NEW PSB H$^-$ INJECTION AND 2 GeV TRANSFER TO THE CERN PS

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Abstract

At CERN Linac4 is being commissioned as first step in the LHC injector upgrade to provide 160 MeV H$^-$ ions. In order to fully deploy its potential, the PSB conventional multiturn injection will be replaced by a charge exchange injection. An expected brightness improvement of about a factor 2 would then be difficult to digest at PS injection due to space charge. Therefore the transfer energy between PSB and PS will be increased at the same time from 1.4 to 2 GeV. This paper describes the new PSB injection system and the status of its test stand. Modifications of the PSB extraction and recombination septa and kickers in the transfer line are shown. A new focussing structure for the transfer lines to match the horizontal dispersion at PS injection and the design of a new Eddy current septum for the PS injection are presented.

MOTIVATION

The described CERN PS Booster (PSB) upgrades - undertaken within the LHC injector upgrade (LIU) - aim at providing brighter beams for the LHC after Long Shutdown 2 (LS2) and at preparing the beams for the High Luminosity upgrade of LHC (HL-LHC) in Long Shutdown 3 (LS3).

The upgrade of the PSB injection has two main ingredients. Linac4 will provide beams at 160 MeV instead of the present beam energy of 50 MeV from Linac2. Considering the present incoherent space charge tune shift as acceptable, the intensity which can be accumulated during the multi-turn injection process can be doubled within a given emittance [1].

The second important upgrade at injection is the change from a conventional multi-turn injection of protons from Linac2 to a charge exchange injection of H$^-$ from Linac4. The injection of H$^-$ onto an already occupied phase space area allows to better tailor the brightness of the various beams used in the CERN accelerator complex. In addition, the conventional multi-turn injection process is inherently loss dominated due to the exploitation of a septum (40% loss with respect to delivered intensity by Linac2). The septum width together with the available aperture at PSB injection also limits the number of injection turns to about 13. The new H$^-$ injection will allow to significantly reduce the losses per injection turn to the order of a few percent, dominated by the stripping efficiency of the foil.

In Figures 1 and 2 the brightness limitations before and after the upgrades are compared for the standard production of the 25 ns LHC beam in the LHC injector chain [2] . Before the upgrades of its injection system, the PSB represents the limit in brightness of the LHC beams. After upgrading the PSB with the potential factor two gain in brightness, the injection into the PS would replace the PSB as the brightness bottleneck in the accelerator chain. Thus, an increase of the PS injection energy from 1.4 to 2.0 GeV is foreseen, which shall give the possibility to increase the brightness by about 60% at PS injection. In order to reach the HL-LHC beam requirements for after LS3, also upgrades concerning the SPS beam loading are required [2].

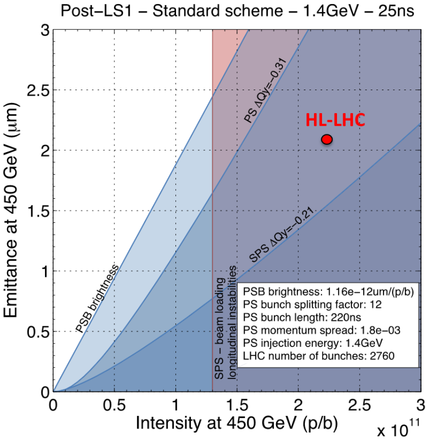

Figure 1: Emittance as a function of intensity at SPS extraction for LHC beams after LS1.

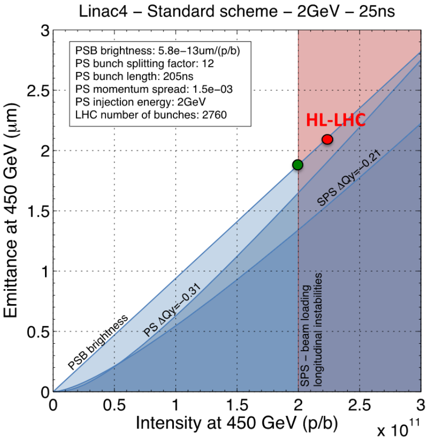

Figure 2: Emittance as a function of intensity at SPS extraction for LHC beams with the foreseen upgrades of the LHC injectors after LS2.

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PSB H^- INJECTION

Presently the PSB injection performs first a splitting of the Linac pulse into 4 beam lines which are vertically separated. Further downstream these 4 beams are horizontally injected into the 4 rings over several turns deploying a septum magnet and a varying orbit bump. The present 50 MeV beam pulse from Linac2 is deflected vertically along the pulse with different kick strengths separated by 100 ns from a staged kicker system. The kicker system consists of 5 terminated magnets which are energised by 5 PFN type generators operating at 28 kV. The first part of the pulse is not deflected and dumped on a so-called head dump within the vertical septum magnet tank. The flat part of the Linac pulse is then separated by the kickers into 4 beamlets which are deflected by a vertical steerer and three septum magnets onto the vertical position of the PSB rings 1,2 and 4. The beam for ring 3 is deflected only by the vertical steerer and passing in between the septa without further deflection. The end of the pulse sees the maximum deflection of the kicker system and is dumped on the tail dump. The parts of the pulse which overlap with the kicker rise-time are intercepted by scrapers protecting the septum coils. However, these losses are about three orders of magnitude smaller than the losses during the multiturn injection process in the horizontal plane deploying a varying bump and a septum magnet where about 40% of the injected beam is lost.

The future kicker system has to cope with a 160 MeV H^- beam which means an increase of a factor 1.9 in magnetic rigidity. In order to reach the required increase in integrated magnetic field, the magnets are short circuited inside the vacuum vessel. Since not only the beam rigidity but also the possible number of injected turns will be increased and consequently the required kicker pulse length, the beam pulse from Linac4 will not be continuous but chopped to provide gaps for the kicker field to rise. This allows for rise-times of up to 2 μs without risking to sweep this part of the beam over the downstream vertical septa allowing scrapers to be omitted. The PSB straight section occupied presently by the horizontal injection septa, injection instrumentation and one of the painting bumpers will be used to install a 4 magnet chicane bump, a foil handling system and related instrumentation within a length of 2.564 m, Fig. 3. A dump taking care of partially stripped or unstripped particles is placed directly downstream of the fourth chicane magnet. This dump is fully made of metallic components to reduce as much as possible the number of interventions and thus, the integrated radiation dose for personnel.

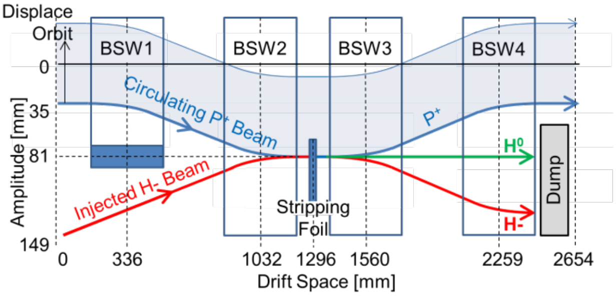

Figure 3: Configuration of the injection straight section.

A chicane bump displaces the beam by a constant 46 mm at the foil location, while a painting bump is used to vary horizontally the orbit and angle offset of the beam at the foil in order to paint in transverse phase space. Figure 4 shows the current decay in the painting magnets for LHC and high intensity beams, one turn corresponds to about 1 μs. The minimum number of required turns is defined by the longitudinal painting, which requires about 40 turns [3]. The maximum number of turns depends on the current delivered by the Linac4 source. For the nominal source current of 80 mA, a maximum number of about 100 turns is sufficient to reach the required target intensities. In case of 50 mA source current, the number of required turns will increase to 150 which is the maximum possible pulse length for all injection equipment. The transverse painting is optimised for each beam type. In case of LHC beams, no transverse painting is taking place and only foil scattering is contributing to emittance blow-up [4]. For high intensity beams, Fig. 5 and Fig. 6, the painting bump is reduced very quickly at the beginning to move the injected beam away from the centre of transverse phase space. When the injected beam has reached the outer part of phase space an almost constant plateau of the painting function with variable length is used to reach the required number of injection turns.

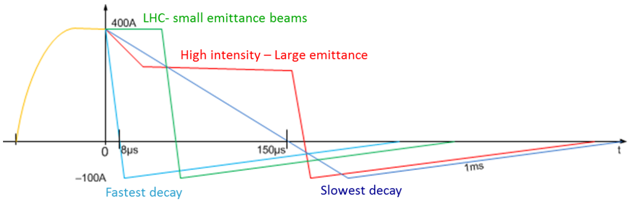

Figure 4: Current decay in painting bumpers for different beam types.

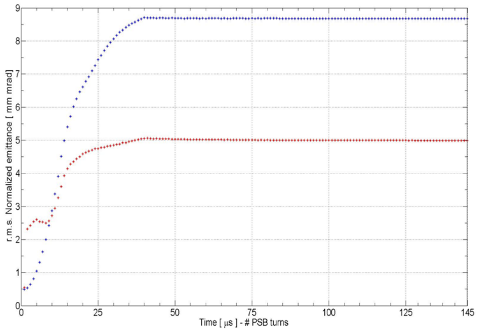

Figure 5: Horizontal (blue) and vertical (red) emittance evolution for ISOLDE fixed target beam during painting.

After injection the chicane bump is reduced to zero within 5 ms. The varying bump height during the decay generates a

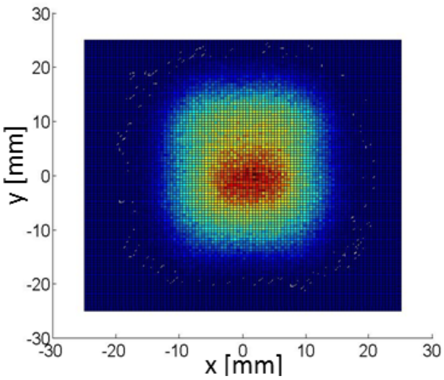

Figure 6: Real space intensity distribution of ISOLDE fixed target beam.

detuning of the machine. Two options of compensation were studied, bending magnets with rectangular or sector edge shape, with active or passive compensation. Even though at injection there is higher risk to cross a vertical resonance line, bending magnets with rectangular edge shape were chosen together with an active compensation of the varying edge focussing by trim power supplies. Also in case of sector bends vertical edge focussing cannot be avoided due to the varying beam angle with respect to the magnet edge during painting and the values of the betatron functions at the trim quadrupoles favour a correction of the vertical detuning [5]. Also multipole perturbations generated by Eddy currents induced by the varying chicane field in the vacuum chamber can be compensated [6].

Test Stand

The new injection equipment will be tested prior to commissioning in two test stands to be installed in Linac4. One setup concerns a permanent installation of the H^- stripping foil [7], Fig. 7. It is foreseen to measure the stripping efficiency at the percent level by measuring the beam current before and after the foil with a current measurement resolution of 0.1 mA. A rough estimation of the emittance growth due to foil scattering could be obtained by measuring beam profiles with SEM grids. The rigidity of foils and the foil holding mechanism can be tested as a function of many mechanical cycles. The foil control system and the foil–screen interference interlock shall be commissioned. The operation of this test stand shall start autumn 2015. The second test stand includes a temporary installation of half of the future PSB H^- injection chicane in the transfer line between Linac4 and PSB. The equipment inventory includes a stripping foil and screen unit, Fig. 8, two chicane magnets with the internal dump and the H^0/H^- current monitor. In addition there will be diamond and ionisation chamber beam loss monitors, beam current transformers, an additional screen and an external dump, Fig. 9. The full installation will be enclosed by two vacuum valves. The aim of this test is to measure more precisely the stripping efficiency deploying an H^0/H^- current monitor. The powering and controls of two chicane magnets will be tested for current stability and interlocking. The aperture, temperature and pressure behaviour of the internal H^0/H^- dump will be measured. Diamond loss monitors should allow to measure secondary particles close to the internal dump which allows to evaluate operational conditions with respect to foil degradation. These tests are foreseen to take place in 2016.

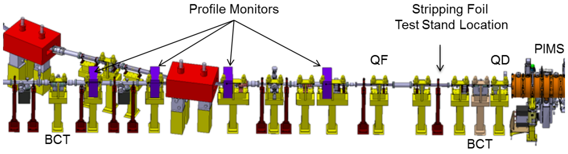

Figure 7: Layout of stripping foil test stand between Linac4 PI-Mode Structure (PIMS) and main dump.

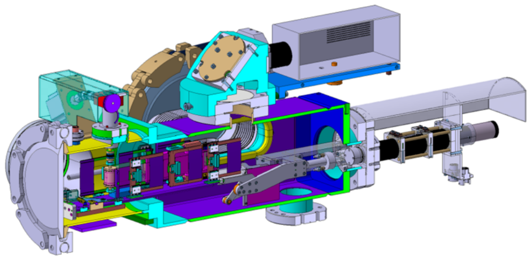

Figure 8: Cross section of the stripping foil unit design with the foil exchange mechanism and a beam observation system (BTV).

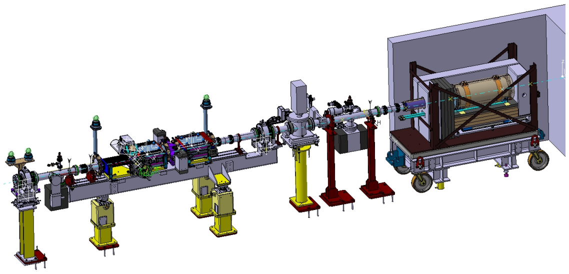

Figure 9: Layout of second test stand in the Linac4 transfer line with the external dump. Courtesy Jerome Humbert.

PSB-PS 2 GeV TRANSFER

The 2 GeV upgrade is required to keep the incoherent space charge tune shift at PS injection below 0.31. The higher injection energy is also beneficial for beams where brightness is not the figure of merit, like high-intensity fixed target (FT) beams. Those beams generate losses during the injection process which can be reduced due to the smaller beam size at 2 GeV. In order to further reduce the losses generated by these beams, the transfer between PSB and PS will be upgraded such that beams with different destinations in the accelerator chain can be transferred with dedicated

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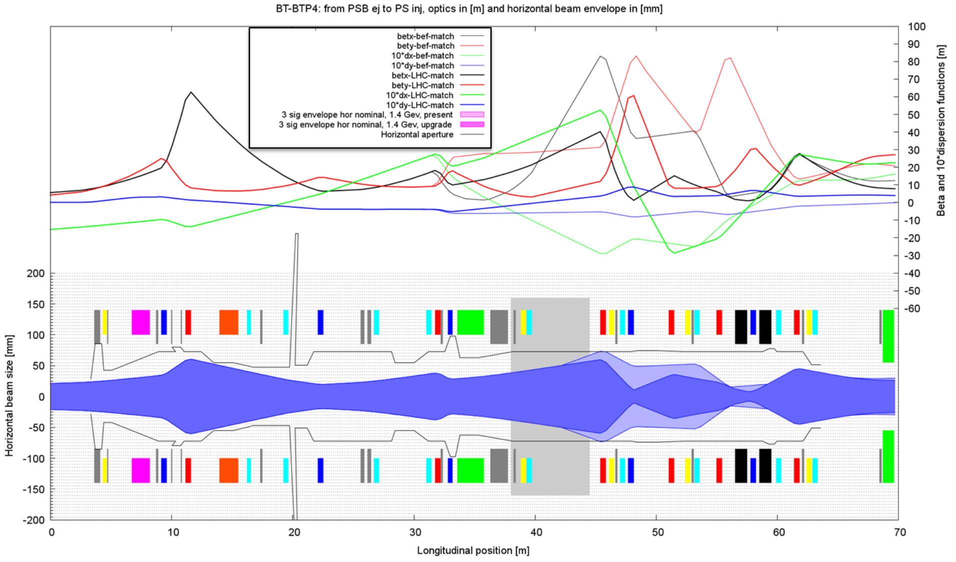

Figure 10: Optics functions from PSB ring 4 extraction to PS injection in the top part; present optics (thin lines) and proposed high-intensity FT beam optics for the upgrade (thick lines). The bottom part shows the horizontal 3 σ beam envelope for the present optics in light and for the proposed optics in dark shade. The grey line represents the physical aperture.

optics settings in the transfer line, so called pulse-to-pulse modulated operation. This flexibility in optics settings requires to partly replace quadrupoles in the transfer line with a laminated yoke design. These quadrupoles are not only replaced but also re-arranged such that the present mismatch in horizontal dispersion at PS injection can be suppressed. Thus, a source of emittance blow-up in the LHC beam production can be removed. Due to the small emittance of LHC beams, the beam fits nicely in the line aperture. The main difficulty in matching the optics for these beam types lies in keeping the minimum beam size at least at the level of the present optics to avoid space-charge effects in the line due to the increased brightness with Linac4 beams after the PSB upgrades.

In contrary to the LHC beams which are aimed to be produced with highest possible brightness, the high-intensity FT beams should be delivered with highest possible intensity – as long as they can be produced at an acceptable loss level. Due to the linear brightness behaviour of the PSB, the high intensity beams have large emittances. Thus, a dedicated optics for the FT beams aims at reducing the beam size in the separation wall between PSB and PS where a particularly long distance between quadrupoles leads to naturally high beam sizes, Fig. 10. Also at the PS injection septum the beam size was optimized with respect to the available aperture. This FT optics leads to modifications of the PS injection optics which requires additional quadrupoles in the PS.

Hardware Upgrades

All beam transfer elements between PSB extraction and PS injection have to be upgraded to cope with 2 GeV beam rigidities, while still accepting 1.4 GeV beam envelopes. For the PSB extraction kicker the operating voltage can be increased by 30%, but this will drive the field in the ferrite of the end cells 10% above the saturation limit. Measurements of the kick linearity have to be performed to validate the existing kicker for 2 GeV.

For the first recombination kicker it is foreseen to build a spare tank equipped with new magnets, install the new unit and keep the old tank as a full spare. In the second recombination kicker system, the magnets are charged with the pulse forming line. The required voltage for 2 GeV is very close to the magnet breakdown limit which means that voltage conditioning of the magnets will be necessary. In case of voltage breakdown problems, a system configuration as for the first recombination kicker will have to be adopted.

The PSB extraction septa will have a reconfigured cooling circuit and an increased bus-bar cross section to cope with the increased Joule heating for the higher required current. The recombination septa magnets will be rebuilt within the same vacuum vessels. The instrumentation presently installed inside the septa tanks will be removed and make space for longer magnets. The cross section of these magnets can remain the same [8].

The hardware of the PS injection has to be upgraded for both, kicker and septum systems. Presently the septum shares a short straight section in the PS with an injection bumper magnet. This bumper will be integrated next to the septum in the same vacuum tank. This allows increasing the septum length to deal with the 30% increase in rigidity.

Instead of a pulsed direct drive septum as presently used, an Eddy current septum option is being studied. Also the bumper shall be of an Eddy current design, Fig. 11. The improved robustness of the septum blade in case of an Eddy current septum will be at the expense of a more complicated powering scheme. The effect from the much slower decaying

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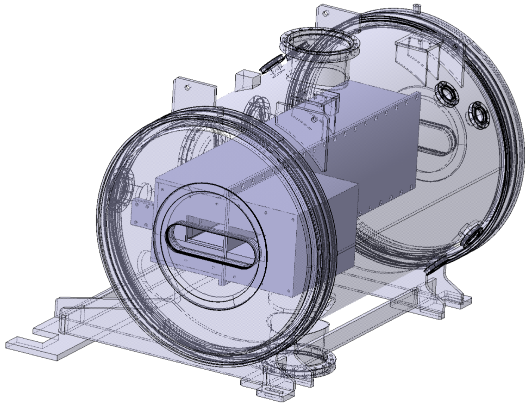

Figure 11: Assembly of PS injection Eddy current septum and bumper magnet in common vacuum vessel.

Eddy current field with respect to the main field onto the orbiting beam is studied together with an optimisation of the injection bump. Particular attention is required for the powering of the under vacuum injection bump magnet. Due to the different magnet and powering design compared to the remaining four bumper magnets, the injection bump may not be perfectly closed and generates a beating of the machine orbit during the injection process of a few hundred turns. Measurements were performed to estimate the acceptable orbit deviation and relate this value to a maximum delay of the under vacuum bumper with respect to the bumper magnets outside vacuum. The delay of one injection bumper was changed in steps of 10 μs and the peak-to-peak orbit variation recorded from turn-by-turn position monitors. The same situation was simulated with MADX. Figure 12 shows a good agreement between measured and simulated data. For delays within $\pm 20\mu$s the measurement is dominated by the injection kicker flattop ripple.

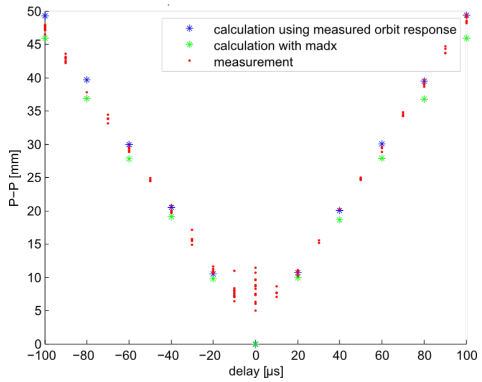

Figure 12: Peak-to-peak orbit variation for different delays of one injection bumper. Measurement of beam position in the ring (red), calculated beam position using real orbit response from four bumpers (blue) and MADX simulation (green).

The present PS injection kicker system allows to inject LHC beams also at 2 GeV by short-circuiting the magnets. However, this increases the kicker flattop ripple by about 10% compared to the terminated mode. Also, high-intensity beams cannot be injected with short circuit mode due to their shorter bunch spacing. For the upgrade it is foreseen to either install a second kicker system 180^o downstream of the present injection kicker to compensate for the remaining kick due to the increased beam rigidity, or to rebuild the existing kicker system for the future rise-time and kick requirements.

SUMMARY

In order to fully deploy the beam brightness potential from Linac4 H$^-$ beams at 160 MeV, major upgrades of the beam transfer systems for PSB and PS are foreseen in LS2. The conventional multi-turn injection system of the PSB will be replaced by a charge exchange injection system. This shall significantly reduce the losses at injection and allow for more flexibility in tailoring target emittances for different beam types. Preparations for a test stand to validate the required equipment are ongoing with the aim for measurements in 2016.

In order to digest the beams from Linac4 and PSB, the PS requires an increase in injection energy to reduce space charge detuning. Consequently, all beam transfer elements between PSB extraction and PS injection will be upgraded for 2 GeV beams. The focussing structure in the transfer line between PSB and PS will be modified in order to provide dedicated optics settings for high brightness LHC and high intensity fixed target beams.

REFERENCES

[1] K. Hanke et al., "PS Booster Energy Upgrade Feasibility Study First Report " CERN, Geneva, Switzerland, 2010 `https://edms.cern.ch/document/1082646/3`

[2] G. Rumolo et al., "Protons: Baseline and Alternatives, Studies Plans" LHC Performance Workshop, Chamonix, 2014, `https://indico.cern.ch/event/315665/session/5/contribution/21/material/paper/0.pdf`

[3] C. Bracco et al., "PSB injection: Beam Dynamics Studies" LIU Day, CERN, Geneva, Switzerland, 2014, `https://indico.cern.ch/event/299470/session/1/contribution/8/material/slides/0.pptx`

[4] E. Benedetto et al., "Transverse Emittance Preservation Studies for the CERN PS Booster Upgrade", THO4LR05, Proc. HB2014, East Lansing, USA (2014).

[5] M. Aiba et al., "Assessment of CERN PSB Performance with Linac4 by Simulations of Beams with Strong Direct Space Charge Effects" Proceedings of IPAC'10, Kyoto, Japan.

[6] E. Benedetto et al., "Detailed Magnetic Model Simulations of the H$^-$ Injection Chicane Magnets for the CERN PS Booster Upgrade, including Eddy Currents, and Influence on Beam Dynamics", TUPRI027, IPAC'14, Dresden, Germany (2014).

[7] W. Weterings et al., "The Stripping Foil Test Stand in the Linac4 Transfer Line", INTDS14, JRNC-D-14-00919, to be published.

[8] J.L. Abelleira et al., "Progress in the Upgrade of the CERN PS Booster Recombination", MOPAB02, Proc. HB2014, East Lansing, USA (2014).