# THE LHC AS A PROTON-NUCLEUS COLLIDER

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## Abstract

Following its initial operation as a proton-proton (p-p) and heavy-ion ($^{208}Pb^{82+}$-$^{208}Pb^{82+}$) collider, the LHC is expected to operate as a p-Pb collider. Later it may collide protons with other lighter nuclei such as $^{40}Ar^{18+}$ or $^{16}O^{8+}$. We show how the existing proton and lead-ion injector chains may be efficiently operated in tandem to provide these hybrid collisions. The two-in-one magnet design of the LHC main rings imposes different revolution frequencies for the two beams in part of the magnetic cycle. We discuss and evaluate the consequences for beam dynamics and estimate the potential performance of the LHC as a proton-nucleus collider.

## INTRODUCTION

In the first stage of its heavy-ion programme, the LHC will collide lead nuclei to study the properties of hot nuclear matter at extreme energy densities. The second stage of this programme, following the pattern at RHIC [1], is expected to be the crucial control experiment in which nuclear matter is studied by colliding lead ions with protons (deuterons offer no particular advantage and are not readily available at the LHC).

In equal species operation, the bunch filling schemes for protons and Pb ions are quite different, reflecting the different pre-injectors [2]. For hybrid collisions to occur at the proper interactions points (IPs), it will be necessary to construct a proton beam with the same bunch pattern as the usual ion beam. For instrumentation reasons, the ion bunch intensity must be the same $N_{Pb} = 7 \times 10^7$ as in Pb-Pb operation. We tentatively assume 10% of the nominal proton intensity per bunch, $N_p = 1.15 \times 10^{10}$, together with the nominal emittances and $\beta^*$ values [2] to ensure matching beam sizes at the IPs. This would give an initial peak luminosity $L = 1.5 \times 10^{29}$ cm$^{-2}$s$^{-1}$, which would be adequate for the physics programme. Increasing $N_p$ might yield more.

## INJECTOR CHAIN OPERATION

With the present hardware, no complicated RF gymnastics (bunch splittings, change of harmonic numbers …) are possible in the SPS. Therefore the proton filling scheme must provide an appropriate bunch structure at SPS injection. First studies identified various possibilities of which we describe two.

### Simple scheme

A very simple scheme to fill one LHC ring provides the bunches at PS injection with a structure already close to that needed at ejection, as follows:

- Each of the four superposed rings of the Booster provides a single bunch. The spacings between
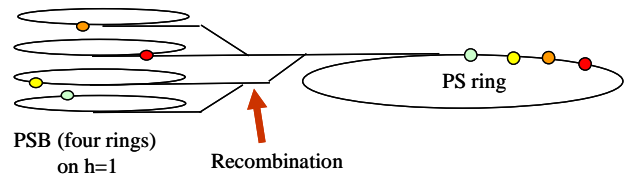


Figure 1: Proton transfer between PS Booster and PS for a simple scheme for filling an LHC bunch with protons.

Table 1: Tentative parameters along the accelerator chain for proton filling of one LHC ring with the simple scheme

| Mach | T | h | n | $t_{rev}$ | $t_{bunch}$ | $\varepsilon_L$ | $N_b$ | $\varepsilon^*_{rms}$ |
|------|---|---|---|-----------|-------------|-----------------|-------|------------------------|
|  | GeV |  |  | µs | ns | eVs/b | p/bunch | µm |
| **PSB** | 1.4 | 1 | 1 | .572 | ~90 | ~0.2 | $\lesssim 10^{11}$ | ≤2.5 |
| **PS** |  |  |  |  |  |  |  |  |
|  | 1.4 | 16 | 4 | 2.286 |  | ~0.2 | $\lesssim 10^{11}$ | ≤2.5 |
|  | 2.69 | 21 | 4 | 2.169 |  | ~0.25 | $\lesssim 10^{11}$ |  |
|  | 25 | 21 | 4 | 2.097 |  | ~0.25 | $\lesssim 10^{11}$ | ≤3 |
|  | 25 | 84 168 | 4 | 2.097 | 4 | ≤0.35 | $\lesssim 10^{11}$ | ≤3 |
| **SPS** |  |  |  |  |  |  |  |  |
|  | 25 | 4620 | ≤52 | 23.1 | 4 | 0.35 | $\lesssim 10^{11}$ | ≤3 |
|  | 450 | 4620 | ≤52 | 23.1 | ~2 | ~1 | $\lesssim 10^{11}$ | ≤3.5 |

bunches ejected out of each Booster ring can be freely adjusted and are only limited by kicker rise times in the recombination line. In practice, the bunches will be injected in adjacent PS buckets with the highest possible harmonic number compatible with the minimum spacing required by the recombination kickers.

- The beam is accelerated and the harmonic number moved to 21 somewhere during the cycle.
- Before ejection, the 80 MHz RF system is used to shorten (higher voltage and bunch rotation) the bunches so that they can be injected into the 200 MHz buckets of the receiving SPS. Note that the bunch spacing (100 ns) is the same as for ion filling, but the harmonic number at PS ejection is 168 for protons and 169 for ions because of the small difference in speed between species.
- Since the pattern at SPS injection is the same as for ions, accumulation in the SPS and LHC filling is carried out almost exactly as in ion operation. Since ther change in proton speed during acceleration is less than for ions, the variable (non-integer) harmonic number is not necessary.
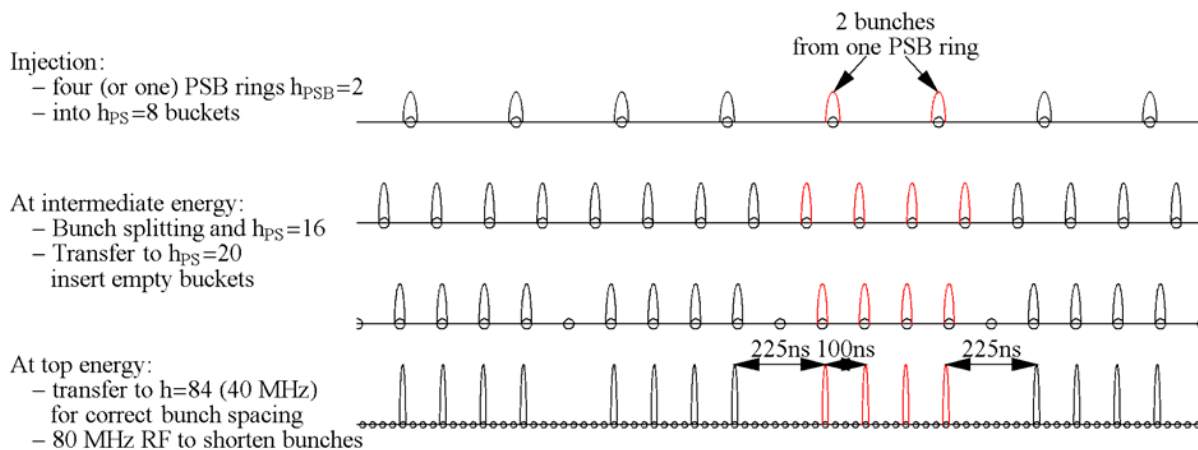
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Figure 2: RF gymnastics in the PS for fast proton filling. Bunches (ellipses) and buckets (circles) around the PS circumference at different stages.
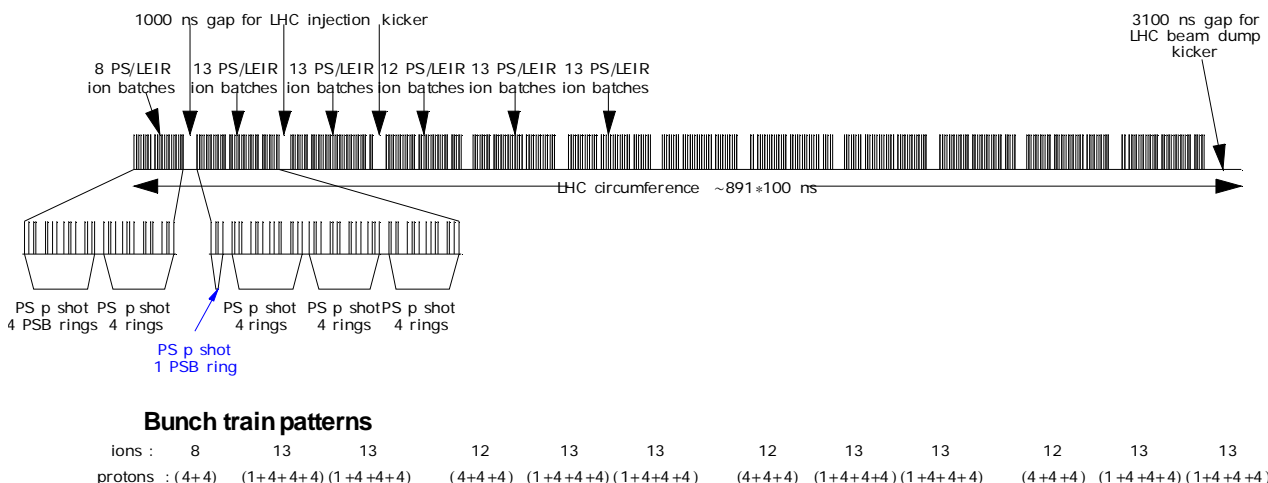


Figure 3: Sketch of LHC filling scheme.

*Elaborate scheme for faster proton filling*

This scheme depicted in Figure 2 Figure 3 is designed to speed up proton filling of one ring as follows:

- The PS Booster runs with harmonic number 2 and all four rings (or just one) transfer bunches into $h = 8$ buckets in the PS as shown in Fig. 2.

- Somewhere during acceleration (Figure 2), the bunches are first split into two and one obtains 16 (or 4) bunches in (adjacent) $h = 16$ buckets. The harmonic number is raised to $h = 20$ so that additional empty buckets are inserted. First simulations [3] show that this gymnastics is feasible. At top energy, prior to ejection, the bunches are transferred to $h = 84$. By appropriate choice of phases, the smaller distances between bunches are decreased and the longer ones (empty buckets) increased. The latter correspond to the distance between different PS/LEIR batches accumulated in the SPS. Prior to transfer to the SPS, the bunches are shortened with the 80 MHz ($h = 168$) system.

- Faster filling of the LHC proton ring (Figure 2) is possible transferring, in one shot, protons corresponding to up to four ion shots. By appropriate combination of PS cycles with injections from all four and only one Booster ring, the ion bunch pattern can be obtained easily at the SPS injection plateau.

## LHC MAIN RINGS

At first sight, p-Pb collisions in the LHC might appear analogous to the successful d-Au collisions in RHIC [1]. However there is a crucial difference in that the LHC is based on a two-in-one magnet design with identical bending fields on the central orbits of the two beams. RHIC, on the other hand, has two independent rings of single-aperture magnets which can be operated to provide different fields for the two beams over most of its circumference.

In the LHC, the momentum of protons and lead ions circulating on the central orbits are related by $p_{\mathrm{Pb}} = Q p_{\mathrm{p}}$ where $Q = 82$ is the lead ion charge. The

proton momentum varies in the range $0.45\,\text{TeV}/c \le p_p \le 7\,\text{TeV}/c$ during the ramp. This simple fact determines the basic parameters of collisions at top energy (Table 2), notably that experiments will be done with a central rapidity shift of 0.46 in the direction of the proton beam. Because of asymmetries in detector design, this should initially be in the clockwise (Ring 1) direction.

Table 2: Kinematics of collisions of protons (red) or deuterons (purple) with Pb ions (blue). In order: beam energy, $E$, per ion, per nucleon; centre-of-mass energy, $\sqrt{s}$, per ion, per nucleon; rapidity, $y$, of colliding ions and (average) per colliding nucleon pair.

|  | p-p | Pb-Pb | p-Pb | d-Pb |
|---|---|---|---|---|
| $E/\text{TeV}$ | 7 | 574 | (7,574) | (7,574) |
| $E_N/\text{TeV}$ | 7 | 2.76 | (7,2.76) | (3.5,2.76) |
| $\sqrt{s}/\text{TeV}$ | 14 | 1148 | 126.8 | 126.8 |
| $\sqrt{s_{NN}}/\text{TeV}$ | 14 | 5.52 | 8.79 | 6.22 |
| $y_{CM}$ | 0 | 0 | 2.20 | 2.20 |
| $y_{NN}$ | 0 | 0 | 0.46 | -0.12 |

For an ion of mass $m$ and charge $Q$, with fractional momentum deviation $\delta = (p - Qp_p)/(Qp_p)$, the revolution period is

$$T\left(p_p, m, Q\right) = \frac{C}{c}\sqrt{1 + \left(\frac{mc}{Qp_p}\right)^2}\,(1 + \eta\delta) \qquad (1)$$

where $\eta = \gamma_T^{-2} - \gamma(p)^{-2}$ is the usual frequency-slip factor and $\gamma_T = 55.8$ at the LHC transition energy. Revolution periods of the two beams can be equalised by choosing

$$\delta_p = -\delta_{Pb} = \frac{c^2\gamma_T^2}{4p_p^2}\left(\frac{m_{Pb}^2}{Q^2} - m_p^2\right). \qquad (2)$$

Figure 4 shows that this can be achieved at collision energy. However for $p_p < 2.7\,\text{TeV}/c$, the orbit displacement exceeds the normally accepted limits in the LHC [2], imposing a lower limit on collision energy and the need to inject and ramp with unequal revolution frequencies at least up to this energy. At injection, long-range beam-beam encounters sweep across the interaction regions at 1.7 km/s, resulting in modulational effects and quasi-random beam-beam kicks. Emittance blow-up and intensity limits were attributed to such effects in studies at RHIC [1], necessitating equal frequency injection and ramp for d-Au operation. However Figure 5 shows that in the LHC case, the modulated beam-beam effects are much smaller, and are unlikely to be a significant performance limitation for the LHC. Moreover, the LHC has independent transverse feedback systems with sufficient bandwidth to act on individual bunches in each plane and ring. These should help to damp coherent effects.
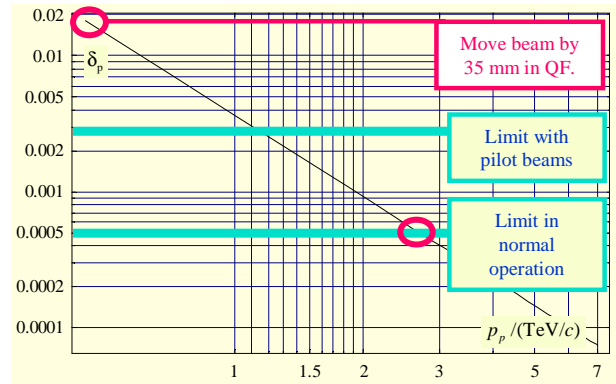


Figure 4: Proton momentum shift $\delta_p = -\delta_{Pb}$ required to equalise p and Pb revolution frequencies in the ramp.
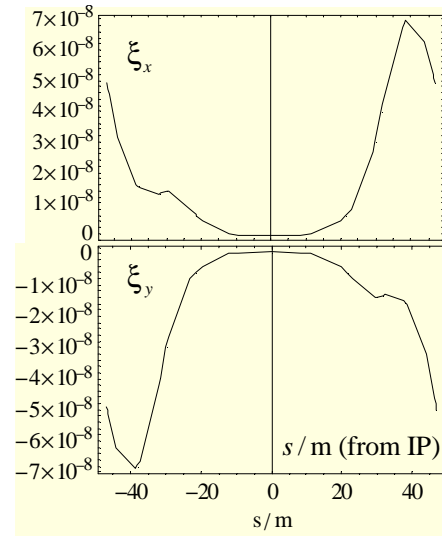


Figure 5: Long-range beam-beam tune-shifts at all possible encounter points around IP2 (ALICE experiment). Other interaction regions are similar. Corresponding beam-beam kicks are of order $10^{-8}$ rad.

## CONCLUSIONS

The heavy-ion and proton injectors of the LHC can be operated together efficiently to fill the LHC for p-Pb collisions. However injection and part of the ramp must be performed with unlocked RF systems and different revolution frequencies for the two beams. Finally, physics conditions involve a central rapidity shift of 0.46.

### ACKNOWLEDGEMENTS

### REFERENCES

[1] T. Satogata et al, PAC2003, TPPB043 (2003).
[2] The LHC Design Report, Vols. I and III, CERN-2004-003, http://cern.ch/lhc/
[3] S. Hancock, private communications.

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