THE LHC INJECTORS UPGRADE (LIU) PROJECT AT CERN: PROTON INJECTOR CHAIN

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Abstract

The LHC Injectors Upgrade (LIU) project at CERN aims at delivering high brightness beams required by the LHC in the high-luminosity LHC (HLLHC) era. The project comprises a new H^- Linac (Linac4) as well as a massive upgrade of the PS Booster, PS and SPS synchrotrons. This paper gives an update of the activities regarding the proton injector chain. We present the target beam parameters, a brief status of the upgrade work per machine and the outcome of the recent reviews. The planning for the implementation of the hardware upgrades and the re-commissioning of the complex will also be discussed.

INTRODUCTION

While CERN's proton injectors deliver today beams within specifications and beyond to the LHC, the requirements of the upgraded high-luminosity LHC exceed their capabilities.

The target beam parameters for the 25ns LHC beam, agreed between the High-Luminosity LHC project and LIU, are shown in Table 1.

Table 1: LIU Target Parameters for 25ns LHC Beam at Injection into the Machines.

	PSB	PS	SPS	LHC
N [10^{11} p]	34.2	32.5	2.6	2.3
$\varepsilon_{x,y}$ [μm] rms	1.7	1.8	1.9	2.1
ε_z [eVs] 2σ	1.4	3.0	0.35	0.50
E [GeV]	0.16	2.0	26	450

The LIU project comprises a massive upgrade and renovation effort with the goal of enabling the machines to deliver the requested high brightness beams [1]. A number of internal and external reviews were held in 2016 notably to assess the readiness for connecting Linac4 to the PS Booster and a Cost and Schedule Review in October 2016.

The project has now entered into the execution phase with procurement of equipment and installations ongoing. The technical stop 2016/17 was an occasion to perform installations in the machines before the full implementation of the upgrade in Long Shutdown 2 (LS2).

LINAC4

Linac4 [2] is a normal conducting, 160 MeV H^- ion accelerator constructed within the scope of the LIU project. Construction of the new dedicated building and tunnel in which the Linac4 is housed started in October 2008. Since 2013, hardware has been progressively installed and phases of installation and commissioning at increasing energy were completed in October 2016, when the final energy of 160 MeV has been reached. Following this milestone the beam from Linac4 has been used to test a part of the PSB injection chicane, the stripping foil and the injection diagnostics [3].

Up to now, Linac4 has not run consecutively for more than 6-8 weeks. In order to observe long-term stability and other effects Linac4 will undergo a "reliability run" as from June 2017. Linac4 will be connected to the PS Booster during the next long LHC shutdown and it will replace the current 50 MeV hadron linac, Linac2.

Due to the increased energy, the H^- injection, the possibility of energy variability and longitudinal micro-bunch tailoring via a fast chopper located at low energy, Linac4 will allow removing the current space charge detuning bottleneck reached with the high-current Linac2 beam.

PS BOOSTER UPGRADE

In the PS Booster, work is in full swing with procurement and construction of equipment for the injection of 160 MeV H^- ions from Linac4 as well as for the 2 GeV energy upgrade of the PSB rings and extraction. The hardware for the new injection is by now available and ready for installation, with a planned installation date during LS2. The 2 GeV upgrade is also progressing according to schedule, with the building for the new main power supply completed and procurement of the power converter launched.

Figure 1: PSB main bending magnet yokes for the new injection and extraction magnets.

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Other upgrade items comprise injection and extraction magnets (Fig. 1), kicker and septa magnets, as well as transfer line magnets and power supplies.

On the beam physics side studies continued during 2016 on the test and validation of the prototype wideband RF system installed in one of the four rings, commissioning of diagnostics and studies with a 160 MeV cycle.

During the 2016/17 technical stop the main activities were the creation of rack space and infrastructure and the clean-up of obsolete cables. Unused cables, which prevented installation of new LIU equipment, had been identified beforehand and were removed from the machine allowing pulling cables for upgrade items. Further installations done during the technical stop concerned a prototype wire scanner, a new beam loss monitoring system and a new turn-by-turn orbit measurement. In addition, the 2 GeV extraction septum was installed which will be used at 1.4 GeV until LS2.

PS UPGRADE

The procurement and construction of upgrade items for the PS has also progressed. During the 2016/17 technical stop a number of installations were done in the machine including a new beam loss monitoring system and new corrector power supplies. On the instrumentation side, a newly developed beam gas ionisation monitor was installed including a dedicated magnet, as well as an additional transverse wide-band pick-up. These devices will be deployed during the 2017 run. Furthermore new injection vacuum chambers have been installed which remove aperture limitations.

The mitigation of longitudinal instabilities in the PS is essential for achieving the LIU baseline beam parameters. Reducing the longitudinal impedance of almost all RF cavities is therefore an important part of the upgrades, as well as a dedicated coupled-bunch feedback.

An improved amplifier unit with increased wide-band feedback gain has been installed on one 10 MHz cavity during the 2015/16 technical stop and extensively tested with beam [4, 5]. Compared to the average impedance of the presently operational systems, the upgrade reduces the cavity impedance by a factor of two. A detailed model of the beam-cavity interaction has been validated by the measurements. The improvements will be rolled out to all cavities during the long shutdown 2 (LS2).

The upgraded 1-turn delay feedback system against transient beam loading in the ten main accelerating cavities has demonstrated to significantly improve the bunch-to-bunch spread of longitudinal emittance and intensity along the batch. It has proven reliable operation with all multi-bunch beams for the LHC during the 2016 run. Similar systems are under development for the in total seven cavities at 20 MHz, 40 MHz and 80 MHz and first impedance reduction has been observed with a prototype installation on a 40 MHz cavity.

The benefits on beam stability of a functional prototype coupled-bunch feedback covering all possible dipole oscillation modes have been explored [6]. A Finemet cavity installed during Long Shutdown 1 [7] serves a longitudinal wide-band kicker for the feedback. An intensity of about 2×10^{11} protons per bunch (ppb) has been regularly attained with excellent longitudinal beam quality. Although still below the LIU baseline performance, it already allowed to study the transfer of LHC-type beams of unprecedented intensity to the SPS.

To reduce losses at transfer between PS and SPS, as well as between SPS and LHC, the second 40 MHz cavity has been operated during the last months of the 2016 run to linearize the bunch rotation [8].

SPS UPGRADE

The work in the SPS has progressed across all the upgrade domains. The LIU deployment in the SPS tunnel has started in earnest, with the re-arrangement and beam-coupling impedance reduction of half of the extraction kickers, the start of the civil engineering for the new beam dump system in LSS5 and the deployment in 10 half-cells of the QF short-straight-section impedance reduction and amorphous carbon coating. In another notable first, eight MBB dipole magnets and 10 QF magnets were amorphous-carbon coated in-situ, in a proof of the industrialisation of this process.

For the major upgrade of the 200 MHz RF power and low-level system, the new solid-state main amplifier topology has been defined, the driver amplifiers have been purchased and prototyping of the full-scale modules begun. A new very high power cavity combiner is under study and could be used to combine the output of sixteen 150 kW modules into the RF transmission lines, and a new type of fundamental power coupler is being developed for the 1.6 MW power transmission into the RF cavity. The low-level will be based on the new (for CERN) µTCA platform, and the timing distribution via White Rabbit. In the SPS machine, the available 800 MHz power was doubled in 2016. Simulation studies on the double RF system showed that the extra 800 MHz voltage has the potential to provide additional margin against longitudinal instabilities on flat top.

For the beam instrumentation, the deployment of the fibre infrastructure for the new orbit and beam loss monitor system is almost complete, and prototype electronics for the orbit acquisition is in place. The prototype wire scanner was tested with beam and the series production launched, and both the synchrotron radiation telescope and beam gas ionisation monitor began giving useful measurements.

The contract for the new carbon-composite transfer line collimators was placed and the simulations and tests for the jaw materials almost completed – the final test takes place in 2017 in the HiRadMat facility. For the extraction protection devices, the space constraints in LSS4 have meant that a new design has been made which uses a short additional diluter upstream of the main machine quadrupole.

The prototyping and engineering for the new beam dump system is in progress with the tests of the new thyristor stack switch for the vertical dump kickers and the construction of the new SPS beam dump block TIDVG4, which is based on the same design principles as the dump for LSS5. A number of integration and layout issues have been solved, and the dump and shielding structure fully defined, Fig. 2. The preparation of the LSS5 zone was started in the 2016/17 technical stop, with the removal of unused cables and the new infrastructure for the kicker system.

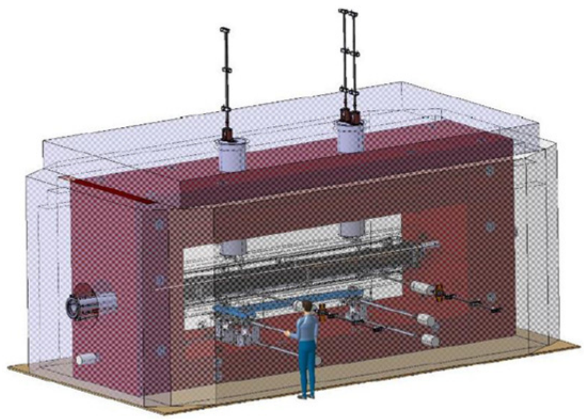

Figure 2: Design of new beam dump block and shielding structure for SPS LSS5.

From the machine performance and beam dynamics side, the measurements in 2016 with the very high intensities available from the PS meant that new regimes were probed. Although the transverse emittances were still a factor of ~2 larger than the LIU target, bunch intensities of up to 2×10^{11} protons were available in the 25 ns structure, crucially within the nominal 0.35 eVs LIU longitudinal emittance. The observations at SPS injection were very interesting, with large beam loss levels of over 20% due to the RF capture and bucket filling on the flat bottom, Fig. 3. The transfer from the PS is made with a non-adiabatic bunch rotation to fit the initially ~10 ns bunch into the 200 MHz SPS RF bucket. Already from simulation this was known to be a delicate process [9]. For the operational beams, the deployment of the second 40 MHz

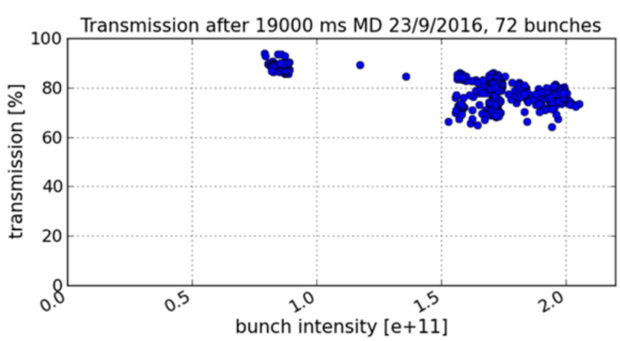

Figure 3. SPS transmission on flat-bottom (no acceleration) for 25 ns high intensity injection test.

RF cavity in the PS allowed a reduction in the capture losses by about 40%. The 2016 measurements have eliminated electron cloud as a source for the loss. Different mitigation measures are now being evaluated, including improved bunch rotation in the PS, Q22 optics in the SPS and extra RF systems for bunch shortening or capture in the PS and SPS, respectively. A decision on the path to follow for the future operation is expected by end 2017.

PLANNING

Most of the LIU implementation is scheduled during the second Long Shutdown (LS2) of the CERN accelerator complex (2019 and 2020). To mitigate this peak in workload, one of the recommendations from a Cost and Schedule review held in 2015 was to anticipate a maximum of activities before LS2.

During the two years of long shutdown, only 15 months are dedicated for the activities in the PSB, 18.5 months for the PS and 19.5 months for the SPS. This is due to the time of radiation cool-down, the hardware tests performed at the beginning of LS2 on the magnets to diagnose any failure and the time to re-commission in a sequence the injectors chain.

The master schedule of LS2 has been defined from the earliest start of work in the different accelerators, and the minimum time for hardware commissioning and beam commissioning. LS2 is a challenge for CERN and the LIU project to manage the work on site, coordinate the activities with respect to safety and level the resources among the different machines.

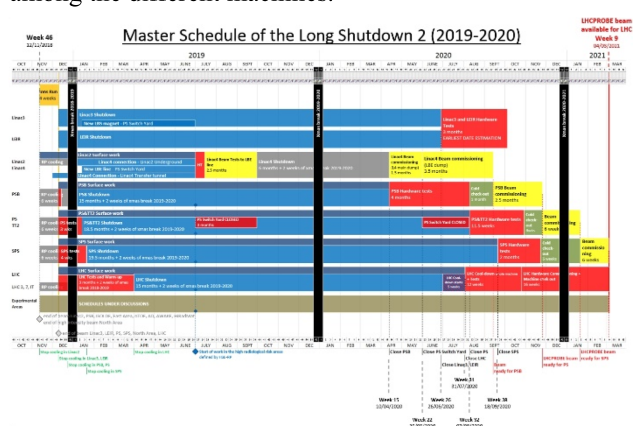

Figure 4: Master plan for Long Shutdown 2.

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