Performance of the LHC injector chain after the upgrade and potential development

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The accelerator complex at CERN serves the Large Hadron Collider (LHC) as well as a number of fixed target experiments. Figure 1 shows a schematics of the complex and the experimental facilities served by the different accelerators at CERN. The LHC Injectors Upgrade (LIU) project [1] is presently implementing major changes to the complex. The main aim of the project is to improve the performance of the accelerator chain for the production of LHC beams. Nevertheless, the fixed target beams are also expected to benefit from the upgrades. This letter summarises the expected performance after the upgrade for the various beam types.

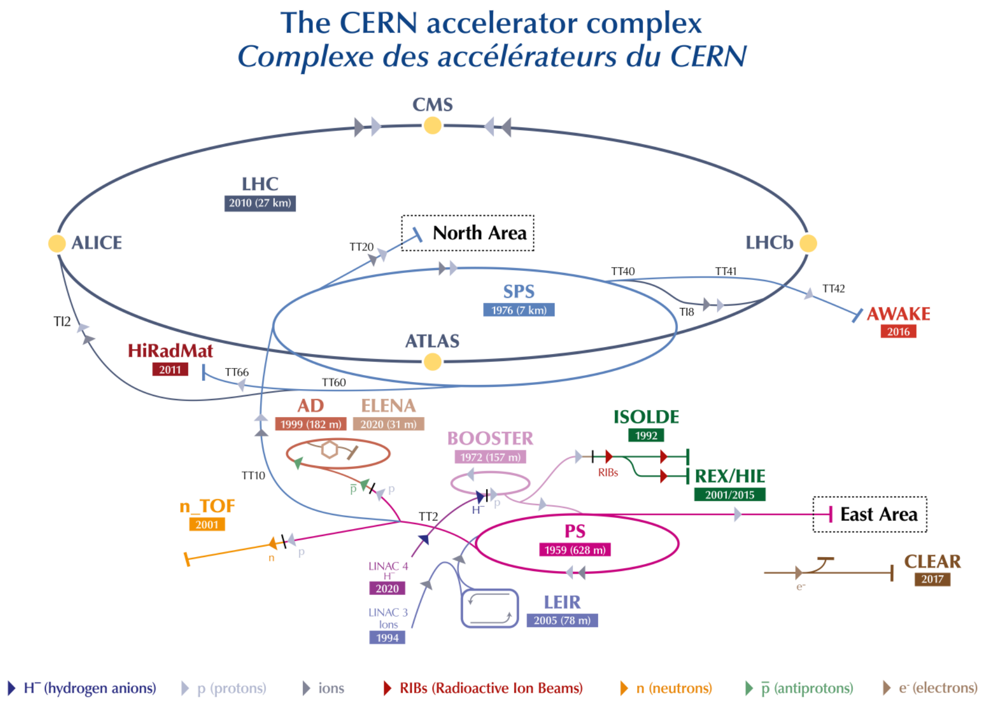

Fig. 1: CERN accelerator complex and experimental facilities.

The first synchrotron of the complex is the Proton Synchrotron Booster (PSB). As part of the LIU project, the PSB will be connected to the new H^--linac (Linac4) and will be able to accelerate proton beams from a kinetic energy of 160 MeV up to 2.0 GeV. The new energy range and the flexibility given by the H^- injection will allow producing about twice the beam intensity and brightness as compared to before the upgrade. With the increased injection energy of 2.0 GeV, the Proton Synchrotron (PS), next synchrotron in the chain, will be able to cope with the increased beam brightness. The PS accelerates beams to total energies ranging from 14 to 26 GeV. The largest machine of the injector complex is the Super Proton Synchrotron (SPS), which accelerates the beams to up to 450 GeV. All machines undergo important RF upgrades as part of the LIU project to improve the intensity reach of the complex, in particular for the LHC beams.

Fixed target beams are available at the extraction of each of the accelerators of the LHC injectors chain serving a variety of experiments. The Physics Beyond Collider (PBC) study [2] has been investigating the future exploitation of the existing accelerator complex taking into account the improved performance after LIU [3]. A short description of the main beam types is provided below. Table 1 provides a summary of the relevant beam parameters.

- The PSB beam can be extracted directly to the targets of the Isotope Separator On Line DEvice (ISOLDE), where radioactive nuclides are produced via spallation, fission, or fragmentation reactions. This is the highest intensity

PSB beam, made up of 4 bunches extracted from each of the 4 PSB rings every 1.2 s, with intensities typically around 8×10^{12} p/bunch before LIU and a kinetic energy of 1.4 GeV. With the LIU upgrades, two potential developments will become available for this type of beam. On one hand, the bunch intensity can be increased to about 1.6×10^{13} p/bunch, basically doubling the production rate on target. On the other hand, the kinetic energy at extraction can be increased to 2 GeV. The current ISOLDE facility will not be able to use the energy upgrade in the next run, while it may already benefit from the intensity increase.

- The PS can extract beam to the neutron Time-Of-Flight facility, nTOF, which has been operating at CERN since 2001. nTOF is a pulsed neutron source coupled to a 200-metre flight path. It is designed to study neutron-nucleus interactions for neutron energies ranging from a few meV to several GeV. The nTOF beam is made of one single short intense proton bunch, typically with 8×10^{12} p before LIU and fast rotated just before extraction in order to achieve 20 ns bunch length. After LIU, higher intensity will be available, similarly to the ISOLDE beam described above. The plan will be however to take only 1×10^{13} p/bunch, compatibly with the upgraded nTOF target as well as with the known vertical instability at PS transition crossing.

- The proton beam coming from the PS can also be sent onto a target with a high yield of antiproton production in order to generate a secondary high-energy antiproton beam for the Antiproton Decelerator (AD), a machine capable of turning it into a low-energy beam that can be used to produce antimatter. The AD beam is made of four bunches with about 3.5×10^{12} p/bunch spaced by about 100 ns and extracted at a total energy of 26 GeV. After LIU, this beam has a large potential for intensity upgrade, which will not be used in the next run due to other limitations coming from the target and the AD facility.

- The proton beam from the SPS can be slowly extracted towards the experimental North Area (NA) and adequately split such as to serve a number of targets per shot. This beam has a total intensity of about 4×10^{13} p and a total energy of 400 GeV, which are planned to remain unchanged after LIU although the losses during the cycle are expected to improve thanks to the lower vertical emittance. However, constraints from losses during the slow extraction also have to be taken into account. In the past (from 2007-2012), the SPS served the CERN Neutrinos to Gran Sasso (CNGS) experiment by fast extracting a high intensity proton beam. This beam featured an operational intensity of 4.0×10^{13} p per pulse and a record intensity of 5.3×10^{13} p per pulse in machine studies (CNGS+). Since the latter had the highest beam power per cycle ever produced at CERN so far, it has been included for reference in Table 1. At the time of the studies, this beam was limited by losses both in PS and SPS due to the large transverse emittances and to the limited SPS RF power. Thanks to LIU and the Multi-Turn Extraction (MTE) deployed at the PS-to-SPS transfer ([4] and references therein), these limitations are expected to be relaxed in the future, making this intensity potentially available for routine operation. The proposed future experiment Search for Hidden Particles (SHiP) will use beam characteristics similar to the operational CNGS, however deploying a slow extraction with 1 s spill length due to mechanical constraints coming from the target. As discussed above, higher beam intensities might be achievable for SHiP in the future similarly to CNGS. Due to the high duty cycle required for this experiment, losses during slow extraction have to be significantly reduced and are subject of detailed studies aiming at a loss reduction of more than a factor 4 compared to the presently achieved operational values [5].

- Finally, the LHC beam in the SPS has been also used for fixed target studies at the High-Radiation to Materials (HiRadMat) facility. This is a users facility at CERN, designed to provide high-intensity pulsed beams to an irradiation area where material samples as well as accelerator component assemblies can be tested. The LHC beam after LIU will preserve the same time structure as before (4 trains of 72 bunches with 25 ns between bunches and 200 ns between trains), but it will have double intensity and brightness.

Tab. 1: Overview of beam types available at the CERN injector complex after LIU.

	ISOLDE	nTOF	AD	SHiP	NA	LHC	CNGS+
Total Energy [GeV]	2.4/3.0	20	26	400	400	450	400
Total intensity [1×10^{13} p]	6.4	1.0	1.40	4.0	4.0	6.7	5.3
Cycle length [s]	1.2	1.2	2.4	7.2	10.8	21.6	6.0
Beam power per cycle [kW]	20/26	27	24	356	237	223	566
Total bunch length [ns]	230/200	20	38	-	-	1.6	4
Number of bunches	4	1	4	coasting	coasting	288	4200
Bunch spacing [ns]	572	-	100	-	-	25	5
Extraction type	fast	fast	fast	slow	slow	fast	fast

References

[1] J. Coupard *et al.*, "LIU Technical Design Report - Volume I: Protons", CERN, Geneva, Switzerland, Rep. CERN-ACC-2014-0337, Dec. 2014

[2] J. Jaeckel, M. Lamont, C. Vallèe, Nature Phys. **16** (2020) 393-401, Apr. 2020

[3] E. Koukovini-Platia *et al.*, "Protons Beyond the LHC Injectors Upgrade Project", CERN, Geneva, Switzerland, Rep. CERN-PBC-REPORT-2019-004, Oct. 2019

[4] S. Abernethy *et al.*, Phys. Rev. Accel. Beams **20**, 014001, Jan. 2017

[5] M. Fraser *et al.*, Phys. Rev. Accel. Beams **22**, 123501, Dec. 2019