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PLANS FOR THE UPGRADE OF THE LHC INJECTORS

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The LHC injectors upgrade (LIU) project has been launched at the end of 2010 to prepare the CERN accelerator complex for reliably providing beam with the challenging characteristics required by the high luminosity LHC until at least 2030. Based on the work already started on Linac4, PS Booster, PS and SPS, the LIU project coordinates studies and implementation, and interfaces with the high luminosity LHC (HL-LHC) project which looks after the upgrade of the LHC itself, expected by the end of the present decade. The anticipated beam characteristics are described, as well as the status of the studies and the solutions envisaged for improving the injector performances.

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INTRODUCTION

In their present state [1], the LHC injectors can supply the beam foreseen for reaching the nominal luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in the ATLAS and CMS experiments (25 ns bunch spacing, $1.15 \cdot 10^{11}$ p/b within 3.5 mm.mrad (1σ norm.)). Thanks to the flexibility of the schemes implemented in the PSB and PS [1], the beam can have many different time structures and, for example, the LHC presently operates with 50 ns bunch spacing and $1.3 \cdot 10^{11}$ p/b within ~ 2 mm.mrad (1σ norm.).

To get a ten-fold increase of the integrated luminosity during the second decade of operation of the collider (~ 2020 -2030), major upgrades will be necessary in the LHC concerning especially the equipment in the straight sections of the experiments [2] and the characteristics of the injected beam will have to be improved [3]. The beam specifications tentatively set by the HL-LHC project is $2 \cdot 10^{11}$ p/b within 2.5 mm.mrad (1σ norm.) for 25 ns bunch spacing and $3.3 \cdot 10^{11}$ p/b within 3.5 mm.mrad (1σ norm.) for 50 ns [3].

Context of the LIU Project

Apart from the replacement of Linac2 by Linac4, the necessary improvement of the LHC beam characteristics has to be obtained by modifying and upgrading the existing accelerators (PSB, PS and SPS). In the first phase of the LIU project, until the end of 2012, the limitations of the accelerators are being studied and the benefits of potential improvements are being estimated in view of defining a feasible set of beam characteristics, compatible with the aim of HL-LHC in terms of integrated luminosity.

LINAC4

Construction of Linac4, the first element in the improved LHC injection chain, is already well advanced [4]. The H⁻ linac is made of a sequence of accelerating structures reaching a final energy of 160 MeV in a length

of about 90 meters; a 70-m long transfer line connects it to the Linac2-PSB transfer line.

The Linac4 project was approved in June 2007 and started officially in January 2008. Civil engineering work was completed in October 2010. Figure 1 shows an aerial view of the construction site, indicating the relative positions of Linac2 and Linac4. The accelerator is located in a tunnel 12 m below the surface building which houses the Radio-Frequency systems and other machine equipment.

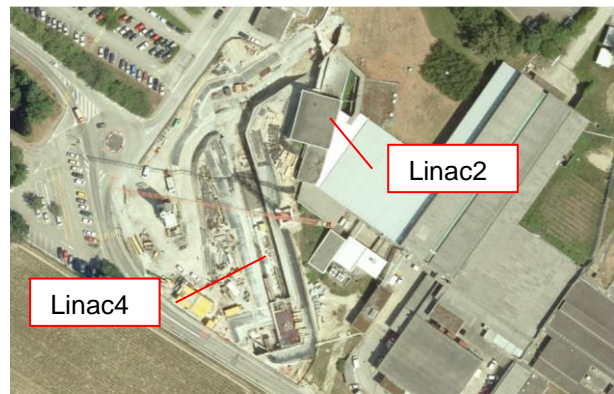


Figure 1: Aerial view of Linac4 construction site (2009).

Infrastructure is presently being installed (electricity, cooling and ventilation, cabling...) (Fig. 2). At the end of this phase, in June 2012, the installation of the accelerator components will begin.



Figure 2: Infrastructure installation (Summer 2011).

Construction of the accelerating structures has started; in particular the low-energy section up to 3 MeV will be completed at the end of 2011 with the delivery of the RFQ. A dedicated test stand is being prepared for this section in view of commissioning it completely with beam before transporting it to the Linac4 tunnel in spring 2013. Afterwards beam commissioning will resume in the Linac4 tunnel at progressively increasing energy until April 2014.

Connection to the PSB including conversion to charge exchange injection at 160 MeV and commissioning of the synchrotrons will take 7 more months. This is incompatible with the present planning of the first long LHC shutdown (December 2012 – September 2014) and the replacement of Linac2 is therefore planned for the second long LHC shutdown. Ample time will then be available for improving the Linac4 reliability before dismantling of the PSB proton injection.

During the important period between these 2 successive shutdowns, the LHC will operate for the first time at its nominal energy and Linac4 will be available as a back-up of Linac2. In case of emergency, Linac4 could be switched to deliver 50 MeV protons and replace Linac2 within a few days, although at the cost of degraded performance for all the CERN users.

UPGRADE OF THE CERN PS BOOSTER

The Proton Synchrotron Booster (PSB) is composed of four superimposed synchrotrons. Commissioned in 1972, it has already undergone several upgrades. In order to allow for reliable operation until ~2030, a comprehensive consolidation program has been put in place. In addition, two major upgrade programs have been launched to further improve performance, anticipating the needs of the LHC Luminosity Upgrade.

Upgrade of PSB Injection

With Linac4 [4], the injection energy has to be brought up from 50 to 160 MeV and the injection scheme has to be upgraded from multi-turn betatron injection to charge-exchange injection with painting in all planes. This new injection scheme will allow for increased intensities, improved brilliance and more flexibility in tailoring the desired transverse emittance via phase space painting.

Increase of PSB Top Energy

To reduce space charge effects at injection in the PS, the kinetic energy of the beam delivered by the PSB will be brought up to 2 GeV. This has been the subject of a dedicated study which endorsed feasibility and stated that the gain in intensity into the downstream PS machine would be at least 65% [5]. The machine components and systems that need to be replaced or upgraded are identified and technical solutions proposed. The study concluded furthermore that the proposed 2 GeV upgrade could be completed by the second long LHC shut down.

Rapid Cycling Synchrotron Option

Following the analysis of the energy upgrade of the existing PS Booster, the need was felt for a comparison with the construction of a new Rapid Cycling Synchrotron, tailored to the present requirements. The obvious advantage of such a scenario would be not only to replace a 40 year old machine by a new one, but also to commission the machine off-line before connecting it to the PS, thus minimising risk and down time. Technical feasibility and performance for LHC were confirmed by a recent study [6] which also analysed cost and schedule.

UPGRADE OF THE CERN PS

The PS has to preserve the transverse emittance of the beam from the PSB and to change its time structure for generating the bunch spacing required by the LHC [1, 7].

Low Energy

To reach the high brightness required by LHC, the PS is filled with two pulses from the PSB: a first batch of four bunches has to wait for the second batch of two bunches during 1.2 s on the injection flat bottom. During this period, the Laslett space-charge tune shift should not exceed ~ 0.3 in both planes to avoid spoiling the transverse beam quality. For the HL-LHC type of beams, this requires the injection energy to be increased from 1.4 to 2 GeV. Studies of the space-charge related limits and of potential improvements are being actively pursued [8, 9].

Another deleterious effect observed on the injection flat bottom is a vertical head-tail instability, which causes large losses if not properly cured. Currently, linear coupling is introduced via skew quadrupoles to distribute the instability between the two planes. For the upgraded beams, if linear-coupling would not be sufficient, the use of the existing transverse damper, or eventually of already installed Landau octupoles is foreseen.

Transition and e-cloud Effects

During acceleration, at transition crossing, a vertical TMCI instability has been observed for high intensity beams. Preliminary investigations indicate that the instability threshold should be higher than the intensity per-bunch proposed for the HL-LHC type of beams.

Electron clouds are also of concern, since electron cloud formation was observed soon before ejection at 26 GeV, but without any effect on beam quality. A campaign of measurement is foreseen to determine if electron cloud might become an issue for the future LHC beams.

Longitudinal Beam Gymnastics

The production of the time structure of the LHC beams with 25 ns bunch spacing is obtained with one triple splitting at the end of the injection flat bottom (changing from $h=7 \rightarrow h=21$) and two double splittings at the extraction energy of 26 GeV (changing from $h=21 \rightarrow h=42 \rightarrow h=84$). The last splitting is transformed in a simple re-bucketing if the bunch spacing required is 50 ns. In total, five different RF harmonics are used, and the relative phases and voltages have to be accurately adjusted to reach a maximum difference of $\pm 10\%$ in bunch intensity between the 72 resulting bunches (36 in case of the 50 ns bunch spacing). Periodic transient beam loading due to the gap without beam and coupled bunch instabilities can deteriorate the processes and increase the difference between bunches. The foreseen cures include the upgrade of the cavities fast and “one-turn delay” feedbacks and the installation of a new broadband longitudinal feedback.

UPGRADE OF THE CERN SPS

Status

The SPS is presently transferring on a regular basis $1.3 \cdot 10^{11}$ p/b within 2.0 mm.mrad (1σ norm.) to LHC with 50 ns spacing, which requires at least $1.5 \cdot 10^{11}$ p/b injected. For the 25 ns beam, intensities of $1.2 \cdot 10^{11}$ p/b have been accelerated with transverse emittances below 3.0 mm.mrad (1σ norm.). The upgrade program aims to significantly improve these figures by overcoming the limitations identified in the past years [10] and confirmed in extensive machine development studies, simulations and theoretical analysis. They result from electron cloud effects, beam loading in the 200 MHz RF system, transverse mode coupling (TMCI) and longitudinal coupled bunch instabilities. There are also operational issues for different equipment systems. A number of major modifications to the SPS are planned to address these various matters.

Planned Actions

For electron cloud, the proposed mitigation strategy is to coat the interior of the machine vacuum chamber with amorphous carbon (aC). This has been shown to suppress e-cloud [11], to be stable for several years and to be applicable in the chambers of the SPS dipoles without needing to disassemble the magnet. The target is to coat some 90% of the SPS circumference to reduce the integrated electron density to an acceptable level for bunch intensities of around $2 \cdot 10^{11}$ p/b for 25 ns spacing.

The reduction of the impedance of the SPS is an ongoing campaign, with shielding and improvements of various elements, in particular the extraction and dump kicker magnets [12]. Simulations and measurements continue for identifying remaining impedance sources.

A major upgrade of the SPS 200 MHz RF system is needed to overcome beam loading limitations and reduce impedance [13]. The upgrade consists of building two new >1 MW power plants, transmission lines and controls, and rearranging the existing cavities (with the addition of two spares) from the present 4 modules into 6 modules. This should allow intensities of $2.2 \cdot 10^{11}$ p/b to be accelerated and extracted for 25 ns spacing.

A new high bandwidth damper system is being prototyped which should be effective against e-cloud instability and TMCI.

A new SPS optics with an integer tune of 20 is being tested, which has been shown to increase the single bunch threshold for TMCI with zero chromaticity from $1.7 \cdot 10^{11}$ p/b (with the present 26 integer tune) to above $3 \cdot 10^{11}$ p/b. The new Q20 optics also improves the margin for other instabilities (e-cloud, multibunch); its deployment requires new optics in the transfer lines.

The beam intercepting protection devices in the SPS and the transfer lines to the LHC need replacement to protect downstream elements from the increased beam energy. In addition the possibility of redesigning the transfer lines to remove the limitation at LHC injection from losses on these devices is being studied, together

with improvements to the SPS scraper system for halo shaping and to the SPS internal beam dump system.

The existing SPS beam instrumentation systems need a number of modifications to cope with the new beam parameters and higher beam energy – in addition improvements are in progress to allow better diagnostics, setting up and analysis. Particular attention is being paid to the measurements of transverse beam size, beam current, orbit and beam loss.

The electrostatic septa (ZS) for slow extraction are sensitive to the LHC beam and can be damaged by high intensity; studies to find acceptable operational parameters are under way, including on a dedicated ZS test tank installed in the SPS. The beam heating of the extraction kickers (MKE) by Higher Order Modes (HOM) limits high duty cycle, high intensity operation with LHC beams, and is steadily improving as the kickers are shielded with serigraphy on the ferrites, as part of the impedance reduction program. Improvements to the SPS vacuum system sectorisation will also benefit some of these equipment systems.

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