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STUDIES FOR AN LHC PILOT RUN WITH OXYGEN BEAMS

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Abstract

Motivated by the study of collective effects in small systems with oxygen-oxygen (O-O) collisions, and improvements to the understanding of high-energy cosmic ray interactions from proton-oxygen (p-O) collisions, a short LHC oxygen run during Run 3 has been proposed. This article presents estimates for the obtainable luminosity performance in these two running modes based on simulations of a typical fill. The requested integrated luminosity, projected beam conditions, data-taking and commissioning times are considered and a running scenario is proposed.

INTRODUCTION

On two occasions, short "pilot runs" of the CERN Large Hadron Collider (LHC), colliding protons with lead nuclei (p-Pb) in 2012 [1], and xenon nuclei (Xe-Xe) in 2017 [2], have constituted major milestones in its heavy-ion physics programme. Although each lasted a mere 16 hours in total (including set-up and physics data-taking)—and the integrated luminosities were correspondingly small—they provided significant data and revealed unexpected physical phenomena (see, e.g., [3, 4]) by virtue of the fact that these were the first multi-TeV collisions with *novel colliding beam species*. An appropriate strategy for an extremely rapid commissioning of new collider configurations was key to their success. Much greater integrated luminosities have been collected in the extended p-Pb and Pb-Pb runs of the past decade [5, 6].

Oxygen beams are relatively easy to create in the ion source. The potential of a third pilot run with O-O collisions, to study collective effects and Quark-Gluon Plasma in small systems, emerged in discussions at the 2018 Quark Matter conference. This found synergy with a long-standing request for p-O collisions to improve the understanding of multi-PeV and EeV cosmic ray interactions with the Earth's atmosphere. These physics motivations were explored in depth at a recent workshop [7]. Such a run would also provide valuable experience with the accelerator complex in view of proposed operation with lighter nuclei [8] in Run 5 (beyond 2030), aiming at higher nucleon-nucleon luminosities.

In the meantime the heavy-ion programme will continue with higher luminosity Pb-Pb or p-Pb collisions [8–10]. A pilot run with low-intensity $^{16}O^{8+}$ beams has been proposed during Run 3 (2022–2024).

A meaningful soft physics programme, the main interest of the ALICE (IP2), ATLAS (IP1), and CMS (IP5) experiments, would require an integrated O-O luminosity of $0.5\,\mathrm{nb}^{-1}$ [7]. Extending to $2\,\mathrm{nb}^{-1}$ would enable the study of hard probes with statistics equivalent to the first Pb-Pb run in 2010. Here ALICE has requested an event pileup $\mu \lesssim 0.2$. The forward experiments, LHCb (IP8) and LHCf (IP1), lead the interest in p-O collisions, requesting $2\,\mathrm{nb}^{-1}$ and $1.5\,\mathrm{nb}^{-1}$ respectively, with $\mu \lesssim 0.02$ at LHCf. There is currently no request for O-p (reversed beams). In the following, we show how these requirements could be met in about one week, longer than the earlier pilot runs, but still acceptably short in the context of the overall LHC programme of Run 3.

LHC SCENARIOS AND COMMISSIONING

We first consider the O beams that the injector complex can produce. We distinguish between the so-called *Early* beam, with separate injections of single bunches into the LHC, and the *Nominal* scheme where multi-bunch trains are injected [11, 12]. The Nominal scheme is intended for high-intensity operation, for which several days of machine protection validation and intensity ramp-up are required. Low-intensity Early beam operation, below the machine protection limit of 3×10^{11} charges per beam, allows a lighter and faster commissioning which is a key component of a pilot run strategy.

In the Early scheme, single bunches of 7.1×10^9 O can be injected in the SPS. With 70% transmission efficiency, 5×10^9 O ions per bunch can be injected into the LHC. However, the intensity in the SPS may be limited by space charge [12], which would make it necessary to split each SPS bunch in two, giving an LHC bunch intensity of 2.5×10^9 O. Since this has not been studied experimentally for O beams, we consider scenarios both with and without the splitting, and we assume that the O normalized emittance is the same as for Pb. In the LHC, we assume an additional 7% intensity loss before reaching collisions, as observed for Pb beams.

Furthermore, two different O beam energies are considered: $7\,Z$TeV, which is the planned energy for the future proton and Pb operation, and a lower value of $5.52\,Z$TeV. The lower energy has the advantage of giving the same nucleon-nucleon centre-of-mass energy as the future $7\,Z$TeV Pb run, meaning that the data can be easily compared, and that the p-p reference run done for Pb operation is also applicable to O-O. On the other hand, the needed commissioning is longer, as detailed below.

Using the two beam energies and the two possible numbers of O bunches, we define four different scenarios (S1a, S1b, S2a, S2b) detailed in Table 1. We assume that IP2 is always levelled at $\mu = 0.2$. For p-O, the LHCf pileup requirement makes it necessary to split the intensity among

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Table 1: Parameters Assumed in Collision at the LHC for the Different Scenarios Considered for Performance Estimates of O-O and p-O

Scenario	**S1a**	**S1b**	**S2a**	**S2b**
Beam energy (Z TeV)	7	7	5.52	5.52
β^* (cm), IP1;2;5;8	50;50;50;150	50;50;50;150	65;65;65;150	65;65;65;150
Net half crossing angle (rad), IP1;2;5;8	170;100;170;305	170;100;170;305	170;100;170;305	170;100;170;305
Normalized O emittance (m)	2.1	2.1	2.1	2.1
O beam energy per nucleon (TeV)	3.5	3.5	2.76	2.76
Number of bunches, O-O	6	12	6	12
Ions per bunch, O-O	4.6×10^9	2.3×10^9	4.6×10^9	2.3×10^9
Number of bunches, p-O	36	36	36	36
O ions per bunch, p-O	8.7×10^8	8.7×10^8	8.7×10^8	8.7×10^8
Protons per bunch, p-O	7×10^9	7×10^9	7×10^9	7×10^9

many more bunches. We assume 36 bunches in each beam, with a bunch charge such that the total injected intensity stays below the 3×10^{11} charges limit with a 10 % margin.

A first estimate of the needed commissioning time for S1a and S1b at 7 ZTeV assumes that the machine configuration from a previous Pb run with β^*=50 cm can be re-used, since the magnetic rigidity is the same. We estimate that about 2–3 days are needed to switch from the proton configuration, make minor adjustments and corrections (orbit, optics, etc.), set up injection and capture, and carry out a minimum machine-protection validation. It is assumed here that the optics is rather reproducible so that only a minor adjustment might be needed, which could potentially be done also with proton beams. For p-O, about 0.5–1 day more would be needed to set up the injection frequencies, the so-called cogging[1], and another light machine protection validation.

For S2a and S2b, the existing machine cycle cannot be re-used, and the energy ramp must be cut at 5.52 ZTeV. Then a new so-called optics squeeze has to be commissioned in order to reach a small β^*. The exact limit in β^* remains to be quantified, and for this study we use conservatively a constant-aperture scaling from β^*=50 cm at 7 ZTeV to 65 cm at 5.52 ZTeV. This would also require additional setup of collimators and a subsequent full validation, giving an overhead of about 1-2 days compared to S1a and S1b.

PERFORMANCE

To evaluate the luminosity performance in a typical fill, we use two independent simulations, as in [9, 10]. The first one, Collider Time Evolution (CTE) [10, 13] is a particle tracking simulation, where bunches of macro-particles are subject to a number of physical processes, notably luminosity burn-off, intrabeam scattering (IBS), and synchrotron radiation damping. The second, the Multi-Bunch Simulation (MBS) [10, 14] provides a numerical solution of a system of coupled differential equations, modelling the dimensions and intensity of each single bunch. Both evaluate the luminosity and beam evolution over time and have been in excellent agreement with LHC data [9, 10].

[1] After the energy ramp at unequal revolution frequencies of the two species, the RF frequencies are locked and the bunch encounters are shifted to the proper collision points [1].

Table 2: Cross Sections Assumed For O-O and p-O Collisions at 7 ZTeV at the LHC for Bound-free Pair Production (BFPP), Electromagnetic Dissociation (EMD), and Hadronic Interactions [8, 9, 14–16]

	Pb-Pb	**p-Pb**	**O-O**	**p-O**
BFPP (b)	281	0.044	< 0.01	$< 10^{-5}$
EMD (b)	226	0.035	0.133	0.0012
Hadronic (b)	7.8	2.12	1.343	0.45
Total (b)	515	2.20	1.48	0.45

The machine parameters in Table 1 are taken as input, together with the burn-off cross sections in Table 2. We assume also a 50 h non-collisional beam lifetime. This is more pessimistic than the 100 h typically observed with Pb ion beams, but there will be very little time to optimise the machine so the same lifetime cannot be assumed.

Figure 1 shows the simulated evolution of instantaneous and integrated luminosity from CTE in a single O-O fill for the different scenarios, demonstrating that the 0.5 nb^{-1} target at IP1, IP2, and IP5 could be reached in one single, long fill. Assuming a turnaround time of 4 h, which is slightly longer than what is assumed for future Pb operation [9] but motivated by the non-standard operation, one single fill is indeed the fastest way to reach the target in all scenarios except S2b, where it is more efficient to use two fills of about 12 h each. The fastest way to reach the target based on the CTE studies, as well as the total time needed, is shown for all scenarios in Table 3. The MBS results (not shown) agree within 5%.

It should be noted that in S1a and S2a with 6 bunches and the higher bunch intensity, IP1 and IP5 profit from the higher instantaneous luminosity and reach the target significantly faster than the levelled IP2. In S1b and S2b with double the bunches but half the bunch intensity, there is no need to level IP2, which in those scenarios reaches the target sooner than IP1 and IP5 thanks to the smaller net crossing angle. Overall,

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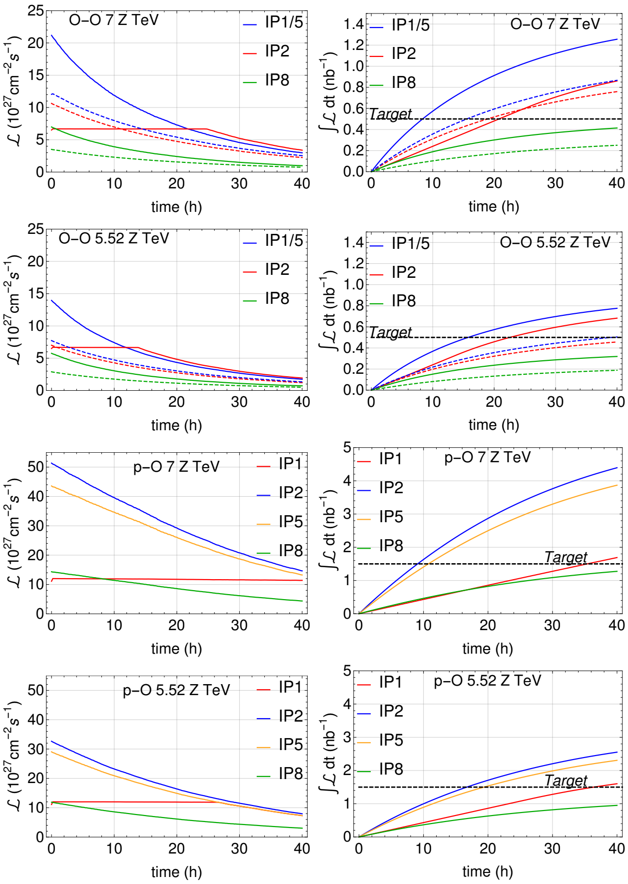

Figure 1: The simulated evolution of instantaneous (left column) and integrated (right column) luminosity in one fill for O-O (top rows) and for p-O (bottom rows). For O-O, solid lines represent 6 bunches (S1a and S2a) and dashed lines 12 bunches (S1b and S2b). The black, horizontal dashed lines show typical targets for data collection (0.5 nb^{-1} for O-O and 1.5 nb^{-1} for p-O).

Table 3: Number of Fills Needed and Total Time Needed in Each O-O Scenario to Reach the 0.5 nb^{-1} Target at IP1, IP2, and IP5, Assuming a 4 h Turnaround Time

Scenario	Limiting IP	Time per fill	Fills	Σ time
S1a	IP2	21 h	1	25 h
S1b	IP1/5	19 h	1	23 h
S2a	IP2	23 h	1	27 h
S2b	IP1/5	12 h	2	32 h

the fastest scenario is S1b, closely followed by S1a, since levelling in IP2 is not required in S1b. This is the bottleneck in S1a. About one full day without contingency is needed for both. At 5.52 Z TeV, a few hours more are needed for S2a, while up to about 9 h more are needed for S2b. The most efficient scenario is to use 7 Z TeV beam energy, and the gain from the higher energy is larger if the 6-bunch scheme cannot be achieved in the injectors. At IP8, 0.1–0.3 nb^{-1} could be collected depending on the scenario.

The simulated p-O luminosity is shown in Fig. 1. With the stringent requirement of $\mu \lesssim 0.02$, about 36 h in collision is needed to reach the IP1 target of 1.5 nb^{-1} at 7 Z TeV (S1a and S1b) and the levelling at IP1 can be sustained for the full period in a single fill. On the other hand, 3 fills of about 15–16 h each in collision are needed to reach the 2 nb^{-1} target at IP8. Including turnaround time, this implies a total running time of about 2.5 days without contingency and margin for faults or delays. In those fills, a total of 6–7 nb^{-1} could be collected at IP2 and IP5. At 5.52 Z TeV (S2a and S2b), one additional fill with about 15 h in collision is needed to reach the IP8 target.

These estimates carry a large uncertainty as the O beam parameters have not been demonstrated experimentally. Furthermore, unforeseen faults and downtime could cause premature beam dumps and longer waiting times between fills, increasing the total time needed.

CONCLUSIONS

We have presented LHC machine scenarios for a potential short low-intensity run with $^{16}O^{8+}$ beams. We considered two beam energies (7 Z TeV and 5.52 Z TeV) and two different $^{16}O^{8+}$ beams from the SPS (with and without bunch splitting, giving 6 or 12 bunches for O-O). Simulations show that it is possible to reach the experiments' luminosity targets in a few days using low-intensity beams that remain below the LHC machine protection limit of 3×10^{11} charges.

For a first idea of a possible run schedule, we consider the 7 Z TeV beam energy, where both the commissioning and data collection are significantly faster. After 2–3 days of O-O commissioning, the O-O physics run would take 1–1.5 days in order to collect the requested 0.5 nb^{-1} at IP1, IP2, and IP5. After 0.5–1 days of commissioning for p-O, 2.5–3 days of p-O collisions would be needed to reach the targets of 1.5 nb^{-1} at IP1 and 2 nb^{-1} at IP8. In total about 6–8 days are needed for the full run in an optimistic scenario without significant machine downtime, for which additional margin should be added. Significant uncertainties on the beam parameters, and hence the achievable luminosity and required LHC time, remain until the O-beam production is set up and demonstrated in the injector chain.

At 5.52 Z TeV, about 2.5–5 days more would be needed, dominated by the longer commissioning, but with contributions also from the longer running time. However, it should be studied whether a p-p reference run is needed at 7 Z TeV. If so, the needed run time should be estimated and added to the total time at 7 Z TeV. At 5.52 Z TeV such a p-p run is not needed, since it will anyway be done for Pb-Pb.

It remains as future work to study further performance optimisations, e.g., a decrease of β^* or crossing angles, as well as possible limitations, such as the transmutation effect, where colliding $^{16}O^{8+}$ ions fragment into other nuclei that could potentially stay in the beam and pollute the collisions.

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