LONG-TERM BEAM LOSSES IN THE CERN INJECTOR CHAIN

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Abstract

For the production of the LHC type beams, but also for the high intensity ones, the budget allocated to losses in the CERN injector chain is maintained as tight as possible, in particular to keep as low as possible the activation of the different machine elements. Various beam dynamics effects, like for example beam interaction with betatronic resonances, beam instabilities, but also reduced efficiency of the RF capture processes or RF noise, can produce losses even on a very long time scale. The main different mechanisms producing long term losses observed in the CERN injectors, and their cure or mitigation, will be revised.

INTRODUCTION

The three synchrotrons forming the CERN LHC injector chain, namely the PSB (PS Booster), the PS (Proton Synchrotron) and the SPS (Super Proton Synchrotron), were built in laps of time of about 20 years with the goal of providing the largest variety of beams to the physics user community, thus leading to the implementation of very versatile machines. The PS was built as a sort of prototype machine in the late 50s and it is the first proton synchrotron with strong focusing ever operating [1]. The PSB was built to increase the PS injection energy from the 50 MeV of the Linac1 to 800 MeV. Then in the course of the CERN history, the extraction energy was increased first to 1 GeV, then to 1.4 GeV [2] and finally it will be upgraded to 2 GeV [3], with the goal of reducing the effect of direct space charge at PS injection. For the very same reason, the injection energy of the PSB is going to be increased from the 50 MeV of the proton Linac2 to the future 160 MeV provided by the H^- Linac4. The last in the chain, the SPS, was built to produce high intensity beams for fixed target physics [4], but then was transformed first into a proton-antiproton collider, then – as the PS – into a lepton injector for LEP, and finally – as the PSB and the PS – is today operating as LHC injector.

All the three machines are producing two main families of beam types: high brightness beams for the collider, high intensity beams either for the following machine or for fixed target local users. The goal of this paper is to present a review of the loss mechanisms identified and eventually limiting the production of these two categories. Special attention will be given to the losses appearing on very long time scale, up to few hundreds ms or few thousand turns, considering that the synchrotrons magnetic cycles last few seconds. Some details are also given to the injection and extraction processes and related losses.

LHC Beam Production Schemes

The LHC collider operates for luminosity production with two different bunch spacing, either 50 ns or 25 ns, the latter being the nominal configuration. The role of the injectors in the beam production is as follows: the PSB defines the initial transverse emittances, the PS the bunch spacing whereas in the SPS, on top of adapting the bunch length to the longitudinal acceptance of the LHC, tails in the transverse plane are scraped to avoid eccessive losses during the LHC filling process.

The production of the 25 ns bunch spacing beam is realized as follows. Linac2, or Linac4 in the future, fills each of the 4 PSB rings into h=1+2 bucket. Each PSB bunch is injected to the PS on $h = 7$ and after 1.2 s, the PS receives two other PSB bunches. A first acceleration takes place up to 2.5 GeV, where the bunches triple split. Eighteen bunches are accelerated up to 26 GeV/c on h=21 where two consecutive double splittings produce the final bunch spacing of 25 ns creating a batch of 72 bunches. The 50 ns spacing is realised by eliminating the last splitting. Prior to the transfer to the SPS, the bunches are rotated in the longitudinal plane to reduce the total bunch length to about 4 ns. Up to five consecutive batches of 72 bunches can be injected in the SPS at 26 GeV/c, and accelerated to 450 GeV/c to be delivered to the LHC. The longitudinal emittance is increased in the PS and SPS to reduce longitudinal instabilities, whereas transverse scraping is done in the SPS before reaching the extraction energy to eliminate tails. Besides the classical production scheme, alternative ones were proposed to overcome the current brightness limitation of the PSB. One realised during the 2012 run is BCMS (Batch Compression Merging and Splittings). It comprises the injection of 2×4 bunches on the 9th harmonic in the PS, batch compression from h=9 to h=14, bunch merging followed by a triple splitting all done at low energy instead of the triple splitting only. These evolved RF gymnastics are performed at an intermediate kinetic energy to avoid transverse emittance blow up due to space charge and to relax the requirements on the longitudinal emittance at injection. The resulting 12 bunches are accelerated to the extraction flat top where two bunch splittings occur to obtain the final 25 ns bunch spacing as for the nominal scheme. The advantage with respect to the traditional scheme results from the smaller splitting factor of the PSB bunches (6 instead of 12). Before extraction to the SPS, 25 ns spaced bunches can have the same intensity in only half of the transverse emittance. Typical beam parameters realised for the 25 ns beam and expected after the injector upgrade within the LIU (LHC Injector Upgrade)

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Table 1: Proton Beam Parameters for LHC and Neutrino Production Beams. The asterisk (*) indicates that feasibility including operational viability (especially in the PS) remains to be demonstrated.

	Operation		**Record**		**After LIU (2020)**	
					Aim	**Study**
	LHC	**CNGS**	**LHC**	**CNGS**	**LHC**	**post-CNGS**
SPS beam energy [GeV]	450	400	450	400	450	400
Bunch spacing [ns]	50	5	25	5	25	5
Bunch intensity [10^{11}]	1.6	0.105	1.3	0.13	2.5	0.17
Number of bunches	144	4200	288	4200	288	4200
SPS beam intensity [10^{13}]	2.3	4.4	3.75	5.3	6.35	7.0(*)
PS beam intensity [10^{13}]	0.6	2.3	1.0	3.0	1.95	4.0(*)
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2/2.4(*)
SPS cycle length [s]	22.8	6.0	21.6	6.0	21.6	6.0/7.2
PS momentum [GeV/c]	26	14	26	14	26	14

program [5], together with the ones for the high intensity beams, are presented in table 1.

High Intensity Beam Production Schemes

High intensity multi-bunch beams for fixed target physics at the SPS were regularly produced until 2012, in particular for the CNGS (CERN Neutrinos to Gran Sasso) [6] experiment now concluded. Table 1, summarises the last beam performances and the study case for a Laguna [7]-type high-intensity neutrino production beam. Two bunches per PSB ring, operating on h=2, are injected in the PS into buckets at harmonic h=8. After a first acceleration, a double bunch splitting takes place at 3.5 GeV/c and acceleration to the final 14 GeV/c extraction momentum is done on h = 16 harmonics. Finally, prior to extraction, the beam is debunched to allow imposing a 200 MHz structure before extraction for the recapture in the SPS. The extraction is realised on five consecutive turns, either using the so called CT [8, 9] (Continuous Transfer) technique or, in the near future, using the MTE (Multi-Turn) extraction [10]. Thus, two consecutive 1.2 s long PS cycles, with 5-turn extraction each, are used to fill the 10/11th of the SPS circumference. In the SPS, after re-capture at 14 GeV/c, the beam is accelerated up to 400 GeV, thus crosses transition at about 22.8 GeV and in the case of the CNGS, the machine is emptied on two consecutive extractions of about half machine separated by 46 ms.

The injector complex is also producing high intensity beams delivered at low energy either by the PSB or by the PS. The maximum intensity produced by the PSB, about 10^{13} p per ring, is delivered to the ISOLDE target for rare isotope production [11]. In this case the PSB takes the maximum current deliverable by the Linac2 per ring. For the PS, a single bunch high intensity beam used for the nTOF experiment is delivered to a lead target to study the interaction of neutrons with different materials [12].

LOSSES FOR LHC BEAMS

The double injection in the PS is needed to maximize the number of bunches after the longitudinal splitting, requiring also very high intensity injected in the PSB. Every PSB bunch is split up to 12 times to get finally 72 bunches at 25 ns spacing at PS extraction. This requires Linac2 to inject a high intensity beam with a limited brillance, due to the multi-turn injection process and large space-charge. The direct space-charge tune shift in the PSB, considering the typical LHC beam parameters, can be as large as ($|\Delta Q_x|$=0.51, $|\Delta Q_y|$= 0.61) [13]. Clearly, a certain number of resonances is crossed during the injection process: being the injection on a non-zero dB/dt , the effect on the beam is reduced. The tunes at injection are about $Q_x \approx 4.4$ and $Q_y \approx 4.5$, to reduce the interplay between the beam and the integer resonance. During acceleration the working point is moved dynamically towards the design value of about Q_x= 4.17 and Q_y=4.23, thanks to the reduction of the indirect space-charge neck tie. A very detailed study of space charge effects can be found in [14] and the discussion on emittance preservation is presented in [15], whereas resonance compensation studies can be found in [16]. Once the first batch is injected into the PS, there is a 1.2 s long waiting time on the PS flat bottom before the second injection. During this period the beam has a very large tune spread induced by the direct space charge, in the vertical plane up to |0.3|, while the synchrotron period is of the order of 1 ms and the chromaticity is very large (-0.8, -1) and uncorrected. The beam, due to the synchrotron motion, crosses several times the integer and the $4q_y$=1 resonance, creating transverse emittance increase and beam losses. While the presence of the integer is pretty obvious, the fourth order resonance seems to be the result of the coupling of space-charge with one of the structure resonances, either the $4Q_y$=25 or $8Q_y$=50, being the machine tune 6.25 and the machine periodicity either 25 or 50 [17–19]. The space charge limitation is reduced, for the fourth time in the PS history, with the future increase of the injection energy, this time from 1.4 GeV to 2 GeV. Other techniques like breaking the symmetry of the lattice as proposed in [18], or fully coupling the horizontal and vertical plane to create vertical dispersion, or using flat bunches (both described in [13]), are under investigation to create some margin for the space charge limit.

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Headtail instabilities of mode 5 or 6 also appear during the long injection flat bottom. They are currently cured by introducing linear coupling by dedicated skew quadrupoles and forcing the tune close to the coupling resonance [20]. This solution, however, firstly creates round beams, secondly forces the transverse working point in a well defined region. In the future, the transverse damper [21] will be probably preferred to the linear coupling, adding some flexibility to the choice of the working point. A chromaticity correction will be also introduced, to reduce the frequency range at which the damper has to act, but also to eventually mitigate the losses due to space charge coming from the multiple crossing of the betatronic resonances due to the synchrotron motion.

After the triple splitting, the beam is accelerated and right after transition crossing, coupled bunch longitudinal instabilities are observed [22]. The consequences are beam losses and a significant variation of longitundinal emittance, intensity and bunch length along the extracted batch. This lack of reproducibility is an issue, creating capture losses up to 1-2% in the SPS. This limitation should be eliminated thanks to the use of a longitudinal damper, a function provided by a newly installed Finemet© cavity [23]. Electron cloud is regularly observed on the extraction flat top, even if there is no evident sign that the beam quality is affected. There is instead a clear horizontal instability appearing, together with electron cloud, if the bunches are shorter than nominal or if the beam is kept artificially in the machine 50 ms longer than necessary [24, 25]. In case this becomes a limitation for the future beams, it was shown that the transverse damper can effectively delay the instability by about 10 ms [21] or eventually the adjustment of the bunch length at extraction by a reduction of the cavity voltage might be beneficial [25]. Close to the extraction, the bunches are rotated longitudinally to fit the bucket length of 5 ns of the SPS. Despite the fact that the beam transfer is bunch-to-bucket, the bunch rotation can create long tails in dp/p, that are not properly recaptured in the 200 MHz bucket of the SPS. Losses are thus observed during the capture process, as presented in [26]. The cure in this case would be the increase of the voltage available for the 40 MHz system used for the first bunch shortening [26]. Once the beam is transferred, the first limitations appearing in the SPS cames again from the long waiting time at flat bottom due to the multiple injections (up to 5 from the PS), followed by the lack of RF power during acceleration and at flat top. Space-charge is limiting the maximum brightness at injection, bounding for the moment the maximum acceptable direct space-charge tune shift to about ΔQ_x = -0.11 and ΔQ_y=-0.20 [5].

Transverse Mode Coupling Instability (TMCI) used to limit significantly the maximum intensity of the single bunch beams to 1.6×10^{11} p/b for a longitudinal emittance of 0.35 eVs. The introduction of a new special optics, changing γ_{tr} from 22.8 to 18 and thus increasing the slip factor $\eta = 1/\gamma_{tr}^2 - 1/\gamma^2$ all along acceleration, pushed the TMCI limit at 4.5×10^{11} p/b [27], well beyond the needs even of the future HL-LHC type beams. Another major limitation of the SPS could be caused by electron cloud effects resulting in pressure rise, beam instabilities, emittance growth and losses. It is commonly accepted that either scrubbing, or coating with aC [28] all or a part of the vacuum chambers, or a combination of both will solve the electron cloud issue [5]. Recent studies proved that the scrubbing can be improved by using a special doublet beam, where the beam is composed of trains of 2 bunches spaced by 5 ns and these doublets are in turn separated by 20 ns. Experiments and simulations showed a net improvement of the secondary emission yield threshold with respect to the nominal 25 ns beam used for the scrubbing [5]. During the acceleration, done with the 200 MHz system alone, the beam becomes longitudinally unstable for an intensity of about 2-3 $\times10^{10}$ p/b, well below the performances required for the LHC beam production. This instability is mitigated by the 800 MHz RF system operating in bunch-shortening mode and a significant controlled longitudinal emittance blow up from 0.35 eVs to 0.5 eVs done with the 200 MHz system. On top of that, there is a clear lack of RF power available to maintain the high intensity bunches sufficiently short, of the order of 1.5 ns, to be transferred to the LHC 400 MHz system and without causing capture losses in the collider. The solution proposed to overcome this limitation is the upgrade of the 200 MHz system, with an increase of the available RF power by at least a factor of 2 obtained by increasing the number of cavity modules and by rearranging sections to reduce the impedance by about 20%. Once the full upgrade of the 200 MHz system will take place the maximum available power for the 2 longest (4 sections) cavities would be instead about 1.6 MW, bringing the maximum intensity per bunch up to 2.0×10^{11} p/b for 25 ns without any performance degradation [23, 29, 30] in the hypothesis that no new beam instabilities would appear in the new working regime.

LOSSES FOR HIGH INTENSITY BEAMS

The losses during the CNGS-like beam production are particularly concentrated in the PS and the SPS. The PSB, designed with the margin necessary to produce high intensity beams, does not suffer from any particular limitations. A detailed analysis of source of losses and impact on the different machine devices can be found in [31], whereas a more specific work related to the PS can be found in [32]. A report on the most recent intensity record realised by the injectors complex can be found in [33]. The PSB injection from the Linac2 causes losses of the order of 30-40%, not unusual as result of the transverse painting and longitudinal adiabatic capture. They are considered acceptable because limited at 50 MeV, with a very good beam transmission up to extraction. The H^- injection scheme and chopping from Linac4 will greatly improve injection losses to only few percents. Small losses are observed during the fast extraction process in correspondence to the extraction septum. The transverse damper is always active during acceleration to avoid the development of a headtail instability [34]. Once the beam is injected into the PS, in a bunch-to-bucket transfert,

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large transverse beam losses of the order of 5% are observed during the first few ms. The results of studies realized in past years [35,36] proved that the high beam losses observed during the first few hundred turns are related to two different mechanisms. Losses appearing during the first few turns are caused by a too small aperture of the injection septum, considering the transverse emittances that the PSB can deliver at 1.4 GeV. Losses appearing on a longer time scale, few hundred turns, are caused by intra-bunch injection oscillations, resulting from the effect of indirect space combined with the presence of unavoidable injection errors.This mechanism is enhanced by the fact that the PSB is composed of 4 vertically superposed rings, and that the 8 bunches can feature 4 different trajectories. Furthermore, the presence in the PS of the horizontal injection bump reduces also the available aperture for about 500 turns while the beam is oscillating in the vertical plane. It was experimentally proved that the injection oscillations can be effectively eliminated by the transverse damper, as described in [36,37]. The accelerating RF system of the PS is composed of ferrite loaded cavities tunable from 2.8 MHz to 10 MHz which was installed in the early 1970s [38]. Longitudinal losses were identified during acceleration for intensities beyond 3.5×10^{13} p/b, in particular at transition crossing, where the RF-phase jump takes place. A single bunch transverse instability at transition crossing, a vertical TMCI, appears for single bunch intensities of about 6×10^{12} p/b and causes losses of the order of few percent [35,39]. TMCI appears as an intrabunch vertical oscillation with a central frequency of 700 MHz driven by a broadband impedance source. This frequency range is well beyond the capabilities of the existing transverse damper, whose bandwidth is limited today to about 23 MHz. According to preliminary results [40], the driving impedance has been identified as generated by the several kickers installed in the PS ring. Currently the solution adopted to avoid this instability is a significant increase of the longitudinal emittance [41]. Losses at extraction, taking place on few turns, are due to the CT extraction technique [8]. The horizontal fractional tune is set to 0.25, and the beam is cut in 5 equally populated slices on 5 consecutive turns by shaving it with an electrostatic septum. Each portion of the beam cut by the septum is extracted in one turn. Losses appearing during the shaving process and dispersed along the entire machine circumference are due to the interaction with the beam and the blade of the electrostatic septum [9]. About 10% of the total circulating intensity is lost, causing significant machine activation. A new extraction technique, MTE [10], should definitely replace during the 2014 run the CT extraction, thus reducing significantly the losses at the extraction, from a maximum of 10% to about 1-2%, as proven during a brief part of the CNGS run [42]. The MTE extraction is based on beam trapping in stable islands of the transverse phase-space [10]: the beam is split in five beamlets by crossing of a fourth-order resonance and, once sufficiently separated in the horizontal plane, each beamlet is extracted on five consecutive PS turns. The adiabaticity of the trapping process requires a long extraction flat top. The losses during the MTE extraction are produced, as expected, by the fact that the beam has to be transferred de-bunched from the PS and SPS. A portion of the beam intercepts the blade of the extraction septum during the kicker rise time causing unavoidable losses. A passive device, called dummy septum, was installed in 2013 to protect the extraction septum by intercepting these particles in the straight section before the extraction point [43]. The commissioning of the device should be concluded by the end of 2014. The beam is then transferred at 14 GeV/c to the SPS with a double batch injection, with observed losses up to 10%. Injection losses are both transverse and longitudinal. Considering the transverse plane, the CT extraction cannot produce 5 equally populated slices with the same transverse emittances [10]. If on one side, the horizontal transverse emittance is reduced by the extraction process by a factor of three and becomes significantly smaller than the vertical, on the other side it is very difficult to have a unique optics to minimise the mismatch at SPS injection of the 5 slices [44]. An emittance exchange section is installed in the transfer line between the PS and the SPS to take advantage of the smaller horizontal emittance resulting from the CT extraction, and transforming it into the vertical being the SPS mechanical aperture smaller in the vertical plane. On top of this, fast kickers are installed in the same line to correct the trajectory of each beam portion, as described in [45], and thus minimise injection oscillations that might be different depending on the PS extracted turn. The SPS transverse damper has to be active since the beginning to reduce the injection oscillations which are clearly PS-turn dependent and a transverse coupled bunch instabilities caused by resistive wall (dipole modes) [46]. Longitudinal losses are observed already at injection. Certainly one of the main causes is the fact that the transfer between PS and SPS is not bunch-to-bucket. In the SPS, the recapturing process has some inefficiencies, causing losses also during the second PS injection. The capture is done using the main 200 MHz system at 800 kV, which gives the best beam transmission. A part of the un-captured beam is filling the empty gap between two PS injections, i.e. the 1/11th of the machine left empty on purpose for the rise time of the extraction kickers. A first fraction of this beam is lost at the beginning of the acceleration, the second unfortunately eventually at high energy if not properly cleaned by the transverse damper used as abort cleaning device. Transition crossing is another critical moment in the accelerating cycle in the SPS, where the usual phase jump occurs but no gamma transition scheme is implemented as in the PS. Typical losses through transition at high intensity were around 7% for settings not optimised for very high intensities. During past operation, the maximum available voltage was used due to uncontrolled emittance blowup during transition crossing and any voltage reduction led to beam losses. A careful adjustment of the voltage program of the 200 MHz cavities and of the one-turn-delay feedback system could improve the situation, but this requires continuous monitoring of the longitudinal beam parameters, depending also on the beam quality received from the PS. Slow losses were observed also during acceleration after transition. A review of the longitudinal studies for the preparation of the CNGS production can be found in [47]. The improvements proposed to reduce longitudinal losses are: a) realise a separate capture of each PS batch in the SPS (possible due to large bandwidth of the main 200 MHz TW RF system) that would allow voltage capture modulation (0.8 MV increased to 2.5 MV); b) implement a variable gain of 1-turn-delay feedback and upgrade of the frequency range of the feed-forward system below transition energy. All of these will be realised in 2020 in the framework of the LHC Injector Upgrade Program. The 800 MHz upgrade will place in 2014, with a new feed-forward and feed-back system and could be used to improve the longitudinal Landau damping.

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