam a fraction of the halo that then impinges on a target, safely retracted from the beam core envelope. A specific implementation of this scheme, which we call "double crystal" setup, was proposed [3] for an experiment in LHCb, to study magnetic dipole moment of baryons [5] (see also [20]). Later, this idea was extended to measure also the electric dipole moment [7, 8, 21]. In this scheme, the target is followed by a second crystal with a much larger bending angle.

A possible layout of this experiment, elaborated for the LHC point 8 (P8), is given in Fig. 2 [3]. The first crystal is located upstream of the P8 inner triplet for Beam 1. A bending angle of 150 μrad is sufficient to steer beam halo particles onto a target located a few meters upstream of the LHCb VELO [22]. For a first study, a 5 mm-long tungsten crystal was considered. A second crystal, attached to the target, is used to bend into the LHCb acceptance area the produced baryons. A much larger bending, of the order of 12-15 mrad, is required in this case. Further downstream, at least one collimator is needed to dispose in a controlled way of protons and other interaction products that emerge from the first crystal and the target.

The feasibility of this scheme is being studied both from the accelerator and the experiment points of view. There are three main areas of study that are subject of simulation and experimental verifications: the feasibility of producing large-angle crystals with the required accuracy and channeling efficiency at the energy of interest; the assessment of realistic rates of protons on target for different LHC operational scenarios; the implementation of the collimation system downstream of LHCb, to be integrated into the present LHC collimation system.

Recently, very promising results towards a feasibility demonstration of the double-crystal concept were achieved by the UA9 collaboration at the CERN SPS, where a complete double-crystal test stand has been setup [23]. In 2017, the double channeling was demonstrated for the first time, by placing a crystal into the halo channeled by a first crystal in a setup equivalent to that proposed for the experiment, although with the second crystal at lower bending angles and still without target. Tests will continue in 2018 with the goal to assess achievable extraction efficiencies and possibly adding a target [23, 24].

Solid Targets at the LHC

The crystal experiment described above can also be used in a single-crystal setup where the deflected halo interacts with a solid target internal to the beam pipe close to an existing detector. More conventional solid target setups where the beam halo directly interacts with the in-vacuum target are also being envisioned. As in past and current experiments [13, 16, 25], wire or foil targets of the order of 500 μm thickness could be considered. It would be valuable to use various target materials from low to large atomic mass numbers and the compatibility of each of them with the LHC conditions should be studied. In addition, a retractable target system is required to cope with the main beam envelopes at beam injection. Although the ALICE collaboration expressed interest in these possible scenarios [26], detailed layouts for these setups have not been studied yet.

Gaseous Targets at the LHC

A rich fixed-target physics programme [27, 28] has been initiated in LHCb, at LHC P8, by exploiting the forward geometry of the detector and the availability of SMOG [29], a gas injection system originally implemented for measuring by beam-gas imaging the luminosity of the colliding beams [30]. This triggered new proposals for internal gas targets at the LHC, with or without polarization. In Fig. 1, middle and bottom plots, the unpolarized and polarized gaseous targets in front of a forward spectrometer are sketched.

One salient feature of these proposals is the use of a storage cell (SC), a cylindrical open-ended tube located around the beam, which allows one to enhance the target thickness as compared to a free polarized atomic beam or an equivalent flux of unpolarized gas injected directly in the beam vacuum. The storage-cell principle, and its genesis, has been described extensively in Ref. [31] (see the sketch in Fig. 3) and has been used in several storage rings since the 1980's. Gas is injected in the middle of the tube. Before escaping, the atoms or molecules undergo a large number of wall collisions. The resulting density profile $\rho(z)$, with z along the tube axis, is approximately triangular with a maximum $\rho_{\max}$ in the center (at $z = 0$).

A proposal has been made to upgrade the fixed-target luminosity obtained with SMOG by injecting the gas in a SC attached to the end of the VELO RF shields, as depicted in

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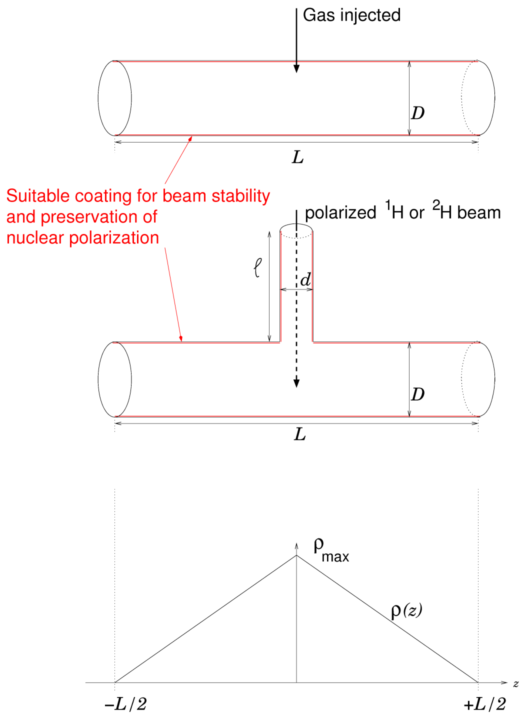

Figure 3: Principle of storage cell with triangular gas distribution (see e.g. [31]). Top: typical situation for unpolarized gas (or polarized ^{3}He). Middle: the case with a feed tube for an atomic beam (^{1}H, D). Bottom: resulting density profile along the beam axis.

Fig. 4. The cell must be split in two halves in order to respect the LHC injection aperture requirement of about 50 mm minimum diameter. When closed the cell radius is limited by LHC aperture requirements and possible background rates to the LHCb detector originating from beam-halo interactions.

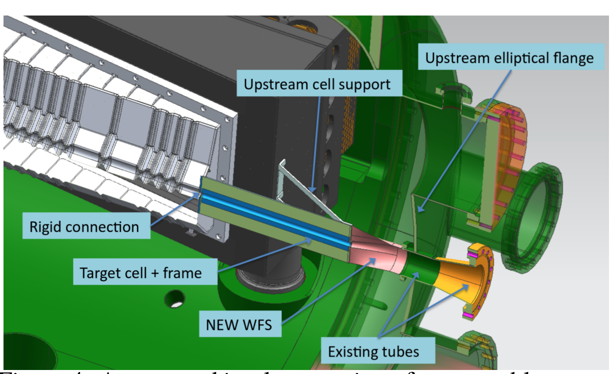

Figure 4: A proposed implementation of an openable storage cell in LHCb to increase the unpolarized gas target thickness. Only one half is shown, for clarity. *Courtesy of V. Carassiti (INFN Ferrara).*

As an example, the He density during the 2016 SMOG run [27] was approximately $5 \cdot 10^9$ He/cm^3 with an injected flux of $3.7 \cdot 10^{15}$ He/s. Using a SC with a diameter of 0.8 cm and a full length of 20 cm with the same He flux one would obtain a central density of $\rho_{\mathrm{max}} \approx 1.2 \cdot 10^{12}$ He/cm^3. Considering the longitudinal vertex position integration, an enhancement of the target thickness by about a factor of 50 can be obtained with the SC when compared with the current SMOG setup.

In order to mitigate possible beam-induced desorption or electron cloud effects, the SC inner surface must be coated with suitable materials (see Section 5.8 of [1]). In the case of unpolarized noble gases, a non-evaporable getter (NEG) coating could be considered. For getterable unpolarized gases a carbon coating solution could be investigated. For polarized targets, the additional requirement to preserve nuclear polarization imposes the need for R&D to demonstrate that a suitable coating, compatible with both LHC and target requirements, can be found. Impedance effects have to be carefully analysed and mitigated. Simulation studies of beam losses and instabilities induced by the enhanced gas pressure are ongoing.

CONCLUSION AND OUTLOOK

Three different implementations of proposed fixed target experiments at the LHC were outlined. Although not an exhaustive list of what could be done with the LHC beams, these three options are currently the most actively studied by several groups, in particular the double-crystal setup and the gaseous target experiment. Possible implementations at different LHC locations are being elaborated by the proponents, the PBC Fixed-Target working group's members and the relevant machine experts. Not all proposals have reached the same level of maturity. However, a preliminary feasibility assessment will be written up by the end of 2018. The various efforts and contributions, addressing feasibility and open points, will be summarized in a document that will serve as input for the upcoming discussions at the European Strategy for Particle Physics.

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