INSTALLATION SCHEDULE AND EXPECTED PERFORMANCE FOR THE PS COMPLEX WITH LINAC4

M. Vretenar, C. Carli, CERN, Geneva, Switzerland

Abstract

The main part of the Linac4 facility can be commissioned in parallel to the operation of the CERN injectors for the LHC, while the modifications to the existing transfer line and to the PS Booster (PSB) injection region require a long shut-down. The project planning is presented, together with considerations on shut-down length and flexibility of the schedule, which will allow coordinating the Linac4 installation schedule with the LHC operation schedule for the next years. The expected performance for the LHC of the PS complex with Linac4 (Linac4, PSB and PS) is presented.

EXTENSION OF THE LINAC4 PROJECT

The Linac4 Project, whose layout is presented in Fig. 1, is composed of three main parts [1]:

1. Construction and commissioning of the Linac4 linear accelerator (160 MeV), up to a dump placed in a straight line at the end of the linac (Fig. 2).
2. Construction and commissioning of a new transfer line, from a bending magnet in front of the linac dump up to the LT.BHZ20 magnet in the present Linac2 to PSB line, plus upgrades and modifications of the existing LTB line (Linac to Booster) and of the LBE and LBS measurement lines (beam emittance and energy spread at PSB entrance) (Fig. 3). Transport of the beam to the measurement lines and commissioning of the lines.

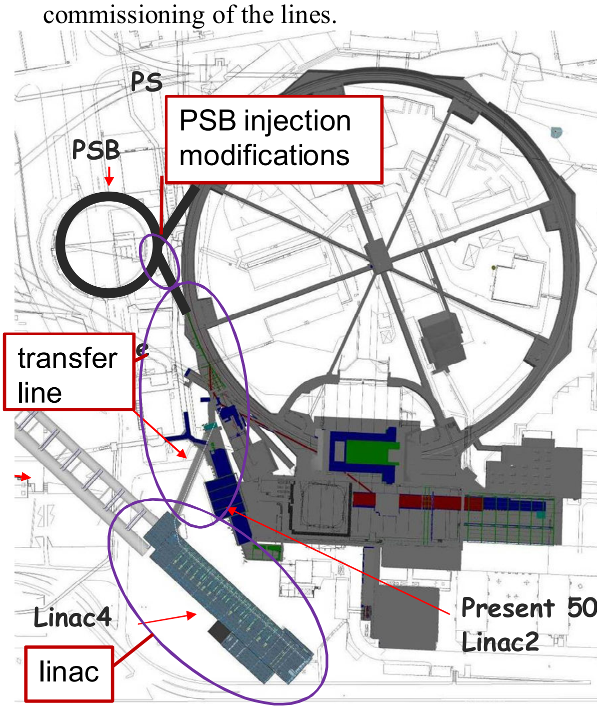

Figure 1: The three main parts of the Linac4 project

3. Modification of the PSB injection region, including the implementation of a H- charge exchange injection and upgrade of magnetic elements and power supplies for 160 MeV (Fig. 4). Commissioning of the PSB up to “nominal” performance (production of the same beams as before the Linac4 installation) in dedicated mode, and to “ultimate” performance (production of the maximum beam brightness possible in the PSB with Linac4) in parasitic mode.

The linac constitutes the main part of the project in terms of extension, complexity and cost, however the modifications to the line and to the PSB injection region present a not negligible cost (almost 20% of the overall project material cost, civil engineering and infrastructure excluded) and complexity. Whereas a basic requirement in the design of Linac4 was the capability to build and commission the linac without any interference with the operating CERN accelerators, the connection to the LTB line, the modifications to PSB and its re-commissioning have to be done during a dedicated shut-down period.

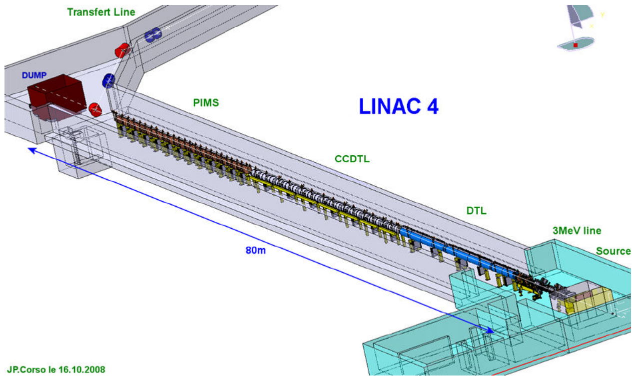

Figure 2: The Linac4 machine.

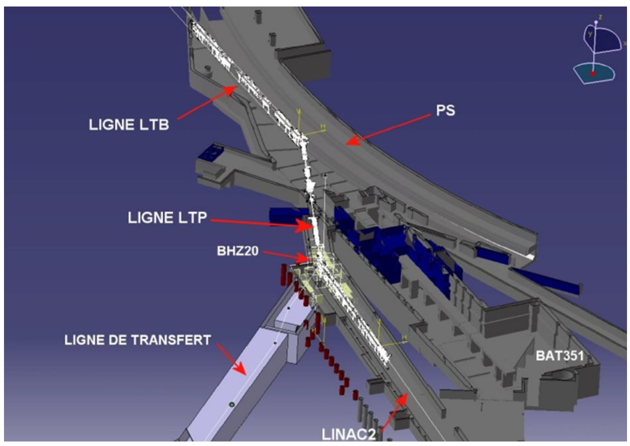

Figure 3: Transfer lines Linac4-PSB (new and old).

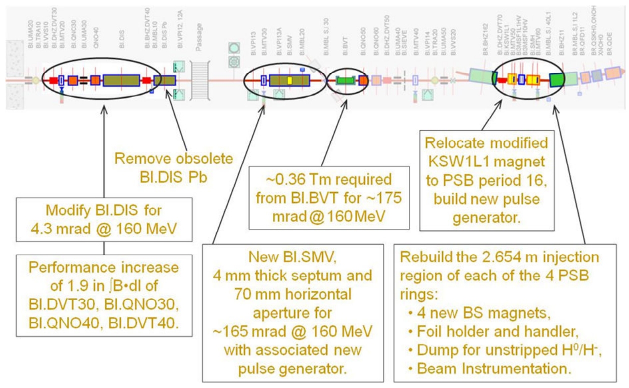

Figure 4: Overview of the modifications to the PSB injection region.

FLEXIBILITY IN THE LINAC4 SCHEDULE

The present Linac4 Master Plan (Fig. 5), as approved in April 2009, is divided into three main parts: a) a construction phase covering the period 2009-2012; b) an installation and commissioning phase in 2011-2013 (with an overlap between construction and installation) and c) the phase of connection to the PSB and of PSB re-commissioning, in 2013-14.This plan is consistent with the delay of the project by one year decided in 2009. It foresees end of commissioning in September 2013. So far there are some minor delays, but the project follows in the main lines the approved schedule.

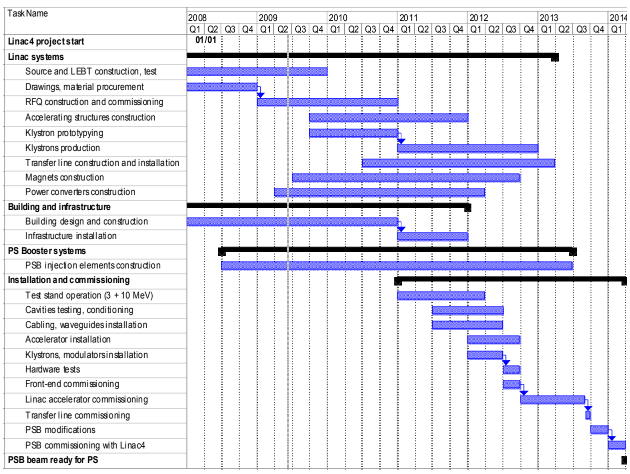

Figure 5: Linac4 Master Plan (2009 version).

However, it should be noticed that the recent risk analysis has underlined the risk of delays of the order of few months, mainly due to missing manpower resources, and of initial reliability issues. In conclusion, a delay by one year of the connection to PSB would provide a safety margin against possible delays, allowing to reduce the pressure on the teams, and at the same time could allow to add in the planning a "reliability run" at the end of the commissioning, meant to test the equipment with beam over time and to assess and solve possible reliability issues. The main consequences on Linac4 would be a change in the design of the main dump, which should be able to stand beam over a period of several weeks. An additional commissioning dump in the transfer line to the PSB could be considered too, in order to allow profiting of the additional time to commission the new part of the transfer line. Another concern would be the availability of manpower during the additional commissioning-reliability run, the same people having to run both Linac2 and Linac4.

In more general terms, it can be stated that Linac4 can continue to operate and to improve reliability and performance until the moment when the injector complex is ready for the long shut-down required by the connection to the PSB.

DURATION OF THE LINAC4 SHUT-DOWN

The long LHC shut-down required for the connection of Linac4 to PSB is composed of the following parts:

1. One month of cooling time for the radiation in the PSB injection area, to minimise the dose to the personnel involved in the PSB modifications. During this period the Linac4 line will be connected to the old LTB line and the measurement lines LBE and LBS will be modified, the radiation levels in the linac lines being much lower than in the PSB.
2. Three months for the modification of the PSB injection hardware (detailed in Fig. 4).
3. Three months for the re-commissioning of the PSB with the new hardware, with the goal of providing at least the same performance in the PSB as before the connection of Linac4 for all the standard PSB users.
4. One month (2+2 weeks) for starting up PS and SPS after the shut-down. This corresponds to the usual allocation after a long shut-down period.

The total time required for the above activities corresponds to 8 months, which is the duration of the LHC proton shut-down required for the connection of Linac4. It should be noticed that there is almost no interference between the ion complex (Linac3-LEIR-PS) and the connection of Linac4 to PSB, because access to the LTB line and to the PSB is possible during ion runs and work on the measurement lines can be anticipated to a previous shut-down. The duration of the LHC shut-down for Linac4 can therefore be reduced by the duration of an ion run at the end of the LHC run. It would be also possible to start the following run with ions; this would further reduce the duration of the LHC shut-down but would require sorting some issues concerning starting the injectors with a low-intensity beam. The overall schedule for the long Linac4 shut-down is presented in Fig. 6.

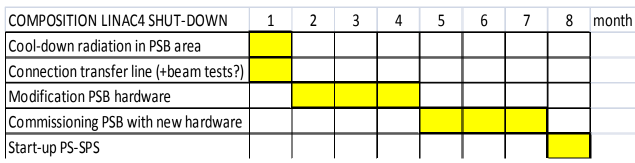

Figure 6: Activities during the shut-down for Linac4.

PERFORMANCE FOR LHC OF THE PS COMPLEX WITH LINAC4

The main challenge of the LHC beams in the PS complex consists in creating high brightness beams, i.e. in accumulating the highest possible beam current within the small emittances specified for the LHC. The reference emittances in this context are 2.5 μm for the PSB and 3 μm for the PS, rms (1σ) normalised values. Linac4 is designed to deliver a current of 40 mA during 400 μs (corresponding to 10^{14} particles per pulse) within 0.45 μm emittance, i.e. much more than what is required by the LHC beam. Instead, the place where the beam brightness is generated is the PSB injection, where space charge forces define the minimum achievable emittance for a given beam intensity, or the maximum achievable intensity for a given emittance. Increasing the PSB intensity and brightness limitation is the main motivation for the construction of Linac4, whose energy of 160 MeV provides exactly a factor of 2 higher $\beta\gamma^2$ at injection with respect to the present 50 MeV Linac2. The accumulated intensity being limited by the incoherent tune shift, which scales as $1/\beta\gamma^2$, for the same tune shift Linac4 should make possible accumulating twice the present intensity within the same normalized transverse emittances. Since it is presently accepted that the PSB limit for LHC beams corresponds to about 1.8 $\times 10^{12}$ protons per ring (ppr), Linac4 should allow bringing this limit to 3.6 $\times 10^{12}$ ppr.

It is not straightforward to analyse how this improvement in the PSB will impact the PS (and the SPS), the intensity out of the PS depending on the transfer scheme between PSB and PS, on the particular intensity limitations of the PS and on beam loss. An attempt to give a global view of the present and future situation for the 25 ns LHC bunch train, the most challenging for the PS complex, is presented in Table 1.

In the first two columns the present achieved intensities during the LHC tests and the expected maximum values [2] are given. For the PS, the intensities in protons per pulse (ppp) and in protons per LHC 25 ns bunch (ppb) after bunch splitting are reported in the Table. The ppp value corresponds to the present double batch transfer

LHC INJECTORS WITH LINAC2		Nominal LHC Double Batch	Expected Maximum Double Batch	Original proposal, 1997 Nominal	Original proposal, 1997 Ultimate
PSB out	ppr	1.62 x10^{12} *(1bunch/ring)*	1.8 x10^{12} *(1bunch/ring)*	1.05 x10^{12} *(1bunch/ring)*	1.8 x10^{12} *(1bunch/ring)*
($\varepsilon^* \leq 2.5\ \mu m$)		↓ *(6 bunches, h=7)*	↓ *(6 bunches, h=7)*	↓ *(8 bunches, h=8)*	↓ *(8 bunches, h=8)*
PS out, per pulse	ppp	9.72 x10^{12}	10.8 x10^{12}	8.4 x10^{12}	14.4 x10^{12}
PS out, per bunch	ppb	1.35 x10^{11} *(72 bunches)*	1.5 x10^{11} *(72 bunches)*	1.0 x10^{11} *(84 bunches)*	1.7 x10^{11} *(84 bunches)*
($\varepsilon^* \leq 3\ \mu m$)		↓ *15% loss*	↓ *15% loss*	↓ *no loss*	↓ *no loss*
SPS out	ppb	1.15 x10^{11}	*1.27 x10^{11}*	1.0 x10^{11}	1.7 x10^{11}

LHC INJECTORS WITH LINAC4		Nominal LHC Single batch	Maximum Single batch	Maximum Double batch	Single batch + PS h=14, 12 bunches scheme
PSB out	ppr	3.25 x10^{12} *(2bunch/ring)*	3.6 x10^{12} *(2bunch/ring)*	2.05 x10^{12} *(1bunch/ring)*	*3.6 x10^{12} (3bunch/ring)*
($\varepsilon^* \leq 2.5\ \mu m$)		↓ *(6 bunches, h=7)*	↓ *(6 bunches, h=7)*	↓ *(6 bunches, h=7)*	↓ *(12 bunches, h=14)*
PS out, per pulse	ppp	9.72 x10^{12}	*10.8 x10^{12}*	*12.3 x10^{12} (scaled 1998 limit, 206ns bunches)*	*14.4 x10^{12} (larger ΔQ possible in single batch)*
PS out, per bunch	ppb	1.35 x10^{11} *(72 bunches)*	*1.5 x10^{11} (72 bunches)*	*1.7 x10^{11} (72 bunches)*	*2.0 x10^{11} (72 bunches)*
($\varepsilon^* \leq 3\ \mu m$)		↓ *15% loss*	↓ *<15% loss*	↓ *20% loss*	↓ *20% loss*
SPS out	ppb	1.15 x10^{11}	*>1.3 x10^{11}*	*1.37 x10^{11}*	*1.6 x10^{11}*
Goal:		Nominal intensity in single batch: shorter filling time, lower losses and emittance growth.		Potential for ultimate intensity out of PS in double batch.	Potential for > ultimate with a new PS scheme (in PSB: new recombination kicker, new RF gymnastics).

Table 1: Expected maximum performance in the PS complex (with estimates for the SPS) without and with Linac4, in terms of intensity for LHC. Limitations are highlighted in yellow; values to be demonstrated are in italic.

scheme, where two trains of three bunches coming from three different PSB rings are transferred to the PS, which operates on h=7. The remaining empty bucket in the PS provides a gap for the extraction kicker. The ppb value comes from the subsequent splitting of the 6 PS bunches into 72 bunches, obtained with RF gymnastics. This beam is then transferred to the SPS. Using a usual convention for the LHC beams in PS and SPS, the losses in the process are given by an overall loss factor, applied at the transfer between PS and SPS. Most of this loss (~10%) is in the SPS, but other losses (~5%) take place between PSB ejection and PS transition [2]. Column 2 shows how in the present conditions only intensities 10% higher than the so called "LHC nominal" 1.15 $x10^{11}$ ppb can be obtained from the SPS. In the Table, limiting values (i.e. intensities where the corresponding machine is at its maximum, while the other machines still have a margin) are highlighted in yellow. From column 2, it is clear that in the present configuration the limitation in the PS complex comes from PSB, justifying the construction of a new linac to overcome it.

The third and fourth columns present, for comparison, the intensities that were assumed in the original proposal from the beginning of the 90ies for the injector upgrade for LHC, for the "nominal" and "ultimate" case respectively, the latter corresponding to 1.7 $x10^{11}$ [3]. The original idea was that for the production of the ultimate beam, both PSB and PS would operate at their space charge limit. The new PSB energy (1.4 GeV) was defined based on pure beam dynamics considerations, in order to bring the PS limit at what was available from the PSB. The first reason why the PS cannot presently provide the ultimate intensity is that because of a microwave instability discovered during the LHC beam preparation the transfer scheme was changed. Instead of filling eight h=8 buckets of the PS with two transfers and one bunch provided by all four Booster rings, only 6 out of h=7 buckets in the PS are filled and not all Booster rings provide beam for both transfers. The second reason for the lower intensity is the beam loss in the process, which was not considered in the original scheme. It should be noticed that at the time, based on the experience with the PS, the maximum achievable intensity (i.e. the space charge limit) was estimated at 14.4 $x10^{12}$ ppp.

With Linac4 and twice higher intensity in the PSB it will be possible reaching and slightly exceeding the nominal intensity (column 5 and 6) with single batch transfer instead of double batch transfer. The single batch transfer will reduce the filling time and will reduce the emittance growth in the PS because the PS beam does not have to wait 1.2 s on a flat porch for the second batch to come, with an expected reduction in beam loss and a higher intensity with respect to the present maximum (column 6).

The way to push the PS complex to its limit with Linac4 is to come back to double batch transfer. In this case the limitation will come from the PS, and column 7 assumes bringing the PS to its limit, obtained scaling the PS limitation of column 4 to the present case (h=7), which in turns assumes that we operate with the same bunching factor and with slightly longer bunches that at present, 206 ns instead of 170 ns. For this case, it is expected to obtain the ultimate intensity out of the PS.

In order to increase even further the intensity while keeping the present machines, there are only two ways. The first is to change the transfer scheme, and the second is to increase the PS limit by further raising the PSB energy. The last column presents a possible case using a different transfer scheme [3]. By changing the PS harmonic number in order have a single batch transfer using all 4 PSB rings instead of only 3, one could use all the available PSB intensity profiting at the same time of the advantages of the single batch transfer. In column 8 is presented a case with h=14 in the PS and 12 bunch transferred from the PSB, 3 per each PSB ring. The intensity out of PS could be then increased to 2.0 $x10^{11}$ ppb, at the cost of a new PSB RF system for h=3, new recombination kickers in the PSB, new RF gymnastics in the PS and provided that the beam can support a larger direct space charge tune shift for a short duration.

The second option, increasing the PSB energy, is the subject of a dedicated paper and will not be presented here [4].

CONCLUSIONS

The Linac4 schedule provides enough flexibility to allow the connection to the PSB to take place any time after September 2013, with a shut-down of the LHC of a total duration of 8 months (in case there is no LHC ion run) or of 8 months minus the duration of the ion run.

It is foreseen that Linac4 will allow reaching the nominal LHC intensity in PS single batch mode and the ultimate intensity out of the PS in double batch mode. Further improvements could come from a change in the transfer scheme or from an increase in the PSB energy. The ultimate intensity will be reached about one year after the connection of Linac4.

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