SLHC-PP

MILESTONE REPORT

EU MILESTONE: 5.1

Document identifier:	**SLHC-PP-M5.1-982404 -v1.0**
Contractual Date of Delivery to the EC	**End of Month 12 (March 2009)**
Actual Date of Delivery to the EC	**30/3/2009**
Document date:	**25/3/2009**
Milestone Title:	**Compilation and evaluation of design parameters and details relevant for the assessment of radiological impact; Identification of critical parameters and potential design constraints.**
Work package:	**WP5: Radiation protection and safety issues for accelerator and experiments**
Lead Beneficiary:	**CERN**
Authors:	**H.G. Menzel and T. Otto**
Document status:	**Released**
Document link:	https://edms.cern.ch/document/982404/1

History of Changes

Version	Date	Comment	Authors
1.0	-	-	-

The Preparatory Phase of the Large Hadron Collider upgrade (SLHC-PP) is a project co-funded by the European Commission in its 7th Framework Programme under the Grant Agreement n° 212114. SLHC-PP began in April 2008 and will run for 3 years.

SLHC-PP Milestone 5.1: Compilation and evaluation of design parameters and details relevant for the assessment of radiological impact; Identification of critical parameters and potential design constraints.

Meeting with stakeholders in accelerator and experiments, to define an agreement on design parameters

Due: M12 (before March 31st, 2009)

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1. INTRODUCTION

The purpose of this report is to review all accelerators forming the injector chain into the sLHC for points where higher-than-usual radiation levels may occur. Once these points have been identified, the radiation protection aspects of their design can be addressed already in the conceptual design stage of the accelerators.

Figure 1 shows, schematically, the present injector chain and the envisaged upgrades for sLHC and other future colliders.

In its present version, this report is limited to a review of beam loss in LINAC 4, the PS Booster (PSB), PS2 and an upgraded SPS.

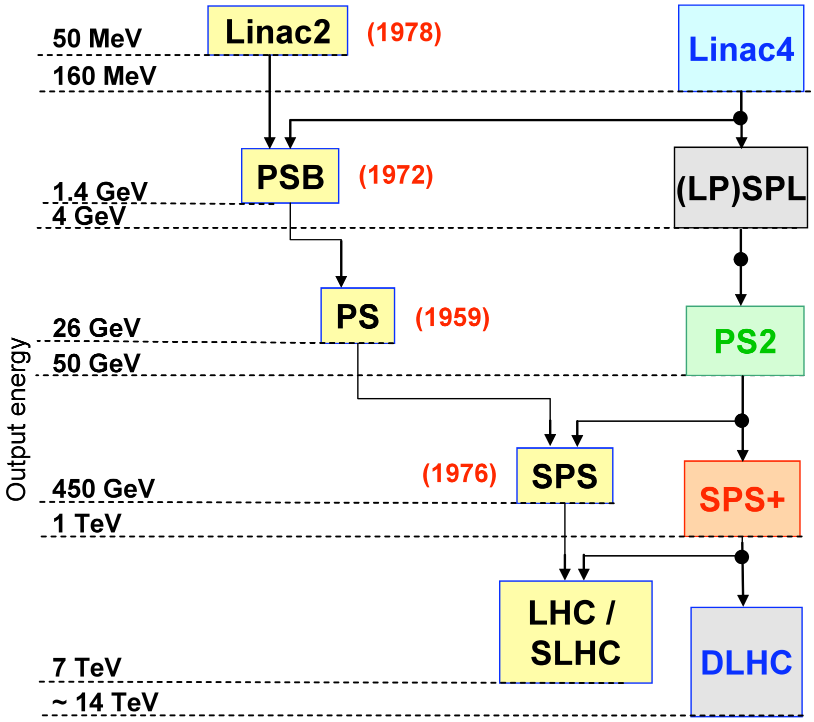

Figure 1: Existing accelerators (in yellow on the left) including the LHC or sLHC, and the components of the new injector chain. On the left edge of the scheme the terminal energy of each accelerator is noted.

2. LINAC 4

LINAC 4, the first part of CERN's injector chain, is a linear proton accelerator with a terminal energy of 160 MeV. In 2007, Council approved the construction of LINAC 4 as an injector to the Proton Synchrotron Booster (PSB), in replacement of LINAC 2. Connection to the PSB and commissioning are foreseen during a long winter shutdown from Nov. 2013 until June 2014, at the same time when the inner triplet magnets at ATLAS and CMS will be replaced by the Phase-1 upgrades. LINAC 4 is built with a large flexibility in view of future extensions of CERN's accelerator park. It can be easily upgraded to serve as an injector to the low-power Super Proton Linac (lp-SPL) where it would deliver 2.5 times as many protons at 160 MeV. A more complex upgrade would make LINAC 4 the injector to the (full power) SPL, with a 140-fold increase in beam power.

In order to preserve all options, the LINAC 4 underground structures are constructed from the beginning so that no upgrade of the building would be necessary for future upgrades of the accelerator. This means that the building is over-shielded for the use of LINAC 4 as a low-power injector. In addition, the LINAC 4 accelerator is optimized for beam losses. Even as an injector to the SPL, the average linear beam loss will have a power of less than 1 W per meter. With low-power operation either into the PSB or the lp-SPL, the intensity of beam loss will be one or two orders of magnitude lower than this figure (estimated fractional loss rate of 1.5 10^{-5} per meter). Prompt ambient dose rates either in the Klystron hall on top of the accelerator tunnel or in the publicly accessible areas will be significantly lower than the relevant ambient dose equivalent constraints.

Table 1: Operational parameters of LINAC 4

	Linac 4 operates as injector to …		
	PSB	**lp-SPL**	**SPL**
Pulse repetition	1.1 Hz	2 Hz	50 Hz
Pulse duration	0.4 ms	1.2 ms	1.2 ms
Pulse current	40 mA	20 mA	40 mA max.
Protons / Pulse	1 E14	1.5 E14	3.0 E14
Protons / s	1.1 E14	3.0 E14	1.5 E16
Power @ 160 MeV	1.1 kW	3.0 kW	150 kW

Conclusion: Due to its construction as a high-power proton injector, operation of LINAC 4 as an pre-injector for sLHC does not pose any specific radiation hazards which must be addressed in the frame of the sLHC preparatory phase study.

3. PSB (FROM 2014 UNTIL COMMISSIONING OF LPSPL, PS2)

3.1. BEAM TRANSFER AND INJECTION

Until commissioning of a new accelerator following the LINAC 4, for example the low-power SPL, protons will be injected into the PS Booster at E = 160 MeV. LINAC 4 will send a beam of negative hydrogen ions H^- by a special transfer line to the PSB. The injection schema of H^- ions by stripping two electrons is inherently more efficient. Capture losses will be reduced with respect to the present injection scheme and they will be localized in the injection region. This advantage is partially cancelled by the higher energy of the protons from LINAC 4 (160 MeV instead of 50 MeV). A particularity of the PS Booster is its construction with 4 identical accelerator rings. This requires distribution of the incoming H^--pulses by a beam distributor and a magnetic septum. The stripping foil mechanism and neutral dump have to be built in four exemplars, one for each of the PSB rings.

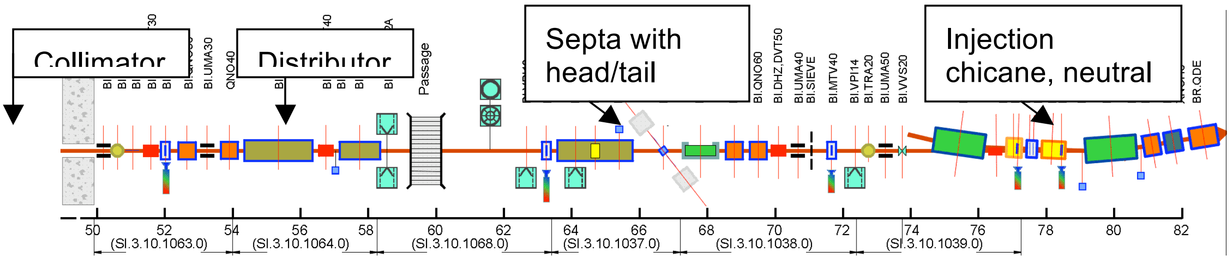

Figure 2: Schematic view of the PSB injection region. Protons travel from left to right. The PSB can be recognized by the curved arrangement of the bending dipoles (green). The main elements where beam loss may occur are indicated.

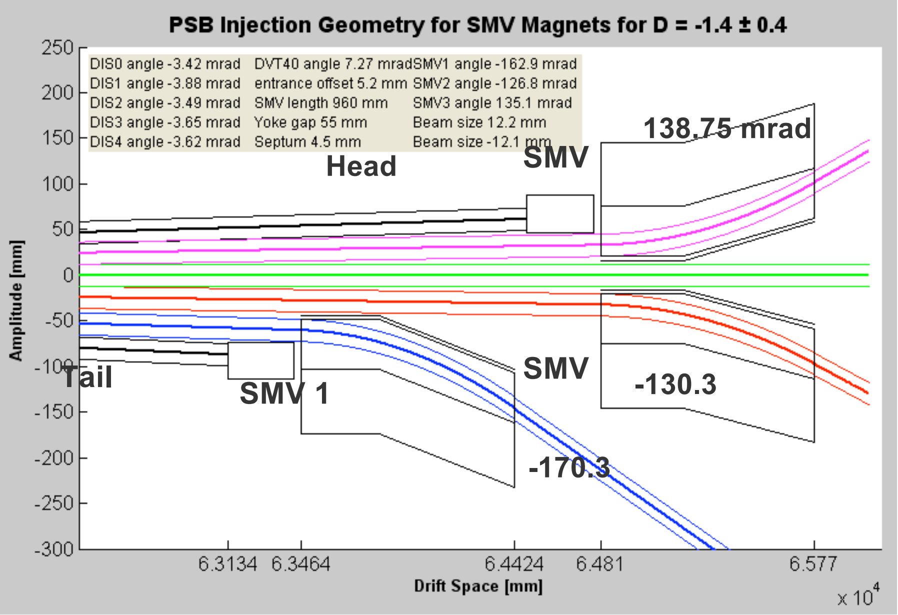

Figure 3: Schematic beam optics in the magnetic septa. The position of the head- and tail dumps are indicated.

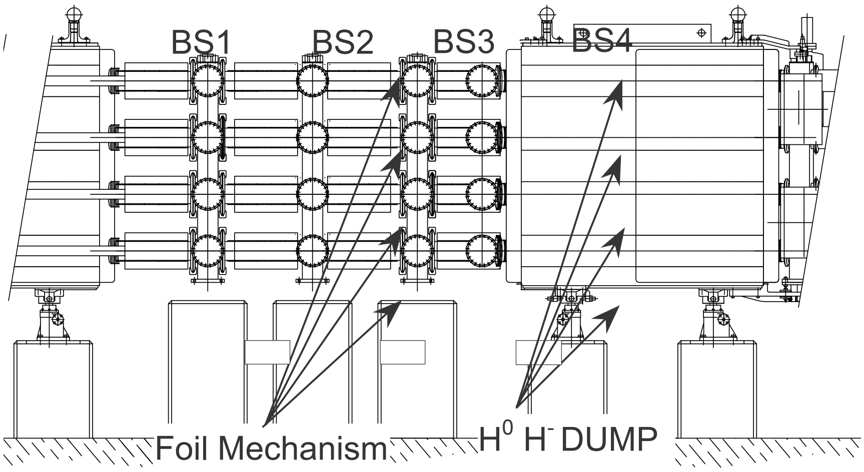

Figure 4: Side view of the injection chicane in the PS Booster. Note the four-fold foil mechanism and H^0/H^- -dump, one for each PSB ring. Secondary radiation from the dumps will affect the dipoles from the injection chicane as well as the PSB main dipole (to the right). During maintenance, radiation from the strongly activated area around the dumps will expose maintenance personnel.

The beam pulses from the LINAC 4 will have a finite rise- and fall time, caused by the beam chopper and by the accelerating radiofrequency fields. Because the particles in the head- and tail of the beam pulse do not have the nominal momentum, they will not be transported on the same path as nominal particles. The beam transfer and injection system from LINAC 4 to PSB foresees the following elements intercepting the beam: a collimator in the transfer line, absorbing off-momentum protons, a head- and tail dump in the magnetic septum, and a neutral particle dump following the injection chicane, absorbing those particles where the charge transfer was incomplete. Table 2 lists the beam line elements on which losses occur together with the instantaneous beam load and the cumulated number of lost protons in one year.

Table 2: Elements in the transfer- and injection region of LINAC 4 to the PS Booster and conservative estimates of associated beam loss. The energy of the protons is 160 MeV. The loss figures in the first two lines are quoted for conservative estimates of off-momentum particles in the head and tail of each pulse.

Beam line element	**Remark**	**Load [W]**	**Beam loss [p^+/y]**
Collimator, Head Dump	Duration 60 µs	213	$1.44\cdot10^{20}$
Tail Dump	Duration 20 µs	71	$4.8\cdot10^{19}$
H0/H- dump	2 % unstripped	14.2	$1.04\cdot10^{19}$

The instantaneous beam powers on the dumps/ absorbers will not require active cooling. With exception of the collimator in the transfer line, beam loss in the injection region into PSB will occur in areas which are already occupied by elements. While the dumps are passive objects not requiring maintenance, it will be difficult to geometrically separate them from other, existing or modified elements in the beam line with the need for regular maintenance, for example the septa magnets in the distributor and the dipoles in the injection chicane.

The design of the beam dumps must integrate options for quick dismantling or for removable local shielding during stops and shutdown.

Conclusion: the design of the transfer-collimation and injection regions of the PS Booster must take into account radiation protection considerations in order to avoid high individual and collective doses during maintenance after their commissioning.

4. PS2

In the new LHC injector chain, PS2 will accelerate the beam from the lp-SPL (or an alternative accelerator following LINAC 4) to an energy of 50 GeV for transferring it to the SPS. In the time between LHC fills, PS2 will accelerate and transfer beams to the SPS for fixed target experiments, or it supplies a dedicated experimental area with proton beams of 50 GeV.

The PS2 synchrotron is approximately twice as long as the PS (1300 m), and protons reach twice the end energy. In the PS2, the LHC beam will contain 4 10^{11} p^+ /bunch with 25 ns bunch spacing. One pulse will contain 3.2 10^{13} protons. The beam power in PS2 at 50 GeV will reach 100 kW.

Table 3: Main operation parameters of PS2 in comparison to the present PS accelerator.

Beam Parameter	**PS (LHC)**	**PS (FT)**	**PS2 (LHC)**	**PS2 (FT)**
E_{kin} (injection) (GeV)	1.4	1.4	4	4
E_{kin} (extraction) (GeV)	26	14	50	50
Protons per LHC “bunch”	1.7 10^{11}	-	4 10^{11}	-
Protons per pulse”	9.2 10^{12}	3.4 10^{13}	3.2 10^{13}	1.4 10^{14}
Cycle length (s)	3.6	1.2	2.4	2.4
Filling time SPS for LHC	21.4 s		13.2 s	-
Extracted power		60 kW	100 kW	400 kW

4.1. INJECTION REGION

The low-power SPL will send a beam of negative hydrogen ions H^- at E = 4 GeV by a new constructed transfer line to the PS2. The loss mechanisms in the transfer line and in the injection region will be similar to those discussed in section 2 for the injection into the PSB, albeit at different energies and intensities of the proton beam.

For the charge transfer injection, a stripping foil is removing the two electrons with an efficiency of approximately 95 %, depending on the chosen thickness of the foil. The remaining hydrogen atoms and few H^- ions leaving the foil will pass a second, thicker foil which will remove the electrons with 100% efficiency. Adding beam load during accelerator set-up at the beginning of each year of operation, the injection dump, will receive nearly 6 % of the total beam intensity from the lp-SPL. This translates to an average beam power of *P* = 2 kW at an energy of 4 GeV or 6.4 10^{19} protons per year. The dump core must be designed to withstand the beam- and heat load. It is probable that the core must be cooled. For interventions on the cooling circuit, it is essential to know the activation of the dump after operation and the resulting ambient dose rates. They may be so high to justify remote handling equipment for removal of the core in case of interventions. Around the beam-absorbing core, radiation protection shielding must be constructed in order to reduce prompt and residual ambient dose rates to acceptable values.

4.2. OTHER DUMPS IN PS2

Routine or excpetional beam aborts have been identified in PS 2. They require dumps or absorbers to safely abort the beam. The energy and annual beam load during these aborts have been estimated and a destination given.

Table 4: Various modes of beam aborts with beam energy, number of protons per year and possible dump locations.

Function	E [GeV]	Load [p+]	% of total	Possible beam destinations					
				Int. or ext. emerg. dump	Ext. beam line or TI -dump	Inj. transfer line	Int. fast inj. dump	Int. or ext. H- dump	Int. or ext. emerg. dump
Emergency abort	20-50	2.7×10^{18}	0.25	X					
Machine development	20-50	2.2×10^{18}	0.2	X	X				
Machine setting up	20-50	3.3×10^{18}	0.3	X	X				
Extr. line setting up	50	3.3×10^{18}	0.3		X				
Slow extraction	50	3.6×10^{18}	0.33	X	X				
Inje. line setting up	4	3.1×10^{18}	0.28			X			
Fast inj. setting up	4	1.1×10^{18}	0.1				X		
H^- injection losses	4	6.4×10^{19}	5.92					X	
Emergency abort	20-50	2.7×10^{18}	0.25						X
Machine development	20-50	2.2×10^{18}	0.2						X
Machine setting up	20-50	3.3×10^{18}	0.3						X

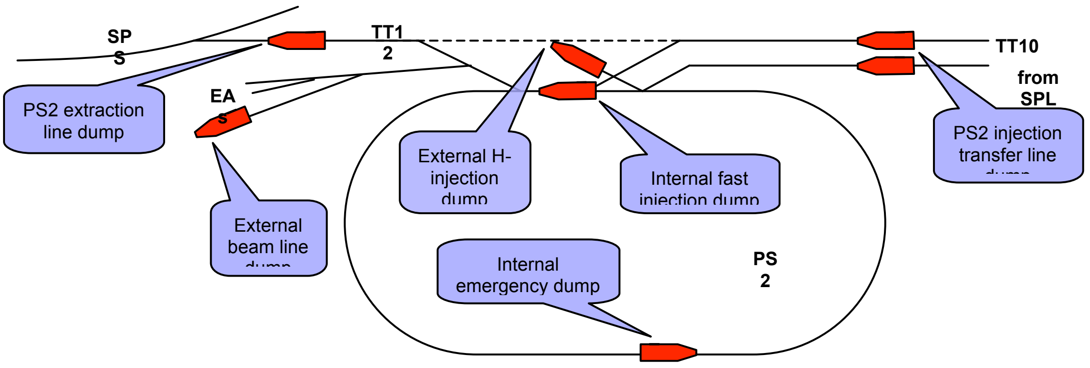

Figure 5: Schematic overview of the proposed PS2 dump concept

Based on these numbers in table a and b,, shielding concepts can be developed for each dump. The aim of the radiation protection shielding is twofold:

- To prevent excessive activation of the surrounding structures, walls and soil
- To afford working conditions during technical stops and shut-downs where the radiation from the dumps is as low as reasonably achievable

PS2 dumps	**Beam loads [p+ /y]**			
	4 GeV	4-20	20-50	50 GeV
TL (injection)	3.1E18	-	-	-
Fast inj. (I)	1.1E18	-	-	-
Emergency (I)	-	8.2E18	2.7E18	-
Beamline (E)	-	-	5.5E18	6.9E18

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4.3. COLLIMATORS

Collimators in PS2 will “clean” the beam from its halo and from off-momentum particles in one dedicated location which can be properly designed. The beam will impinge on the collimator jaws with any energy between 4 and 50 GeV. Beam loads on the collimators are at this stage of the design not known but it is anticipated that the prompt and induced radiation from the collimators will require particular attention.

Conclusion: All beam dumps the injection region, and the collimator region in PS2 must be built under respect of the principle of radiological optimization**.**

5. SPS UPGRADE

The Super Proton Synchrotron (SPS) accelerates protons from a kinetic energy of 25 GeV to 450 GeV for injection into SPS or, later, into SLHC. SPS also delivers proton beams to various fixed target experiments, including the CERN Neutrinos to Gran Sasso (CNGS) production target. Fixed target experiments require a higher number of protons than the storage ring collider LHC / sLHC, where the circulating beam is dumped and newly injected a few times per day. Nevertheless, operating LHC at the ultimate luminosity of 2 10^{34} $cm^{-2}s^{-1}$or sLHC at 10^{35} $cm^{-2}s^{-1}$ exceeds the capabilities of the SPS at this day and various upgrades are necessary.

5.1. BEAM LOSS

At present, the LHC beam in the SPS consists of 288 bunches with an intensity of 1.1 10^{11} protons each and 25 ns spacing. Per injection cycle, a total of 3.2 10^{13} protons are accelerated to E = 450 GeV and transferred into the LHC. The bunches are grouped to a "bunch train" or a "batch". In every SPS cycle, two batches are formed in the accelerator , accelerated and transferred to LHC. In the process, multi-bunch effects cause beam loss of approximately (7 – 10) % of the beam intensity. Experimental measurements have shown that the relative intensity of beam loss upon capture in the SPS depends on the batch intensity (Figure 6). The relative rate of beam loss is roughly proportional to batch intensity, i.e. the absolute losses scale with the square of batch intensity. This situation must be overcome if higher beam intensities are delivered from the present (or future) injector chain. As a first step for improvement, a new working point for the accelerating radiofrequency fields yields approximately 30 % lower relative losses (data points "2004")..

Apart from capture losses, beam instability and loss originate from beam-beam-interactions ("space charge effect") in the SPS. The introduction of a bunch spacing of 50 or 75 ns, reducing the interaction between bunches would also be advantageous in terms of beam loss, but it is not favored by the LHC experiments.

Collective effects, like beam-beam couplings, are enhanced by impedance of the accelerator. Attempts to identify the origin of the impedance in SPS have not been successful so far.

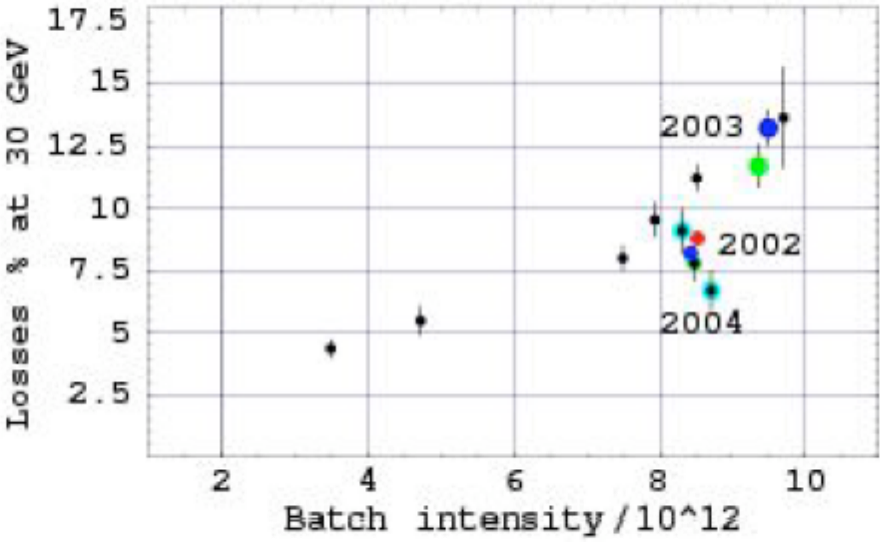

Figure 6: relative intensity of beam loss at capture (E = 30 GeV) as a function of batch intensity

5.2. INTERNAL BEAM "DUMPS"

The SPS operates an internal beam "dump" of type TIDVG which is dispersing the stored energy of the circulating particle beam in case of a beam abort over a large surface. The TIDVG has a length of 4.5 m and a shielding mass of 22 t. The energy-absorbing, water-cooled core consists of carbon, copper, aluminum and tungsten. Since the TIDVG does not absorb a large fraction of the beam energy, it should rather be called beam spoiler or beam disperser. The beam is sent into the absorber within TIDVG by kickers, which exhibit a number of high-intensity limitations.

Figure 7: TIDVG internal beam dump