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Prospects for light-ion operation at the HL-LHC: machine developments and physics opportunities

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In recent years, the interest of the ion-physics community for conducting experiments at the CERN Accelerator Complex with lighter ions than lead has increased significantly. This has motivated the creation of the Future Ions Working Group in the CERN Accelerator and Technical Sector whose mandate is to define future ion operation needs based on the requests from LHC and fixed target experiments and their implications for the Ion Accelerator Complex. This particular contribution focuses on the recent requests of small-system collisions at LHC, as a complementary physics programme to the highest-luminosity-highest-density lead ion collisions. It reviews the physics opportunities and the capabilities of the current CERN Accelerator Complex to meet the challenge.

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1. Introduction

In recent years, the number of experiments and facilities seeking lighter ions than lead has increased. The LHC experiments, particularly the ALICE 3 upgrade [1], aim to maximize nucleon-nucleon luminosity, which could be achievable with lighter ions. The discovery of Quark-Gluon Plasma (QGP) properties in small systems, such as proton-proton and proton-ion collisions at the LHC, has further motivated the physics community to study light-ion collisions in greater detail [2]. The NA61/SHINE collaboration has proposed continuing their physics program with light-mass ion beams of different species and energies after Long Shutdown 3 [3]. Additionally, CERN is proposing a radiation-to-electronics facility, HEARTS++ [4], which aims to deliver different ion species on the same day with switching times of no more than 15 minutes—something not currently possible with the existing complex, largely due to the limitation of having only one ion source. Despite this, significant tests were conducted during Run 3 with oxygen, magnesium, and krypton to assess source performance with new ions and gather data across the complex, thanks to the Future Ions Working Group in the CERN Accelerator and Technical Sector [5].

2. The CERN Ion Accelerator Complex

The current CERN Ion Accelerator Complex [6], Fig. 1-top, consists of an Electron Cyclotron Resonance Ion Source (ECRIS) and a linear accelerator, Linac 3. The source produces ion beam pulses few milliseconds long, though, ≃200 μs of the pulse length is accelerated and not all pulses are sent to LEIR. The beam is extracted from the source at 2.5 keV/nucleon, accelerated to 250 keV/nucleon by a Radio Frequency Quadrupole (RFQ), and finally to 4.2 MeV/nucleon by a system of 3 Interdigital-H RF tanks. Besides lead ions, Linac 3 has delivered indium (2003), argon (2015), xenon (2017), oxygen (2005 and 2023), krypton (2023) and magnesium (2024). After the source, a 135^o spectrometer selects the proper charge state, e.g. lead 29+. Lead 54+ selection takes place after acceleration to 4.2 MeV/nucleon, but depending on the ion, this stripping stage might not be needed. The following accelerator is a synchrotron called the Low-Energy Ion Ring (LEIR), which transforms the long-low-intensity ion pulses from Linac 3 into short-high-density (≃200 ns) bunches by accumulation and phase-space cooling. Two operational cycles are used by downstream experiments. The EARLY cycle (Fig. 1-bottom-left) consists of one injection into LEIR, captured in one bunch, and is used to prepare the beam for fixed-target physics in the SPS North-Area and LHC pilot runs. The NOMINAL cycle (Fig. 1-bottom-right), used for delivering high-luminosity to the LHC, consists of multiple injections into LEIR captured in two bunches. In LEIR all beams are accelerated to 1.44 Q GeV/c, where Q is the ion charge, and extracted to the Proton Synchrotron (PS), where the beam is accelerated to 26 Q GeV/c. In PS the NOMINAL cycle is further split to get four bunches at extraction. In the transfer line between PS and the Super Proton Synchrotron (SPS), the beam is fully stripped by a dedicated foil. Fourteen PS to SPS injections, i.e. 56 bunches, are accumulated in the SPS, slip-stacked longitudinally to reduce the bunch separation from 100 ns to 50 ns, accelerated and extracted to the LHC. Two times 22 injections from SPS to LHC are needed to fill with 1240 bunches each ring.

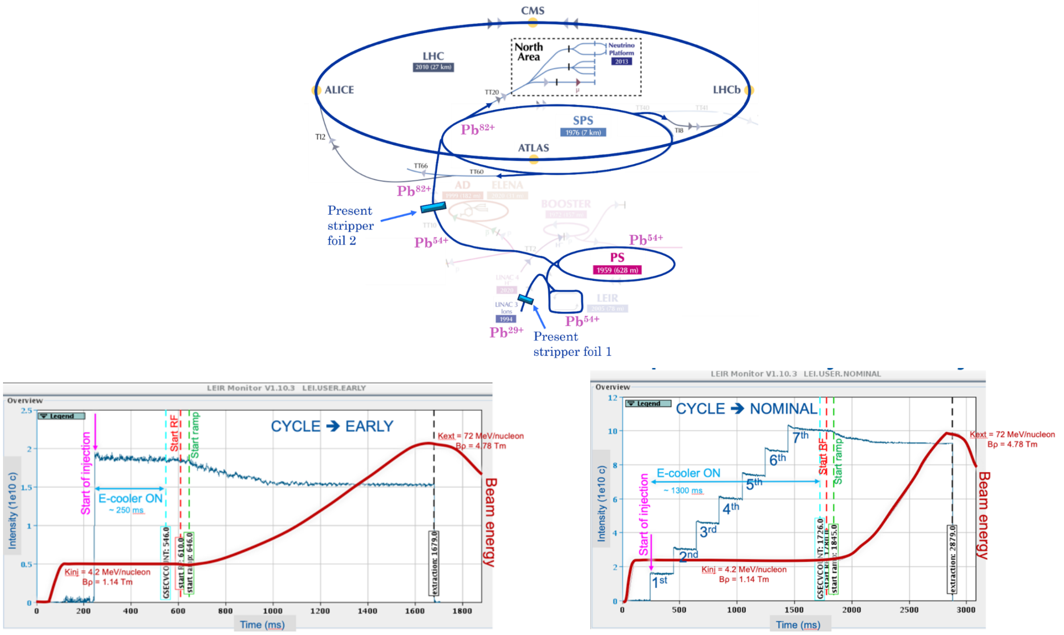

Figure 1: Top: CERN Ion Accelerator Complex layout. Bottom-left: EARLY cycle. Bottom-right: NOMINAL cycle.

3. The Ion Complex Upgrade proposal

After several years of feasibility studies, with experimental tests complementing theoretical development, the Future Ions Working Group concluded that an upgrade of the ion injector complex is needed to be able to lift up the encountered limitations and be able to test the future ions for LHC after Long Shutdown 4. The upgrade proposal consists of:

- A new source to operate up to 4 different ion species per year, and perform parallel operation and commission of new ions at the source.
- New beam diagnostic lines per source for automatic beam monitoring and optimization.
- Convert the low-energy circuits to be able to pulse at different currents as a function of the ion, to be able to switch ion species in 15 minutes.
- Add an alternative stripping stage between LEIR and PS to accelerate the beam to higher energy and mitigate space charge and intra beam scattering effects in SPS.
- Add two new PS RF cavities to achieve batch compression to 50 ns. SPS slip-stacking will result in 25 ns bunch separation. In this way the complex could deliver up to 1740 bunches per beam to LHC, compared to the 1240 delivered today.

4. LHC physics opportunities with lighter ions than lead

Ions lighter than lead could provide higher nucleon-nucleon luminosity, L_{nn}, enabling more accurate measurements of charm and beauty hadrons and studies of correlations across a wide pseudo-rapidity range. This could facilitate the study of heavy quark transport in the QGP down to the thermal scale. Additionally, systematic measurements of multiply heavy-flavoured hadrons could help understand how quarks combine into hadrons based on their thermalization degree. The specific study of thermal di-leptons as final state allows the time-evolution study of the QGP temperature, as shown in the ALICE 3 study in Fig. 2-left. While double-charm hadrons are accessible with Pb-Pb collisions, a larger L_{nn} would allow for more precise measurements, as illustrated in Fig. 2-right, and a scan of multi-charm baryons versus system size would provide new insights into thermalization and hadronization.

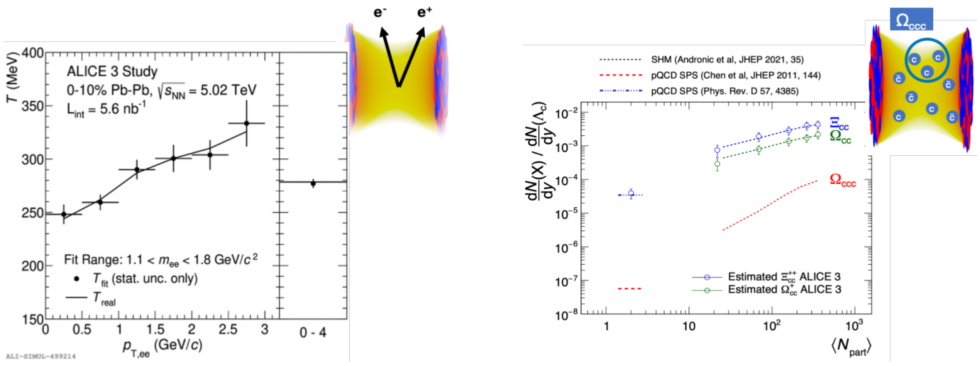

Figure 2: ALICE3 studies with thermal di-leptons and double-charm hadrons.

Other type of studies do not required high luminosity, and a pilot run-type collisions could provide valuable insights. For example, QGP transport coefficients offer a quantitative test of hydrodynamics in small systems, enabling the observation of clear imprints of the initial-state geometry on collective flow. Ideally, collisions of at least two different light ions, such as oxygen-oxygen (O-O) and neon-neon (Ne-Ne), would help cancel theoretical uncertainties, as shown in Fig. 3-left. Additionally, clustering plays a crucial role in studying nuclear structure, as protons and neutrons in many-body nuclear systems tend to form clusters to minimize energy or increase stability. The pilot run with O-O collisions at the LHC during Run 3 is expected to provide solid experimental evidence of the exotic tetrahedral α-clustering structure of the oxygen nucleus.

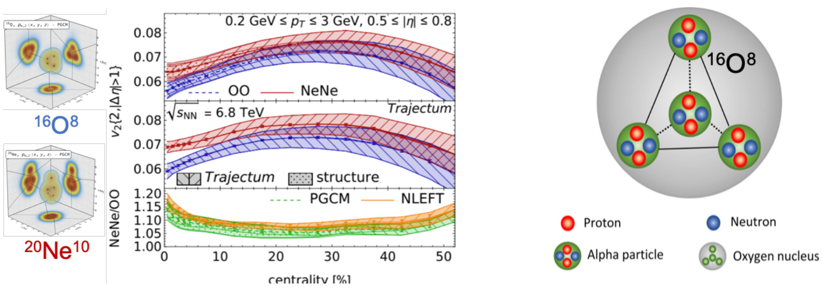

Figure 3: ALICE 3 studies with thermal di-leptons and double-charm hadrons.

The LHC is not only a collider, also offers beam-target collisions at the relativistic energy of $\sqrt{s_{nn}} \simeq 100$ GeV to image nuclear ground states thanks to the LHCb SMOG2. This will allow to scan not only the system size dependence, but also the energy dependence.

5. Performance assessment for LHC beams

The lead physics runs at the LHC during Run 3 benefitted from the excellent performance of the ion injector complex, which is already meeting HL-LHC intensity targets. Linac 3 and the source are operating reliably and stably at over 30 eμA. Longitudinal slip-stacking in the SPS is routinely used to send 1240 bunches per LHC beam, separated 50 ns. Fig. 4-top-left shows the SPS cycle with 14 injections from PS. The yellow curve is the beam intensity and the white line the magnetic cycle. At the slip-stacking plateau of 300 GeV, 28 bunches slip longitudinally over another 28 bunches until they overlap at the right place to be captured at 50 ns bunch separation, as shown in Fig. 4-top-right.

In parallel, oxygen tests up to the PS were conducted in November 2023. A higher-than-target intensity (70 eμA) was achieved from Linac 3 in 10 days of beam commissioning, with a final intensity of 88 eμA. After only two days of beam commissioning in LEIR, the extracted beam intensity reached 85% of the required value for the LHC oxygen run. Fig. 4-bottom-left shows the EARLY cycle for oxygen. The blue curve is the beam intensity injected in LEIR from Linac 3, and the red curve the magnetic cycle. This short, but efficient and fundamental test, indicates that the ion injector complex is ready for the 2025 O-O & p-O collisions at LHC [7].

At the start of 2023, krypton tests were also conducted up to the Linac 3 RFQ. Krypton 22+, the charge state from the source, was delivered with excellent stability and high intensity, 130 eμA from the source and 80 eμA from the RFQ, as shown in Fig. 4-bottom-right. Assuming 50% transmission efficiency through Linac 3, we expect to extract 40 eμA to LEIR.

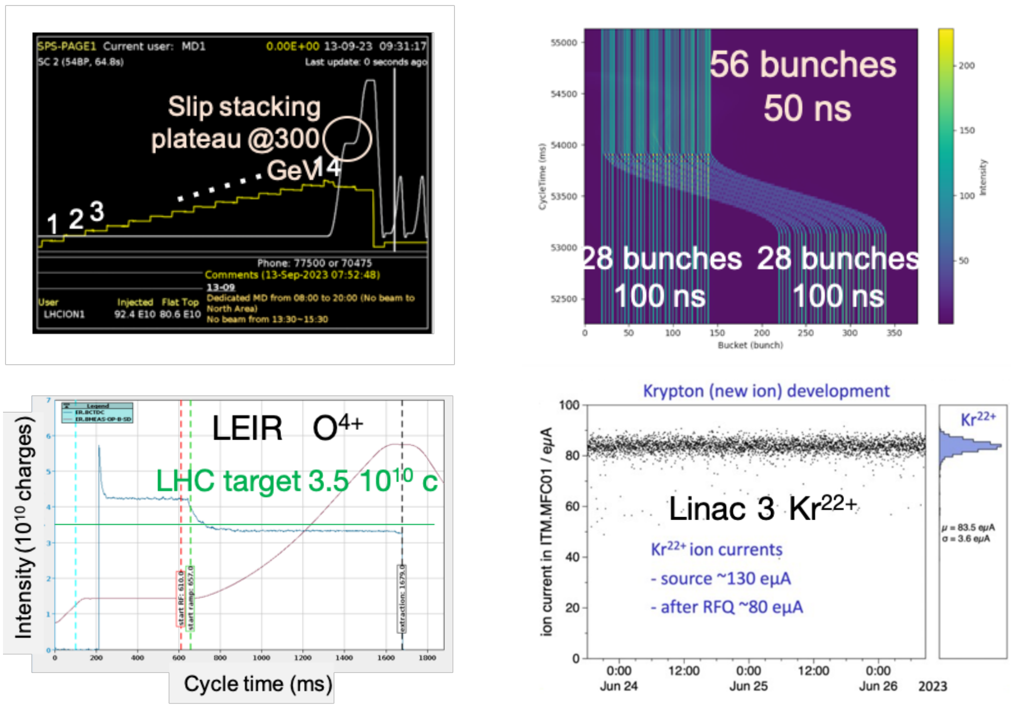

Figure 4: Top-left: SPS 14 injection cycle with beam intensity in yellow and magnetic cycle in white. Top-right: longitudinal slip-stacking gymnastics in SPS. Bottom-left: LEIR EARLY cycle for oxygen. Bottom-right: krypton beam current as measured at the exit of RFQ.

On top of this, detailed measurements with lead were done in 2023 to address beam intensity limitations and emittance evolution to characterise intra beam scattering growth rates and space charge issues. Thanks to all these experimental tests, for the very first time an LHC Injector Model is being developed for ions, which will allow to predict, with the best knowledge possible, the beam intensity out of SPS for any ion species given as input.

6. Conclusions

In recent years, there has been a significant increase in interest within the ion-physics community for conducting experiments at the CERN Accelerator Complex with lighter ions than lead. These experiments show strong synergies, enabling the exploration of different physics landscapes with the same effort.

The current CERN Ion Accelerator Complex provides opportunities to test new ions while fulfilling its physics production commitments. However, significant limitations exist that hinder a more detailed exploration of the challenges involved in operating with these new ions. To overcome these limitations, an upgrade of the Ion Complex is proposed by the Future Ions Working Group. This upgrade will enhance the development capabilities and allow the complex to meet the growing demands of experiments and facilities.

While the current complex can already provide ion beams for LHC pilot runs (e.g., O-O, p-O, Xe-Xe, Ne-Ne) with relative ease, high-luminosity runs require more preparation time and involve greater complexity. If the proposed upgrade proceeds, preparing high-luminosity runs with different ions would become more straightforward.

References

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