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Status of the LIU project at CERN

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CERN has put in place an ambitious improvement programme to make the injector chain of the LHC capable of supplying the high intensity and high brightness beams requested by the High-Luminosity LHC (HL-LHC) project. The LHC Injectors Upgrade (LIU) project comprises a new Linac (Linac4) as well as major upgrades and renovations of the PSB, PS and SPS synchrotrons. The heavy ion injector chain is also included, adding Linac3 and LEIR to the list of accelerators concerned. This paper reports on the work completed during the first long LHC shutdown, and outlines the further upgrade path.

INTRODUCTION

The upgrade of the LHC injectors in order to satisfy the beam requests of the future high-luminosity LHC has recently been endorsed by a review held in October 2013 [1]. The main conclusion of the review was to implement all measures in order to maximise the integrated luminosity of the LHC. At the same time, shutdowns should have a reasonable length and be adequately spaced in order to ensure long and efficient running periods for the LHC. Therefore the CERN management has endorsed an updated schedule, in which the second long LHC shutdown (LS2) starts by mid-2018 and has a length of 18 months for the LHC itself. During LS2 all LIU upgrades will be implemented, including the connection of Linac4 to the PSB. The long and continuous running periods of the LHC injector complex impose a constraint for the LIU project, as this excludes virtually all work on the machines before LS2. Only a 5 month stop at the end of 2016 / beginning of 2017 will allow for some preparatory work. This work will focus on the clean-up of cable trays and other infrastructure measures in order to mitigate the dense planning of LS2.

In the following sections we highlight the main modifications for the machines concerned and give a brief outlook on the project schedule.

LINAC4

The Linac4 project was started in 2008 and integrated at the end of 2010 into the much broader LIU project. Its goal is the construction of a new H- linac of 160 MeV energy, which will replace the 50 MeV Linac2 as injector for the PSB and thus make the accumulation of the high brightness beams required by the high-luminosity LHC possible.

After some years of construction and installation of the infrastructure in a new building delivered at end 2010, beam commissioning at increasing steps of energy has started in 2013 and will continue until the end of 2015. The initial phase concerned the ion source, the Radio Frequency Quadrupole and the 3 MeV transport and beam chopping line that was commissioned in a dedicated test stand between March and June 2013. The RFQ was rapidly conditioned to the nominal voltage level and showed from the beginning a transmission in perfect agreement with simulations. The chopper intended to create beam-free intervals inside the linac beam pulse corresponding to the edges of the PSB bucket was successfully commissioned and operated with rise and fall times better than 10 ns.

Following this initial commissioning phase, the 3 MeV injector and the measurement line were installed in their final location in the linac tunnel (Fig. 1) where another set of extensive beam measurements took place between end 2013 and beginning of 2014. The beam measurement line was then moved downstream in preparation for installation and beam commissioning of the first Drift Tube Linac (DTL) tank that has recently been assembled and tuned. In parallel, a new Cesiated version of the RF-type ion source was installed and commissioned in the test stand. It delivers a current of more than 50 mA and will be installed in the linac during summer 2014, to be used for the commissioning of the other two DTL tanks going up to 50 MeV and of the remaining linac sections.

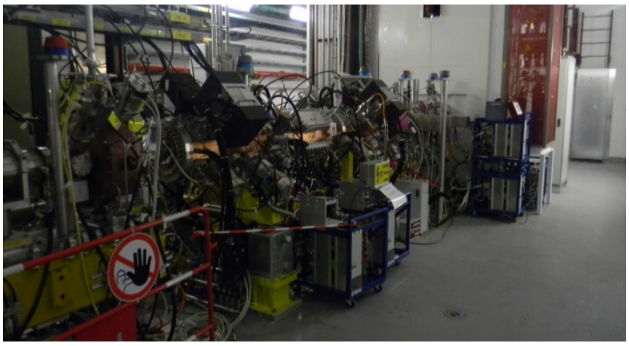

Figure 1: The Linac4 3 MeV section (from right: ion source, RFQ, chopper line) installed in the tunnel.

PS BOOSTER

The upgrade of the PS Booster consists of two major activities.

The injection line and injection region will be upgraded from the present 50 MeV multiturn betatron stacking of protons from Linac2 to the charge-exchange injection of 160 MeV H- ions from the new Linac4. Important design choices have recently been made, for example on the material of the vacuum chambers, the vacuum sectorisation and the injection dumps. This allows the integration of the area to proceed now at full pace. The design and construction of the related hardware is in progress. Although the connection of Linac4 to the PS Booster is nominally planned during LS2, all injection equipment will be ready at the end of 2016, simultaneously with Linac4.

The second main activity is the increase of the top energy of the PSB from 1.4 GeV to 2.0 GeV. This involves the change of the main power supply as well as change or modification of a number of smaller power supplies, magnets, kickers and septa.

During LS1 a number of LIU-related activities have been completed. The main intervention was the change of the beam dump, which was inappropriate for the beam energy and intensity of the upgraded machine [2]. Other activities include installation of additional modules on the prototype Finemet® cavity, cabling, renovation of the handling equipment, some civil engineering work and some upgrade of beam instrumentation (new pick-ups in the injection/ejection lines, new electronics for the orbit pick-ups, new BLMs, new BCTs).

PS

The upgrade program of the PS focuses on issues both in the transverse and longitudinal plane [3]. In the transverse plane, direct space-charge tune spread pushes the beam on betatronic resonances causing beam loss and transverse emittance blow up. The upgrade of the injection energy to 2 GeV foreseen during LS2 will help to overcome this limitation, but alternative techniques to reduce the strength of the resonances are also being explored. In particular, new sextupoles, both normal and skew, as well as octupoles have been installed to test resonance compensation and improve chromaticity control. The transverse damper was also upgraded to improve the control of the headtail instability, to reduce injection errors, and eventually to cope with the transverse instability observed on the extraction flat bottom for LHC-type beam with bunch length shorter than nominal. There has also been progress in understanding injection losses. For example, the mechanism triggering injection oscillations on the injection flat bottom was understood and the losses were fully characterised [4].

Concerning the longitudinal plane, coupled bunch instability appearing after the transition energy would limit the maximum intensity per bunch well below the 2.5×10^{11} p+ per bunch of the future HL-LHC type beam if no countermeasures were taken. A new dedicated longitudinal damper, based on a Finemet® cavity and a new LL-RF were installed during LS1 to stabilise the beam [5]. The electronics of the 1-turn delay feedback was also renovated with a new digital system.

Electron cloud formation will continue to be carefully monitored, although it will most probably not affect future HL-LHC type beams. A simulation campaign was launched in parallel with the installation of two new electron-cloud monitors in one of the main magnets.

The tunnel shielding, designed for the beam intensity of 1958, was not any longer adapted to the future beam intensities and losses in the injection and extraction regions. Significant additional shielding was therefore added on top of the relevant sections during LS1.

Beyond these interventions, the design of the hardware foreseen for installation during LS2 has progressed, as well as studies like the improvement of the impedance model (transverse and longitudinal) of the machine.

SPS

The demanding beam performance required by the HL-LHC and the available beam characteristics from the pre-injectors translate into a set of requirements and a baseline upgrade path for the SPS as HL-LHC injector, to remove or mitigate the identified limitations. The HL-LHC requires 25 ns bunch spacing, with 2.5×10^{11} p+ per bunch and up to 4 batches of 72 bunches per SPS extraction.

For the SPS, the main limitations come from the beam-loading at very high beam intensity which reduces the available RF voltage, longitudinal instabilities linked to the machine impedance, the electron cloud effect which at 25 ns spacing can make operation impossible through high vacuum or transverse instabilities, and the high stored beam energy which requires significant upgrades of all beam intercepting protection devices in the ring and transfer lines.

The instrumentation requires major upgrades to be able to reliably characterise the very bright beams, and other changes to systems like the magnet interlocking and vacuum sectorisation are designed to improve availability, another key requirement for HL-LHC.

The present baseline for the LIU-SPS upgrade results from the extensive effort invested in the analysis and understanding of the SPS limitation during the past decade [6]. Multiple beam tests during that period allowed developing and benchmarking e-cloud simulations as well demonstrating the efficiency of scrubbing [7], with the various effects and dependencies now well understood. In 2012 the secondary electron yield (SEY) of the SPS vacuum chamber had been so much reduced by scrubbing that electron clouds were not anymore a limitation for the operational LHC beams. Effects were however still observed at very high bunch intensity for 25 ns spacing, with some transverse emittance blow-up on the trailing bunches in the batches. Amorphous carbon coating of the vacuum chamber was fully validated as a mitigation measure using a sputtering technique which does not require the removal of the vacuum chamber from the magnet.

The low-gamma transition optics (Q20) was deployed operationally in 2012 [8], after intensive testing and development, necessitating re-matching of the extraction systems and transfer lines to LHC and a re-setup of the transfer line protection collimators. As expected, the longitudinal quality of the beam extracted from the SPS improved, although longitudinal stability remains a limitation due to limited RF voltage. In addition, the transverse brightness increased from an average of 0.92×10^{11} p+/µm to 1.05×10^{11} p+/µm.

A series of reviews was organised on remaining open questions and limited the upgrade possibilities to a more focused baseline. The internal beam dump absorber block will be upgraded to withstand full LIU beam parameters, and the possibility to externally dump the beam at high energy is under investigation. The pumping of the ZS electrostatic septa will be improved and remote voltage modulation implemented. Local correction of the extraction orbit will be investigated using the extraction bumpers, but no new general closed orbit correction system for high energy is required.

During LS1, the fourth harmonic 800 MHz RF system and its Low Level RF is being extensively renovated and its voltage will be doubled bringing in operation the second cavity. The existing transverse damper system is also being upgraded with new low level controls and dedicated pick-ups. The preparation for the upgrade of the 200 MHz RF continues with the prototyping of the power amplifiers under way, the design of the new power couplers in progress and the layout change to the RF cavities and associated SPS straight section defined.

Following the successful test of the wideband (intra-bunch) transverse damper demonstrator in closed-loop mode with a single bunch, the design of a multi-bunch prototype is now in progress.

Concerning beam instrumentation, performance upgrades of almost every system have been defined and specified. Work is progressing with the pulling of fibres and cables, and the prototyping of specific systems, for example a new high-resolution wire scanner.

IONS

In order to increase the luminosity of Pb-Pb collisions, the ion injector chain will also need a series of upgrades [9]. As IBS and space charge detuning on the SPS flat bottom already severely limit the possibility of increasing the bunch intensities, the chosen path consists of increasing the number of bunches in the LHC, preserving the bunch brightness obtained during the p-Pb run in 2013 [10].

The baseline for delivering a Pb-Pb peak luminosity of 4×10^{27} cm^{-2} s^{-1} includes:

- Doubling the Linac3 repetition rate to 10 Hz
- Batch compression in the PS to reach a bunch spacing of 100 ns
- A new injection system in the SPS, allowing a batch spacing of 100 ns

The full upgrade scheme (Fig. 2), delivering up to 1248 bunches per LHC ring, will reach the requested Pb-Pb peak luminosity goal of 7×10^{27} cm^{-2} s^{-1} with the following means:

- Increasing the intensity in the LEIR machine by at least a factor 1.4
- Splitting the bunches in the PS
- Momentum slip-stacking in the SPS, reducing the bunch spacing down to 50 ns

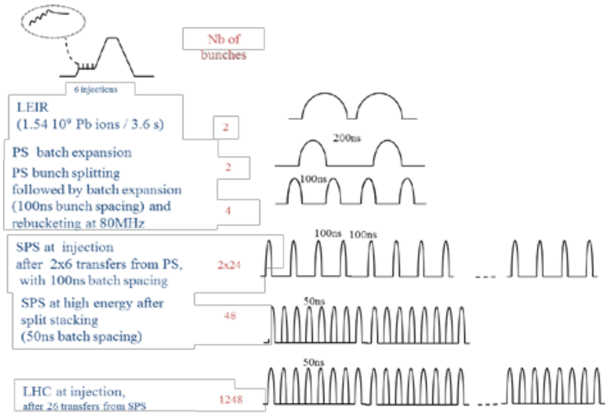

Figure 2: Fully upgraded ion production scheme, with momentum slip stacking in the SPS.

PROJECT SCHEDULE

The LIU project aims at completion during the second long LHC shutdown (LS2), presently planned for 2018/19. This includes the connection of Linac4 to the PSB, as there will be only one major stop of 19 weeks at the end of 2016 / beginning of 2017, which is not sufficiently long for this intervention. LS2 is planned to start in July 2018 with an interruption of 18 months of the beam in the LHC.

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