

A Fixed-Target Experiment at the LHC (AFTER@LHC) : luminosities, target polarisation and a selection of physics studies

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We report on a future multi-purpose fixed-target experiment with the proton or lead ion LHC beams extracted by a bent crystal. The multi-TeV LHC beams allow for the most energetic fixed-target experiments ever performed. Such an experiment, tentatively named AFTER for "A Fixed-Target Experiment", gives access to new domains of particle and nuclear physics complementing that of collider experiments, in particular at RHIC and at the EIC projects. The instantaneous luminosity at AFTER using typical targets surpasses that of RHIC by more than 3 orders of magnitude. Beam extraction by a bent crystal offers an ideal way to obtain a clean and very collimated high-energy beam, without decreasing the performance of the LHC. The fixed-target mode also has the advantage of allowing for spin measurements with a polarised target and for an access over the full backward rapidity domain up to $x_F \simeq -1$. Here, we elaborate on the reachable luminosities, the target polarisation and a selection of measurements with hydrogen and deuterium targets.

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1. Introduction

The important contributions of fixed-target experiments to hadron and nuclear physics, especially in accessing the high Feynman x_F domain and in offering a number of options for polarised and unpolarised proton and nuclear targets need not be recalled. For those who are not convinced, let us simply recall that they have led to particle discoveries ($\Omega^-(sss)$, J/ψ , Υ ,...) as well as evidence for the novel dynamics of quarks and gluons in heavy-ion collisions. They have also led to the observation of surprising QCD phenomena: the breakdown of the Lam-Tung relation, colour transparency, higher-twist effects at high x_F , anomalously large single- and double-spin correlations, and the breakdown of factorisation in J/ψ hadroproduction at high x_F in proton-nucleus collisions (see [1] and references therein).

High luminosities can be reached at fixed-target experiments thanks to the density and length of the target. A wide spectrum of precision measurements at laboratory energies never reached before can be carried out thanks to the LHC beams of 7 TeV protons and 2.76 TeV-per-nucleon lead ions interacting on a fixed-target. In addition, an entire set of heavy hadrons such as the $\Omega^{++}(ccc)$ and exotic states could be looked at with a unique access to the large negative- x_F domain.

7 TeV protons colliding on fixed targets release a center-of-mass energy close to 115 GeV, in a range never explored thus far, between those of SPS and RHIC. With the benefit of the proton runs lasting nine months each year, the production of quarkonia, open heavy flavour hadrons and prompt photons in pA collisions can thus be investigated with statistics previously unheard of and in the backward region, $x_F < 0$, which is essentially uncharted. In addition to conventional targets of Pb, Au, W, Cu, etc., high precision QCD measurements can also obviously be carried out in pp and pd collisions with hydrogen and deuterium targets.

For instance, at large negative x_F , intrinsic heavy quark distributions can be investigated by looking at new mechanisms for the production of hadrons with multiple heavy quarks such as baryons with two or three bottom quarks as well as systems such as $J/\psi + D$ [2]. A deuterium target and gluon sensitive probes –such as quarkonium, open heavy-flavour and prompt-photon production– will allow for a first precision measurement of the gluon content in the neutron. Polarizing the target would allow one to study spin correlations including the Sivers effect beyond conventional factorisation; this effect pins down the correlation between the parton k_T and the nucleon spin. In particular, AFTER can bring much information on the contribution of the gluon angular momentum to the nucleon spin.

2. Luminosities for a bent-crystal-extraction mode on the LHC proton beam

The idea of extracting a small fraction of the CERN LHC beam to be used for fixed target physics is not new. Already, in the early 90's, the LHB collaboration submitted a letter of intent to the appropriate committee [4] to get an experiment based on bent-crystal extraction approved. At the time, this idea was turned down, mainly with the justification that the irradiation limit for the degradation of channeling performance was only known to be higher than 10^{19} particles/cm², and *expected* to be up to 10^{22} particles/cm². Experiments have meanwhile shown that the degradation is approximately 6% per 10^{20} particles/cm², see *e.g.* [5]. For realistic impact parameters and beam sizes at the crystal location, this corresponds to about one year of operation, after which the crystal

has to be moved less than a millimeter to let the beam impact on an intact spot, a procedure that can be repeated almost at will.

Following this, and other important developments in the field of channeling in bent crystals, the Large Hadron Collider Committee now expresses that "...it may well be feasible to bend even the low emittance LHC beam" and that "possible future applications of the bent-crystal scheme abound: including beam-halo cleaning and *slow extraction*" [our emphasis]. Thus, the committee recommends further studies to be performed at the LHC [6].

One possibility that deserves to be studied further is the proposal [7] to "replace" the kicker-modules in LHC section IR6 (the beam dump) by a bent crystal that will provide the particles in the beam halo with the sufficient kick to overcome the septum blade and to be extracted. By this method, a beam of about $5 \cdot 10^8$ protons/s can be extracted in the direction of the dump, at an expense of practically zero - the beam halo has to be removed by collimation anyway. Another possibility would be to integrate the extraction in a "smart collimator" solution, originally proposed by Valery Biryukov [8]. This is presently the route followed by the CERN LUA9 collaboration.

We have summarised the instantaneous luminosities which can be reached with various 1cm thick targets in table 1. The integrated luminosities over one year (taken as 10^7 s for the proton beam) are also given; it is of the order of a fraction of a femtobarn⁻¹. Luminosities for the Pb run can be found in [1]. Note that 1m long targets of liquid hydrogen or deuterium give luminosities close to 20 femtobarn⁻¹.

Target (1 cm thick)	ρ (g cm ⁻³)	A	\mathcal{L} ($\mu\text{b}^{-1} \text{s}^{-1}$)	$\int dt \mathcal{L}$ (pb ⁻¹ yr ⁻¹)	Target (1 cm thick)	ρ (g cm ⁻³)	A	\mathcal{L} ($\mu\text{b}^{-1} \text{s}^{-1}$)	$\int dt \mathcal{L}$ (pb ⁻¹ yr ⁻¹)
solid H	0.088	1	26	260	liquid H	0.068	1	20	200
liquid D	0.16	2	24	240	Be	1.85	9	62	620
Cu	8.96	64	42	420	W	19.1	185	31	310
Pb	11.35	207	16	160					

Table 1: Instantaneous and yearly luminosities obtained with an extracted beam of 5×10^8 p⁺/s with a momentum of 7 TeV for various 1cm thick targets

As aforementioned, 7 TeV protons colliding on fixed targets release a center-of-mass energy close to 115 GeV ($\sqrt{2E_p m_N}$). The boost between center-of-mass system (cms) and the lab system is rather large, $\gamma_{\text{cms}}^{\text{lab}} = \sqrt{s}/(2m_p) \simeq 60$ and the rapidity shift is $\tanh^{-1} \beta_{\text{cms}}^{\text{lab}} \simeq 4.8$. The cms central-rapidity region, $y_{\text{cms}} \simeq 0$, is thus highly boosted at an angle of 0.9 degrees with respect to the beam axis in the laboratory frame. The entire backward cms hemisphere ($y_{\text{cms}} < 0$) is easily accessible with standard experimental techniques. The forward hemisphere is less easily accessible because of the reduced distance from the (extracted) beam axis which requires the use of highly segmented detectors to deal with the large particle density. In a first approach, we consider that one can access the region $-4.8 \leq y_{\text{cms}} \leq 1$ without specific difficulty. This allows for the detection of the main part of the particle yields as well as high precision measurements in the whole backward hemisphere, down to $x_F \rightarrow -1$ for a large number of systems.

3. Target polarisation

The choice of a polarised target for AFTER is rather flexible: the intensity of the beam is not large, of the order of 5×10^8 p⁺s⁻¹, with a very high energy (7 TeV), meaning minimum ionizing

particles which produces low heating of the target. The main spin-physics opportunities [1] lie in Drell-Yan pair, photon and meson production with large cross sections and a rate of thousands of interesting events per second, without requiring thick targets. Typically for a 1 cm long target, the heating power due to the AFTER beam would be of the order of $50 \mu\text{W}$, allowing to maintain target temperatures as low as 50 mK and therefore relaxation times as long as one month in the spin-frozen mode. On the other hand, damages on the target arise after an irradiation of $10^{15} p^+ \text{cm}^{-2}$, namely one month of beam [9].

In these conditions, the luminosity would still be larger than $10 \mu\text{b}^{-1}\text{s}^{-1}$. This leaves a wide choice of target materials: most of them being able to withstand the AFTER experimental constraints. It is tempting therefore to choose the target material having the best *dilution factor*, namely the best ratio of polarizable nucleons to the total number of nucleons in the target material molecule. Typical dilution factors are for Butanol ($\text{C}_4\text{H}_9\text{OH}$), 0.13; for Ammonia (NH_3), 0.176; for Li_6D , $\simeq 0.5$; and for HD, $\simeq 0.9$. The time needed to perform an experiment of a given statistical accuracy is directly proportional to the squared product of the maximum achievable polarisation by the dilution factor, through the *figure of merit*, which includes other linear factors linked to the target geometry [10]. Accordingly, it would take ten times less beam time to perform a polarisation experiment using an HD target instead of a Butanol one.

However, other considerations must be taken into account such as the reliability and the complexity of the relevant technology, the available space and, last but not least, the expertise of the target makers. All the above listed materials, except the HD, are polarised using the *Dynamic Nuclear Polarisation* (DNP) by which the polarisation of electrons is transferred to the nuclei by RF transitions [11]. This transfer is done at high field (5T) and "high" temperature (4K) and the build-up polarisation can be kept by continuous excitation under high field or maintained in the frozen-spin mode at low field ($< 1 \text{ T}$) by lowering the temperature below 100 mK. For HD, the "brute force" method using the static polarisation at very high field (17 T) and very low temperature (10 mK) allows one to polarise simultaneously the protons and the deuterons. The polarisation can then be maintained in beam at low field and high temperature, provided that a significant ageing ($> \text{one month}$) of the target has taken place [12]. Both methods can typically reach 90% and 50% vector polarisation for protons and deuterons respectively.

In the case of AFTER, the available space can be a major constraint which would restrict the choice to a target polarised by continuous DNP or a HD target which both take less space than the frozen-spin machinery. The frozen-spin mode usually requires removing a dilution refrigerator containing the target from the high-field polarizing magnet to put it into the beam and therefore moving bulky equipments. The HD polarisation can be done outside the experimental site and the target can be transported at high temperature and low field to the experimental area where a rather standard cryostat is needed [13].

As mentioned, the expertise of the target builders is a key factor. At CERN, there is a long tradition of DNP for various materials (NH_3 , Li_6D) [14] and there are still quite a few experts of DNP all around the world. On the other hand, HD target makers are scarce, with only two groups: one at TJNAF (USA) and the other at RCNP (Japan) [15]. It is likely that when all the specifications and constraints of AFTER are determined precisely, the choice of the polarised target type will be more limited. It is worth noting that DNP of HD, which is in principle feasible, would be the dream choice. The possibility of a rich spin program with AFTER should thus encourage our colleagues

working on DNP to revisit the relevant technology [16].

4. A selection of physics studies with pp and pd collisions

In this section, we limit ourselves to a very brief survey of measurements with the extracted 7 TeV proton beam on hydrogen and deuterium targets. We stress that these are only a small part of the possibilities offered by AFTER. Much more details can be found in [1].

4.1 Yields

Given the notably large quarkonium yields –1000 times those of RHIC–, an a priori very good acceptance at low transverse momenta thanks to the boost, the expected excellent energy resolution for the muons as well as the possibility to rely on novel particle-flow techniques for the photon detection in highly populated phase space, AFTER is ideally positioned to carry out precise measurements of most of the S - and P -wave quarkonia both at the level of the cross section and of the polarisation [2]. Precision studies of open-heavy flavours is also one of the realms of AFTER. Correlation measurements of quarkonia with heavy flavours and prompt photons are also certainly at reach. The aim would be to constrain the production mechanisms of quarkonia [17] –with the help of the forthcoming LHC results– such that gluon PDF extraction by analysing the y dependence of their yields becomes competitive. Quarkonium production in pd collisions –as done by E866 for Υ [18]– would in principle provide information on the gluon distribution in the neutron.

With a detector designed, among other things, for quarkonium precision studies, the detection of Drell-Yan pairs is then nearly a bread-and-butter analysis. Using both hydrogen and deuterium targets, one expects to obtain updated information on the isospin asymmetry of the quark sea. With the requirements for quarkonium P -wave detection, *e.g.* a good photon calorimetry, prompt-photon physics also becomes accessible as well as correlations with jets, charm-jets and beauty-jets. All this provides further tests of pQCD but also an independent means to probe the gluon content in the proton and the neutron – see *e.g.* [19].

4.2 Transverse single-spin asymmetries

As explained above, it is rather easy to polarise the target at AFTER. This directly opens the possibility of studying transverse Single-Spin Asymmetries (SSAs). These allow for studying the correlation between the intrinsic transverse momentum of the partons and the proton spin itself, through the Sivers effect [20]. It is therefore a very rich source of information on the nucleon spin structure. In particular, such Sivers effect for gluon is relatively unknown, although it surely deserves careful studies. A first indication that it may not be zero is the nonzero SSA observed by PHENIX in inclusive J/ψ production [21].

In this context, studies of SSAs of gluon sensitive probes, such as prompt photons, open and closed heavy flavours, are highly relevant. These can be performed at high accuracy at AFTER given the high luminosities which can be reached (see section 2). It is also very important to note that the privileged region for such measurements, namely at medium and large x^\uparrow , corresponds to the cms backward-rapidity region where, in the lab frame, the density of the particles in the detector should be rather low. This is thus an ideal place to perform such measurements.

5. Conclusion

A fixed-target experiment using the multi-TeV proton or heavy ion beams of the LHC extracted by a bent crystal offers an exceptional testing ground for QCD at unprecedented laboratory energies and momentum transfers. We have gathered here the luminosities which can be obtained with the proton beam with targets ranging from hydrogen to heavy-ions such as lead. We have then discussed the options to polarise the target. As we mentioned, the target polarisation at AFTER should not cause any specific difficulties. We have then very briefly presented studies which can be carried out in polarised and unpolarised pp and pd collisions, ranging from quarkonium studies to single-spin asymmetries in photon-jet correlations. All these would then be carried out at unprecedented statistical accuracies owing to the yearly luminosities well above the inverse femtobarn.

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