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PROSPECTS FOR FUTURE ASYMMETRIC COLLISIONS IN THE LHC

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Abstract

The proton-lead runs of the LHC in 2012, 2013 and 2016 provided luminosity far beyond expectations in a diversity of operating conditions and led to important new results in high-density QCD. This has permitted the scope of the future physics programme to be expanded in a recent review. Besides further high-luminosity proton-lead (p–Pb) collisions, lighter nuclei are also under consideration. A short proton-oxygen run, on the model of the 2012 p-Pb run, would be of interest for cosmic-ray physics. Collisions of protons with argon, other noble gases and nuclei of lighter metals are also discussed. We provide an overview of the operational strategies and potential performance of various options. Potential performance limits from moving beam-beam encounters at injection and various beam-loss mechanisms are evaluated in the light of our understanding of the LHC to date.

INTRODUCTION

The simultaneous acceleration of two different particle species were not considered in the initial design of the LHC. The two-in-one magnet design requires them to be injected and accelerated with the same magnetic rigidity [1] and the feasibility of this was doubted, based on experience elsewhere [2, 3]. The slightly different velocities of the two beams lead to moving long-range beam-beam encounters in the interaction regions (IRs) and can cause fast beam losses and emittance blow-up [4]. The successful proton-lead (p–Pb) pilot run in 2012 [5] and, especially, the higher-intensity run in early 2013 [6], showed that the LHC beams are not susceptible to this kind of beam-beam interaction. A second one-month run in multiple conditions took place in 2016 [7, 8]. The p–Pb runs were principally intended as reference data for comparison with Pb–Pb collisions but have proved to be much more than that. Each of these three runs yielded important new results in high-density quantum chromodynamics (QCD).

Further Pb-Pb and p-Pb runs, with higher luminosity, are foreseen for the next 10 years of operation of the LHC and HL-LHC as confirmed in a recent major review by the heavy-ion physics community [9]. This review also made the physics case for collisions of lighter nuclei with each other (A–A) and with protons (p–A) for later. It included preliminary performance estimates for a variety of A–A collisions at beam energies of $E = 7\,Z$ TeV showing that lighter species could yield higher integrated nucleon-nucleon luminosities than Pb–Pb. A potential proton-oxygen (p–O) pilot run, similar to the 2012 p–Pb [5] or 2017 xenon–xenon pilot run [10], is envisaged for Run 3 of the LHC to enhance the understanding of cosmic rays [9]. In addition to oxygen, other lighter ion species are also considered for future asymmetric collisions with protons in full intensity one-month runs. The ion choice is restricted by many parameters but particularly by the temperature required to evaporate the respective material for the ion source. Hence, we consider noble gases like argon (Ar), krypton (Kr) and xenon (Xe). Calcium (Ca) is also studied.

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MOVING ENCOUNTER POINTS AND RF LOCK

At the injection energy of $E = 450\,Z$ GeV, the long-range beam-beam encounter positions in the IRs move by

$$d_t \approx C \frac{c^2}{4p_\mathrm{p}^2}\left(\frac{m_\mathrm{A}^2}{Z^2} - m_\mathrm{p}^2\right) \tag{1}$$

per turn in the propagation direction of the proton beam. Here, C is the circumference, c the speed of light, m_i the particle mass of either p or A and p_p is the proton momentum. The shift per turn for the different ion species in p–A operation are given in Tab. 1. Main parameter defining the shift size is the charge-to-mass ratio difference between the protons and the respective ion species.

During the acceleration to target energy, the RF frequencies of the two beams are independently varied and the RF frequency difference shrinks towards higher energies. Once at target energy, the RF frequencies are locked to the mean RF frequency $\tilde{f}_\mathrm{RF} = \frac{1}{2}(f_\mathrm{RF,p} + f_\mathrm{RF,A})$ of the two systems causing a relative momentum shift for both beams

$$\delta_\mathrm{p} = -\delta_\mathrm{A} \approx \frac{1}{\eta}\frac{c^2}{4p_\mathrm{p}^2}\left(\frac{m_A^2}{Z^2} - m_\mathrm{p}^2\right) \tag{2}$$

with the slippage factor η. The proton (ion) beam experiences a positive (negative) momentum change forcing it onto an outer (inner) orbit. The momentum shift creates β-beating that may require correction [11].

In the case of Pb, the shift of the encounters and the momentum shift are the largest among the ion species considered (see Tab. 1) because Pb has the smallest charge-to-mass ratio. It has been shown in the past that the beta beating can be easily corrected and effects from moving encounters are very small. Recent studies predict that they will remain so, with no operational restrictions for p–Pb in Run 3 and beyond [4]. Hence, the influence of moving encounter points on the other ion species should be even less pronounced and can therefore be neglected.

BEAM PARAMETERS

Following [9], a highly-simplified estimate of the bunch population is derived from past performance of the injector chain supplying beams for fixed-target experiments at

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Table 1: Parameter List of Different Ion Species in Proton-Nucleus Collisions in the LHC in Run 3 and Beyond at a Beam Energy of $E = 7\,Z$ TeV

		$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
		Injection					
Lorentz factor γ	1	242	218	242	223	202	191
encounter shift per turn d_t	cm	8.51	11.17	8.50	10.47	13.37	15.47
momentum shift (RF) $\delta_{p/A}$	10^{-5}	±4.1	±5.4	±4.1	±5.0	±6.4	±7.4
		Collision					
Lorentz factor γ	1	3760	3386	3762	3473	3149	2964
collision energy $\sqrt{s_{NN}}$	TeV	9.90	9.31	9.90	9.51	9.06	8.80
normalised emittance ε_n	µm	2.09	1.89	2.09	1.93	1.75	1.65
ions per bunch N_b	10^8	19.5	18.5	15.8	6.5	3.6	1.9
EMD cross section σ_{EMD}	mb	1.20	4.01	4.08	9.84	18.68	35.47
BFPP cross section σ_{BFPP}	mb	< 0.01	0.02	0.04	0.71	5.41	44.10
hadronic cross section σ_{had}	b	0.45	0.83	0.83	1.14	1.60	2.13
long. rad. damping time τ_z	h	50.3	34.0	20.1	15.4	15.1	12.7
		Performance					
fill length τ_{fill}	h	8.9	9.2	9.2	7.6	6.3	5.0
ALICE levelling $\mathcal{L}_{AA}$	10^{29} Hz/cm^2	65.0	26.0	26.0	13.3	8.1	5.0
peak luminosity $\mathcal{L}_{AA}$	10^{29} Hz/cm^2	228.5	216.6	185.0	76.6	41.7	22.3
peak NN luminosity $\mathcal{L}_{NN}$	10^{32} Hz/cm^2	3.66	8.66	7.40	5.97	5.38	4.63
$\int_{month} \mathcal{L}_{AA}$ IP1/5	nb^{-1}	11432	9427	8323	3331	1678	841
$\int_{month} \mathcal{L}_{AA}$ IP2	nb^{-1}	4969	1996	1998	979	561	323
$\int_{month} \mathcal{L}_{AA}$ IP8	nb^{-1}	215	175	155	61	31	15
$\int_{month} \mathcal{L}_{NN}$ IP1/5	pb^{-1}	182.9	377.1	332.9	259.8	216.5	174.9
$\int_{month} \mathcal{L}_{NN}$ IP2	pb^{-1}	79.5	79.8	79.9	76.3	72.4	67.1
$\int_{month} \mathcal{L}_{NN}$ IP8	pb^{-1}	3.4	7.0	6.2	4.8	4.0	3.2

CERN's North Area and LHC [10]:

$$N_b(Z) = 1.9 \times 10^8 \left(\frac{82}{Z}\right)^p \tag{3}$$

with the phenomenological factor p be in the range between $p = 1$ (pessimistic) and $p = 1.9$ (optimistic). The value of $p = 1$ is based on the low bunch intensity achieved in the 2017 Xe–Xe run [10]; however, only a very limited amount of time was spent on optimizing the beam at that time. The value of $p = 1.9$ is assumed to be the optimistic limit in [9]. We take a conservative $p = 1$ for oxygen and $p = 1.5$ for the heavier species.

The measured loss maps during the Xe-Xe run were acceptable for low beam intensities but full intensity beams would have caused issues assuming the collimation settings at that time [12]. Additional collimators (TCLDs), which will be installed for LHC Run 3 in the dispersion suppressor downstream of the collimation section at IR7, will intercept most of the critical losses in the superconducting region downstream of IR7, allowing full intensity beams of Xe and other ion species in the future.

The geometric beam sizes of each ion species is taken to match that of the Pb beam, i.e., the normalised emittances for all species are $\epsilon_{n,A}/\gamma_A = 0.56$ nm. See Tab. 1 for emittances and intensities.

The proton beam in p–A collisions is expected to have bunch intensities of 3×10^{10} protons per bunch and to have a normalised emittance of $\varepsilon_n = 2.5$ µm in both planes. This makes the geometric proton beam size slightly smaller than that of the ions. In order to achieve this proton intensity, the implementation of the so-called synchronous orbit is required, i.e., the strip-line BPMs in areas where both beams share the same beam pipe are gated to avoid dynamic range issues when low intensity ion and high intensity proton bunches pass through the BPMs in short succession. This was successfully implemented during the 2016 p–Pb run [7].

The total cross section of the p–A interactions includes the hadronic cross section and contributions from electromagnetic dissociation (EMD) and bound-free pair production (BFPP)

$$\sigma_{tot} = \sigma_{had} + \sigma_{EMD} + \sigma_{BFPP} \,. \tag{4}$$

The hadronic cross sections for the different p–A systems analyzed throughout this paper have been estimated using a Monte-Carlo Glauber code by D. d'Enterria [13]. For the p–A systems, the values for σ_{EMD} and σ_{BFPP} are obtained by scaling the A–A values [9] by $\log(\gamma_{c,pA})/(Z^2 \log(\gamma_{c,AA}))$ with $\gamma_{c,AB} \approx 2\gamma_A\gamma_B$ referring to the A-nucleus rest frame. In the cases of interest, these cross-sections are negligible (see Tab. 1).

ONE-MONTH PERFORMANCE

In the following, performance estimates for a one-month proton-nucleus run of the various p–A systems are given. The expected optical functions at the interaction points (IPs)

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in the LHC in Run 3 are listed in Tab. 2. A filling pattern foreseen for Pb–Pb operations [14] (assuming slip-stacking in the SPS) is used to estimate the potential performance for all ion species. The bunch trains comprise 1232 bunches and the number of colliding bunch pairs in each of the four IPs is listed in Tab. 2. The numbers of colliding bunch pairs could be redistributed to increase the number of collisions at IP8 (LHCb experiment).

Table 2: Potential IP Settings and Numbers of Colliding Bunch Pairs in LHC Run 3

		IP1/5	**IP2**	**IP8**
beta function at IP β^*	m	0.5	0.5	1.5
half crossing angle $\theta/2$	µrad	100	100	318
coll. bunch pairs k_c	1	1136	1120	81

Beam Evolution

One-month estimates are based on beam-evolution simulations making use of coupled ordinary differential equations as in [8]. Hence, the effects of luminosity burn-off, a non-colliding lifetime, radiation damping and intra-beam scattering are taken into account. Although larger for lighter ions, a non-colliding lifetime of 100 h is applied for all ion species and is based on observations of Pb in the LHC. In 2016, additional losses for the Pb beam were observed depending on the bunches' collision pattern [8]. Better agreement between observation and simulation was achieved by modeling these losses with extra exponential decays. The extra losses observed in 2016 (see Tab. 2 of [8]) are scaled linearly with proton intensity, energy and crossing angle difference between 2016 and future p–A runs. This proceeding is justified by assuming the extra losses being caused by dynamic aperture restrictions due to beam-beam interactions of the ion beam with the smaller proton beam. The upgraded IP2 (ALICE experiment) p–Pb levelling value will be at a luminosity of $\mathcal{L}_{\mathrm{AA}} = 5 \times 10^{29}\,\mathrm{Hz/cm^2}$. For the other ion species, the levelling value is adjusted to match the p–Pb nucleon-nucleon (NN) luminosity of $\mathcal{L}_{\mathrm{NN}} = 1.04 \times 10^{32}\,\mathrm{Hz/cm^2}$.

In order to estimate the monthly performance, the beam evolution study is used to estimate the optimum fill length for IP1/5 (ATLAS and CMS experiments) and IP2. As the optimum fill length of IP2 is often a factor two larger than that of IP1/5, the geometric mean of the two optima is used as the fill time τ_{fill}. A total run is expected to last 24 d and an operational efficiency of 50 % is assumed. A fast turn-around time (time span between beam dump and collisions of consecutive fills) of 2.5 h is used since the protons are injected faster than ions. The proton bunch trains are flexible enough to reproduce the aforementioned Pb–Pb filling pattern; however, additional 5 % reduction to the total luminosity is applied to take potential deviations into account.

Results

The one-month integrated luminosities and peak luminosities in ATLAS and CMS are given in Tab. 1. The lighter ion species benefit greatly from higher bunch intensities. The integrated luminosity in p–Pb collisions of $0.8\,\mathrm{pb^{-1}}$ is more than one order of magnitude smaller than the integrated luminosity in p–Ar collisions with $9.4\,\mathrm{pb^{-1}}$. The nucleon-nucleon luminosity does not increase by a large amount but is effectively increased by a factor 2 between Ar and Pb. The higher integrated luminosity comes with the downside of a smaller system size. A potential compromise would be the operation with a medium sized ion like Kr.

PROTON-OXYGEN PILOT RUN

A p–O and O–O pilot run could take place in 2022 or 2023. During a p–O pilot run, the LHCf experiment at IP1 would require luminosity levelling at $10^{28}\,\mathrm{Hz/cm^2}$. Otherwise, an integrated luminosity of $0.2\,\mathrm{nb^{-1}}$ per IP is requested by the other experiments. Comparably to the Xe–Xe pilot run, the beam intensities are limited to 3×10^{11} charges by machine protection to avoid extensive beam commissioning. The optics and IP settings will be those of the 2021 Pb-Pb run, which are comparable to the settings listed in Tab. 2. With an intensity of roughly 1.95×10^9 ions per bunch, approximately 19 bunches can be stored. A filling pattern of 18 bunches per beam giving 12 collisions per IP seems reasonable at this point in time. The proton bunch charge would match the oxygen bunch charge to remain below the intensity limit and to have enough bunches to give sufficient collisions to the experiments.

A potential luminosity evolution is displayed in Fig. 1. The low levelling value in ATLAS can be maintained for an extremely long period of time. If the fill is stored for 15 h to 20 h, integrated luminosities between $5\,\mathrm{nb^{-1}}$ and $7\,\mathrm{nb^{-1}}$ can be achieved in CMS and ALICE while the integrated luminosity in LHCb is close to $2\,\mathrm{nb^{-1}}$. The requested luminosity can therefore be delivered in a single fill for each experiment. Three or four fills will achieve an integrated luminosity in the range of $20\,\mathrm{nb^{-1}}$ in CMS and ALICE.

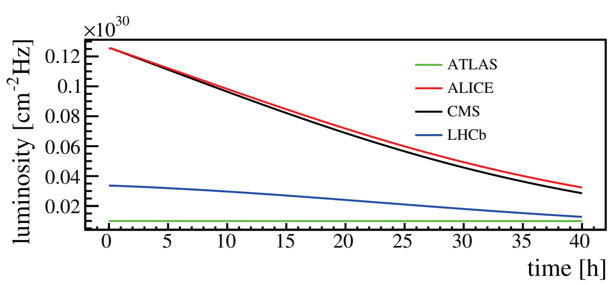

Figure 1: Luminosity evolution of a potential p–O pilot fill. The levelling in ATLAS is maintained for at least 40 h.

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