PS Radiation Working Group

Final Report

Working Group Members:
Luca Bruno (DGS-RP)\(^1\),
Simone Gilardoni (BE-ABP),
Mauro Nonis (EN-CV),
Thomas Otto (TE-HDO, chair)\(^2\),
Rende Steerenberg (BE-OP),
Helmut Vincke (DGS-RP),
Pavol Vojtyla (DGS-SEE),
Markus Widorski (DGS-RP)

\(^1\) BE-SU until 31/12/2010
\(^2\) DGS/RP until 31/7/2010
1 Executive Summary

The Proton Synchrotron, inaugurated in 1959, plays a central role in CERN’s accelerator complex as an injector to higher-energy synchrotrons (SPS, LHC).

In CERN’s new strategy for particle accelerators, the PS shall provide protons for the LHC and the fixed target program for 25 more years, until about 2035. Technical consolidation of the PS and the PS Booster seems to be a cost-effective measure to deliver protons to LHC in this period. The consolidation must also include aspects of safety and environmental protection. While a renovated PS will not be able to match the safety performance of a newly built accelerator, it must be at least assured that all safety and environmental risks are within the perimeter of present laws and regulations. If possible, safety performance shall exceed these minimal standards by a large margin. The PS Radiation Working Group (“the working group”) has been investigating those hazards of continued operation of the PS pertaining to radiation protection and it proposes specific action in the cases where regulations are not respected.

The working group has analyzed the sources of beam loss and possible ways to reduce it, the effects of the secondary radiation emerging beam loss points, such as stray radiation, activation of air and fluids, activation of accelerator components and finally, exposure of personnel to radiation from activation.

Beam Loss (Chapter 2)

The major origin of ionizing radiation in accelerators is beam loss. This term describes accelerated particles colliding uncontrolled with the accelerator structure, generating secondary radiation cascades which in turn, activate air, water and materials, which may irradiate personnel or members of the public.

The working group estimated beam losses in the PS for different operating scenarios. Beam loss occurs predominantly upon injection and extraction of beam into or from the PS.

Up to $8.2 \times 10^{12}$ protons per second are injected into the PS based on the Nighttime supercycle for the year 2010. A beam loss of about 5 % is observed in the injection region, leading to a loss of $4 \times 10^{11}$ per second on average for this region.

Based on the same supercycle, up to $6.4 \times 10^{12}$ protons per second are extracted from the PS for CNGS and fixed target experiments. The extraction towards other experiments and the LHC can be neglected because clean extraction mechanisms are available for them or the intensities are very low, causing only comparatively small beam loss. For the fixed target and CNGS beams, two extraction mechanisms are available:

a) The Multi-Turn Extraction (MTE) scheme has recently been taken into operation in the PS. In an optimized set-up of the extraction, 2 % of the transferred protons would be lost on the extraction septum, SS 16. When MTE was first introduced, the set-up was not optimized, and 4 % of losses were observed.
b) The older Continuous Transfer (CT) method of extraction, where particles of the extracted beam interact with the blade of septum 31. The momentum change experienced causes widely distributed beam loss of approximately 10% downstream from the septum.

Table 1-1: Beam loss per hour and per year upon extraction from the Proton Synchrotron.

<table>
<thead>
<tr>
<th></th>
<th>CT extraction: 10% loss</th>
<th>MTE extraction: 4% loss</th>
<th>Improved MTE extraction: 2% loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per second (nighttime Supercycle)</td>
<td>6.4·10^{11}</td>
<td>2.6·10^{11}</td>
<td>1.3·10^{11}</td>
</tr>
<tr>
<td>Per hour (nighttime Supercycle)</td>
<td>2.3·10^{15}</td>
<td>9.2·10^{14}</td>
<td>4.6·10^{14}</td>
</tr>
<tr>
<td>Per year (2550 hours effective)</td>
<td>5.8·10^{18}</td>
<td>2.3·10^{18}</td>
<td>1.2·10^{18}</td>
</tr>
</tbody>
</table>

Radiation Effects (Chapter 3)

Ionizing radiation after a beam loss in an accelerator occurs in principle in four different circumstances:

*Activation of solid material:* The secondary particle cascade will cause nuclear reactions in material it crosses, making this material radioactive. After the stop of the accelerator, the activated material continues to emit ionizing γ- and β-radiation, irradiating workers present in the vicinity of the accelerator for maintenance and repair.

*Activation of air:* In the same way as solid materials, atoms in air are undergoing nuclear reactions with energetic secondary particles emerging from a beam loss point. The predominantly short-lived gaseous radionuclides are transported with the accelerator’s ventilation system into the environment, where they may expose persons working on the CERN site, but also members of the public.

*Activation of fluids (mainly water):* Liquids found in the accelerator are mainly water for cooling purposes, oil and Fluorinert for insulation of high voltage connectors. Ground water in the soil surrounding the accelerator may be activated.

*Stray radiation:* The secondary particle cascade is weakened during the passage through shielding (concrete, earth), but in an accelerator built on ground-level, measurable levels of radiation, composed mainly of energetic neutrons, may emerge through weak parts of the shielding.

The Working Group has identified the pathways by which ionizing radiation is generated in the PS and by which it may affect workers in the PS tunnel, on the CERN site and members of the public.

The worst cases, also for future operations, have been considered.
Activation of solid material:

The beam loss caused during Multi-Turn extraction is concentrated in a 15 meter long region downstream of the extraction septum, located in SS16. The most radioactive location is directly aside the extraction septum. One hour after the stop of the accelerator, ambient dose equivalent rates of 30 mSv·h⁻¹ and more have been measured. From extrapolation of measurement with results from simulation, one can estimate that build-up of radioactive nuclides in the septum and its vacuum tank may lead to an ambient dose equivalent rate of up to 100 mSv·h⁻¹ at 1 hour after the stop of the accelerators, assuming beam loss figures from the last column of Table 1-1 (optimized MTE transfer).

These ambient dose equivalent rates are so high, that every intervention on the activated septum must be carefully planned and optimized. Feedback from previous shutdowns shows, that the septum could be changed within a fortnight of waiting time after a total failure under the constraint of the personal dose limit for a planned intervention. However, such an intervention would cause a collective dose of 22 person-mSv, one third of the collective dose accrued every year during routine maintenance in the PS complex. The situation has been similar with CT beam extraction, due to which the septum in SS31 became strongly activated. Although overall losses for CT beam extraction are higher than for MTE, the losses are distributed over several sections. This leads to increased radiation levels on average, which still allows performing necessary standard maintenance. The fact that for MTE all losses are concentrated in one single section puts the required maintenance interventions in SS16 at risk. In addition, the ambient dose rate from Septum 16 is higher due to the more massive build of this septum.

Beside the exchange of a septum, the exchange of a main magnet unit, although occurring less frequently, is a major intervention which takes considerably more time than changing a septum tank. Such an intervention might lead to high individual and collective doses depending on the magnet location.

Both cases have been considered as the worst cases for material activation and subsequent exposition of personnel to ionizing radiation.

Activation of air

Beam loss is activating the air in the accelerator tunnel. The PS tunnel has particularly many openings where the air could escape: As a centrepiece of CERN’s accelerator complex it has open connections to its injectors (Linac 2, Linac 3, PSB), to experimental facilities supplied by the PS (AD, East Experimental Area, n_TOF) and to other accelerators by transfer tunnels (SPS via TT2, TT10 and TT70). Furthermore, in 1959, the structure of the PS tunnel has not been built air-tight, as would be required for a controlled ventilation flux [ISO 17873]. Finally, the ventilation system of the PS is generating an overpressure in the PS tunnel instead of a controlled flow to a unique release point above the surface.

As a consequence, activated air emerges in an uncontrolled way from the PS tunnel and is transported downwind on the CERN site and into the environment. The Working Group has made a conservative estimate of the radiological impact on a representative member of the public, assuming the beam loss figures of the optimized MTE transfer and of the CT transfer. The impact is expressed
as a conservative estimate of the annual effective dose received by members of the reference population. The estimation yields an annual effective dose of 0.28 µSv (optimized MTE) or 1.4 µSv (CT). After adding the often higher effective doses describing environmental impact of other facilities on the Meyrin site, these results must be compared with the annual limit of 200 µSv for releases of radioactive substances (air and water), or with the guideline value for optimization measures, 10 µSv.

**Activation of fluids**

Fluids are activated by the same physical mechanisms as solid materials and air. The fluids may carry dissolved or undissolved species (e.g. corrosion products) which are activated and carried to easily accessible areas. Whenever maintenance work is executed on fluid systems, radioactivity measurements are performed. While minute amounts of radionuclides can be identified, the level of radioactivity is usually below legal limits and guideline values due to purifying systems and/or the regular addition of fresh fluids. However, for a better control of releases and to approach currently applied principles for new installations, water circuits carrying activation products shall be leak tight and exclusively used for equipment exposed to activation. Separate water circuits shall be envisaged for activation and non-activation areas.

**Stray radiation**

In the current layout of the PS, stray radiation emerges mainly at two points: slightly downstream of the extraction septum SS16 and on the crossing of Route Goward over the accelerator tunnel, downstream of the injection septum. The causes for the stray radiation are clearly identified: over average beam loss upon beam injection into the PS from the PS Booster (Route Goward) and upon extraction from the PS (Septum 16 and Route Goward during the CT extraction), respectively. At both positions the losses meet specifically weak shielding configurations. Beside these positions a number of other sections could be become an issue if beam losses would increase there, due to weaknesses in the shielding (insufficient chicanes at emergency exits, cabling ducts, ventilation shafts or ovoid openings).

On Route Goward, the measured ambient dose equivalent rate exceeds the limiting value for a non-permanently occupied public area by a factor of 5 to 10 for optimized beam parameters, including the exclusive use of the MTE transfer scheme to the SPS. The zone has been classified as a supervised radiation area, in contradiction with all regulatory practice, following which radiation areas must be designed such that unauthorized persons cannot enter them. In practice, this is impossible for the only passage for vehicles into the centre of the PS Ring. The working group evaluated the thickness of additional shielding necessary to reduce $H^*(10)$ to 2.5 µSv·h$^{-1}$ as 120 cm of concrete. As a margin for future energy and intensity increases the additional shielding thickness shall be in the order of 180 cm.

In the area slightly downstream of Septum 16, the highest measured rate of ambient dose equivalent on top of the PS tunnel is above 200 µSv·h$^{-1}$ for the optimized MTE transfer. The area is fenced and access to it is only possible when climbing a barrier. However, scattered radiation (mainly neutrons) is spreading out from the hot spot and causing an ambient dose equivalent rate of more than 0.1 µSv·h$^{-1}$ in the barracks 561 and 587. Personnel having their offices there receive a dose of more than 100 µSv in a working year (2000 hours). This is not justified for personnel whose
work is not directly related to the operation of the accelerator. The working group proposes to increase the roof shielding of the PS by 180 cm of earth on the lawn east of Bld. 151, resulting in an approximate equal shielding coverage as on the rest of the PS. In this case, a beam loss of $1 \times 10^{11}$ protons per second in the region of SS16 would cause an ambient dose equivalent rate $H^*(10)$ of less than 30 µSv·h$^{-1}$ at the point where the secondary radiation emerges from the ground.

The beam loss point in SS16 also increases ambient dose equivalent levels inside buildings 351 (Linac 3), 151 and the courtyard in front of B.151. Building 351 is located at a weakly shielded position. The levels in building 151 are due to an inefficient design of the PS emergency exit (D.122), weak shielding and ovoid opening towards section 14. In January 2010, at both sides, additional shielding has been installed, reducing the ambient dose equivalent rate at least below legal limits. From practical point of view, these measures can only be considered as a temporary solution. For the Linac 3 side (B.351) the situation remains difficult as further constructional improvements would involve high costs and long-term civil engineering works impacting the ions program. In order to optimize exposure, the permanent workplaces in the Linac 3 area shall be reconsidered.

**Future operation of the PS (Chapter 4)**

When trying to assess the radiological impact of a facility for the next 20 or 25 years, one must also take into account possible modifications of its operational parameters. Radiation effects are proportional to the intensity of the beam loss, and the number of lost particles may grow over proportionally with the beam intensity.

One upgrade plan for the PS complex is the increase of the PS Booster beam energy from 1.4 GeV to 2.0 GeV. The working group has studied a hypothetical scenario in which the rate of lost protons remains constant, albeit at the higher injection energy. An increase of the ambient dose equivalent rate by a factor of 1.6 ensues, demanding an additional increase of the radiation shielding on Route Goward. If the emittance reduction afforded by the higher energy would be used to make the injected beam even more intense, then the ambient dose equivalent rate would not only increase proportionally in the injection region, but also the ejection region would be affected. In order to make meaningful estimates of radiation levels, the expected beam loss must be studied in the next phase of the PSB upgrade project.
Recommendations (Chapter 5)

The Working Group gives the following recommendations for the mitigation of the radiological impact of operation of the PS for different time horizons:

General Recommendations

- Study the impact on radiation protection and the environment of all planned changes of operational parameters of the PS accelerator. Legal limits must be respected and the impact on radiation protection and on the environment must be optimized.

- Integrate beam operation in the optimization process. Because beam loss is the most important parameter affecting ambient dose rates in the accelerator, efforts for its reduction must be made and documented.

- Any new equipment which is going to be installed or to replace existing equipment shall be designed bearing in mind the quick removal and reinstallation.

Before the shutdown LS1 in 2013

- Establish a complete 3D model of the PS tunnel and accelerator as-built and of its implementation on site. Identify areas of weak radiation shielding and penetrations in the ventilation envelope.

- Study additional shielding above straight section 16, above Route Goward and at any other location where shielding is considered too weak for present operational parameters. The recommended additional thicknesses are 180 cm of earth (SS 16) or of concrete (Rte. Goward).

- Constrain and optimize the local and integral losses in the PS accelerator to $10^{10}$ s$^{-1}$ at arbitrary location, $10^{11}$ s$^{-1}$ at the extraction septa and $10^{12}$ s$^{-1}$ integrated over the whole ring. These constraints will enable optimized, major repair interventions within a fortnight after stop of the accelerator.

- Implement suitable beam instrumentation, capable of monitoring beam intensities with an accuracy better than 1% of the measured intensity across different beam current monitors. Beam loss monitors measuring down to losses less than $10^8$ s$^{-1}$.

- Measure local concentration of activated air at workplaces located around the PS accelerator.

- Study monitoring of average air activation in the PS tunnel to improve the assessment of releases and environmental impact of radioactive gases from the PS.

- Perform a feasibility study for the modification of the PS ventilation system. The aim shall be the measurement of radioactive releases for comparison with legal guidelines and limits. The feasibility study must contain the financial cost and the expected collective dose of the operation.
• Study the possibility to separate water circuits for activation areas (accelerators) and other technical areas.

• Study the option of hybrid MTE with the combined use of septa SEH31 and SMH16.

• Study the non-linear relationship between peak beam intensities and relative beam loss.

• Propose an alternative for the permanent workplaces in Linac 3.

• Establish a catalogue of intervention and dose planning for all accelerator equipment, as a base document for optimization measures.

*During and after the shutdown LS1*

• Install additional shielding above SS16, Route Goward, and at other identified locations of weak shielding.

• Install a dummy septum in SS15 for MTE.

• Install a longitudinal kicker for the MTE barrier bucket.
2 Present beam parameters and associated beam loss

2.1 Beam intensities in 2010

2.1.1 PSB and PS supercycles

In the chain of accelerators at CERN, a basic time period for the synchronization of all machines has been chosen. Presently the basic period has a length of 1.2 s. Shortening this period would require hardware modifications in the power supplies, in the radiofrequency system and partly in the magnets. Preliminary studies were done in the past [METRAL& BENEDIKT] to cycle the injector complex at 900 ms, and new proposals about faster cycling of the injector complex were recently summarized [CHAMONIX].

Proton beams from a plasma source are accelerated to a kinetic energy of \( E = 50 \text{ MeV} \) in Linac 2. Every basic period, one pulse containing at maximum about \( 0.5 \times 1.5 \times 10^{14} \) protons (165 mA, 150 \( \mu \text{sec} \)) is injected into the PS Booster (PSB), after having been split into 4 spills for the 4 vertically superposed rings of the PSB. The PS Booster accelerates the protons to a kinetic energy \( E = 1.4 \text{ GeV} \). The beams from the four PSB rings, up to eight bunches, are recombined after the extraction and then directed either to ISOLDE or to the PS. In the PS, one basic period is sufficient to accelerate protons to a momentum of 14 GeV/c, so as for beams with the final destination of CNGS or for fixed target physics at the SPS or at 20 GeV/c for the n_TOF beam. Other beams with higher momenta as for the AD, the PS East Hall and LHC type beams for example, require acceleration over two basic periods. LHC beams with double PSB injections are executed over three basic periods in the PS. Depending on the desired maximum energy each beam requires a certain number of basic periods in the SPS. The combination of these constraints leads to supercycles schematically depicted in Table 2-1.
Table 2-1: Description of the three basic 2010 PS supercycles with beams for the CNGS and Fixed target experiments (SFTPRO). The first supercycle has a length of 39 basic periods. In the PS, 10 basic periods (26 %) are dedicated to high-intensity beams (CNGS and Fixed Target Physics). The second supercycle has a length of 33 basic periods, of which in the PS 10 (30 %) are dedicated to high intensity beams. The last supercycle, for efficient filling of the LHC, contains no basic period for high intensity beams.
2.1.2 Intensities of beams injected into and ejected from the PS

For each of the basic supercycles one can calculate the number of protons injected into the PS by multiplying the number of basic periods of a certain beam with the number of protons typically transferred for this beam. Upon injection of protons from the PS Booster, all beams cause indiscriminately injection losses and related radiation effects must be accounted for. From the total number of protons per supercycle the average number of protons injected per second can be obtained. In Table 2-2, results are given for the Daytime and Nighttime basic supercycles from Table 2-1. Under these conditions, between 7.5·10^{12} and 8.2·10^{12} protons per second are injected into the PS.

Table 2-2: Injection into the PS. Number of protons injected from the PSB into the PS during one basic supercycle. In the bottom lines, the total number of injected protons and the average rate of injection are given (protons s^{-1}). These parameters are used for estimating beam loss and its radiation effects upon injection.

<table>
<thead>
<tr>
<th></th>
<th>Protons per basic period</th>
<th>Basic Periods</th>
<th>Total</th>
<th>Protons per basic period</th>
<th>Basic Periods</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNGS</td>
<td>2.6·10^{12}</td>
<td>8</td>
<td>2.1·10^{14}</td>
<td>2.6·10^{12}</td>
<td>8</td>
<td>2.1·10^{14}</td>
</tr>
<tr>
<td>Fixed target</td>
<td>2.2·10^{13}</td>
<td>2</td>
<td>4.4·10^{13}</td>
<td>2.2·10^{13}</td>
<td>2</td>
<td>4.4·10^{13}</td>
</tr>
<tr>
<td>LHC</td>
<td>1·10^{13}</td>
<td>2</td>
<td>2·10^{13}</td>
<td>1·10^{13}</td>
<td>2</td>
<td>2·10^{13}</td>
</tr>
<tr>
<td>n_TOF</td>
<td>8.5·10^{12}</td>
<td>3.6</td>
<td>3.1·10^{14}</td>
<td>8.5·10^{12}</td>
<td>3.6</td>
<td>3.1·10^{14}</td>
</tr>
<tr>
<td>AD</td>
<td>1.5·10^{13}</td>
<td>0.4*</td>
<td>6.0·10^{12}</td>
<td>1.5·10^{13}</td>
<td>0.4</td>
<td>6.0·10^{12}</td>
</tr>
<tr>
<td>EAST-A +n_TOF</td>
<td>4·10^{12} + 4·10^{12}</td>
<td>1</td>
<td>4.4·10^{12}</td>
<td>4·10^{12} + 4·10^{12}</td>
<td>1</td>
<td>4.4·10^{12}</td>
</tr>
<tr>
<td>EAST B</td>
<td>3·10^{11}</td>
<td>4</td>
<td>1.2·10^{12}</td>
<td>3·10^{11}</td>
<td>4</td>
<td>1.2·10^{12}</td>
</tr>
<tr>
<td>EAST-C + n_TOF</td>
<td>4·10^{12} + 4·10^{12}</td>
<td>2</td>
<td>8.8·10^{12}</td>
<td>4·10^{12} + 4·10^{12}</td>
<td>2</td>
<td>8.8·10^{12}</td>
</tr>
<tr>
<td>TSTPS</td>
<td>3·10^{11} **</td>
<td>1</td>
<td>3.0·10^{11}</td>
<td>3·10^{11} **</td>
<td>1</td>
<td>3.0·10^{11}</td>
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<tr>
<td>Total</td>
<td></td>
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<td>3.5·10^{14}</td>
<td></td>
<td></td>
<td>3.3·10^{12}</td>
</tr>
<tr>
<td>Rate (s^{-1})</td>
<td></td>
<td></td>
<td>7.5·10^{12}</td>
<td></td>
<td></td>
<td>8.2·10^{12}</td>
</tr>
</tbody>
</table>

*The AD target receives one pulse every 108 seconds, which is approximately one in every 2.5 supercycles.

** The maximal achievable intensity

At ejection, the beam loss is dominated by the CNGS and Fixed Target (FT) beams because of their slicing on a septum. By contrast, other beams have much cleaner extraction mechanisms and cause negligible ejection losses. Compared to losses during CT or MTE transfer, their contributions can safely be neglected in this study of radiation effects.

In Table 2-3, parameters for the beams transferred by the CT or MTE mechanisms are given. Typical intensities which can be realized in the accelerators in a stable manner over many hours are given. Record intensities may be up to 30 % higher per cycle, but they cannot be sustained for longer periods.
Table 2-3: Extraction from the PS to the SPS in the CT and MTE modes. Hourly number of PS basic periods with high-intensity beams for the SPS, the number of protons in one basic period and the number of protons accelerated per hour in the PS. The last column indicates the fraction of the total number of protons which is extracted in one of the high-intensity modes CT or MTE.

<table>
<thead>
<tr>
<th></th>
<th>CNGS</th>
<th>FT</th>
<th>Total</th>
<th>Fraction of Total intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycles/hour</td>
<td>Protons/ Cycle</td>
<td>Cycles/hour</td>
<td>Protons/ Cycle</td>
</tr>
<tr>
<td>Daytime</td>
<td>615</td>
<td>2.6×10^{13}</td>
<td>154</td>
<td>2.2×10^{13}</td>
</tr>
<tr>
<td>Nighttime</td>
<td>727</td>
<td>1.8×10^{13}</td>
<td>182</td>
<td></td>
</tr>
</tbody>
</table>

From the rates of the beams transferred and the corresponding losses, the intensity of short-term effects such as stray radiation generation or release rates of air-bound radioactivity can be estimated. For long-term effects, such as the activation of material or annual releases to the environment, the annual number of protons from the PS must also be known. For the estimation of the number of protons annually accelerated in the PS, the following assumptions, based on the initial 2010 injector schedule are made:

1. Due to periods where the LHC is filled, only 20 hours per day are available, distributed pro-rata over day and night time. The typical intensity is assumed.
2. The CNGS receives protons during 180 days.
3. Fixed target experiments receive protons during 170 days.
4. Based on the experience from the past, the availability of the accelerator chain from Linac 2 to the SPS is 75%.

Under these assumptions, 5.8×10^{19} protons in total will be extracted from the PS in continuous transfer (CT) or multi turn extraction (MTE) mode in one year.

2.2 Beam loss

Beam transfer into or out of a circular accelerator is accompanied by beam loss due to mechanical obstacles in the beam path (septa, for example), an imperfect matching of the phase space of the transfer line and the accelerator or beam instabilities. Beam loss can also occur during the acceleration of particles, this is the subject of the last paragraph of this section.

In the PS, beam losses are observed upon injection from the PS Booster, during acceleration at the transition point and upon ejection towards the SPS. The transfer modes and the associated beam loss are described in this chapter.
2.2.1 PS injection from the PS Booster

Beam loss is observed upon injection from the PS Booster, where, depending on the intensity, up to 4-6% of the injected beam at a kinetic energy of $E = 1.4$ GeV is lost in the injection region of the PS.

2.2.1.1 Description

The PS receives beams from the PS Booster, which is composed of four vertically superposed rings. The BTP transfer line between the PSB and the PS [AUMON3] recombines vertically the beams from all rings as shown in Figure 2-1: the ejection from rings 3 and 4 are recombined in the BTU line and rings 1, 2 in the BTL line.

These two lines will join further downstream in the BT-line. At the end of the BT-line, a separation takes place to send the beam either to the ISOLDE facility or through the transfer line to the PS (BTP). The end of BTP passes through the magnetic stray field of one of the PS main magnets before reaching the injection septum. The PS single turn injection consists of the following elements, presented in Figure 2-2: The beam is injected via a magnetic septum on a bump created by four dipole bumpers and a fast kicker deflects the beam on the central orbit. The shape of the horizontal bump was designed to optimize the horizontal aperture at the injection place on one hand and to catch up the large angle between PS and the transfer line on the other hand.

![Figure 2-1: Schematic arrangement of transfer beam lines between the PS Booster (left) and the PS (right)](image-url)
2.2.1.2 Beam loss during injection

Two loss mechanisms during injection into the PS have been identified so far:

a) A very rapid loss at the location of the injection septum due to the limited mechanical aperture of the septum itself, most probably concentrated in the horizontal plane.

b) A slow loss, lasting about 100-150 turns. The source is not yet clear. One of the possible sources could be an imperfect adjustment of the beam’s radial position during the first machine turns caused by the RF phase loop. The second could be because a part of the beam, due to the space charge tune spread, might intercept a resonance, in particular the integer one. In this case, the injection bump would not be closed for this fraction of the beam. Both cases are being studied.

Unfortunately, due to the lack of cross calibration between the beam transformers in the injection line and the PS ring transformers and the lack of instrumentation to precisely measure absolute losses during the first 1000 turns, it is not possible to quantify correctly the absolute losses or the different contributions to the losses due to the different mechanisms.

2.2.1.3 Intensity of the injection loss

When working at full intensity, on average between $7.5 \times 10^{12}$ and $8.2 \times 10^{12}$ protons are injected per second into the PS (Table 2-2). For high intensity beams, a loss figure of about 6 % is a realistic assumption. Due to collective effects, high intensity beams have a larger geometrical extension [STEERENBERG] and a higher probability of collision with the mechanical obstacles. It follows that up to $4.9 \times 10^{11}$ protons per second are lost in the interaction region of the PS.
2.2.2 Continuous transfer (CT) ejection to the SPS

2.2.2.1 Description

Since 1977, protons are transferred from the PS to the SPS by the so-called continuous transfer (CT) process [CTREF]. All high-intensity proton beams for the fixed target research program and for CNGS are transferred with this process, which is filling the SPS in a nearly “continuous” fashion over 10/11 of its circumference. Schematically, it works as follows: Once the beam in the PS has reached transfer momentum \( p = 14 \text{ GeV/c} \), it is “sliced” on the electrostatic septum SEH31 in PS straight section 31 in 5 approximately equal portions during five successive PS turns. Each of the 5 slices of length \( 2 \pi r_{PS} = 628\text{ m} \), containing each 1/5 of the particles in the PS, are deflected out of the PS by the magnetic septum SMH16 in straight section 16. In the SPS each slice occupies 1/11 of the circumference. The process is repeated one basic period (1.2 s) later with the next filling of the PS. 1/11 of the SPS circumference is free of beam and represents the kicker gap, in which the SPS extraction kickers switch from the rest state to the excited state.

2.2.2.2 Beam losses during CT

The CT leads to beam loss through the intercepting septum blade in SS 31. Particles are hitting the septum blade mechanically. Depending on the dynamics of the impact, protons will leave the stable orbit in the PS at different locations downstream of SS 31. A notorious beam loss point in the past was SS 09, by modification of the optics it has been relocated to SS 75 [BARRANCO]. Other sections with beam-loss can be identified from a plot of the signal of beam loss monitors. (Figure 2-3).

Figure 2-3: Signal of PS Beam loss monitors
The only absolute information on beam loss in the PS comes from beam current transformers (BCT) in the PS Ring and in the transfer lines. One observes that the beam is ejected from the PS with an efficiency of about 90 – 95 %, the CT extraction therefore causes a beam loss of 5 – 10 % of the beam circulating in the PS [BARRANCO]. However, the relative calibration of these transformers is not more accurate than +/- 5%.

Figure 2-4: Indication of beam loss points during the CT extraction. Larger, more yellow circles mean higher relative beam loss than smaller, green circles. The numbers in red indicates the PS straight section (SS).

2.2.3 Multi-Turn Extraction (MTE) ejection to SPS

2.2.3.1 Description

The high intensity of beam loss in CT mode (the number of protons lost per extraction corresponds to the number of protons sent for experiments to the East Hall) has motivated studies for a more efficient transfer of continuous beams from the PS. As a consequence of the work of the BLRWG in 2005
[BLRWG], the Multi Turn Extraction (MTE) [MTE] project has been approved. Here, the circulating beam is divided into 5 approximately equal portions not by a mechanical blade, but by the application of non-linear magnetic fields, separating the beam in 5 “islands” in the transverse phase space. Successively, each island is extracted thanks to a slow and a fast bump and finally deflected by the magnetic septum in SS16 out of the PS orbit into the transfer line. A number of modifications of the PS hardware had to be made so that the first tests of MTE were done in 2009 [GILARDONI1, BENEDETTO]. From autumn 2009 on, MTE has been used to transfer routinely a few cycles of the CNGS beam to the SPS [GILARDONI2].

2.2.3.2 Beam loss during MTE

Ideally, beam loss could be very low during MTE extraction. One observes indeed that the beam loss monitors in nearly all sectors of the PS show hardly any signal (Figure 2-5), a striking contrast to CT extraction. Beam transformer measurements in the PS and in the transfer tunnel TT2 leading to the SPS indicate a transfer efficiency of 98 %, i.e. beam loss of 2 %. These on-line observations are confirmed by first ring surveys, where ambient dose rate is measured around the inner circumference of the PS magnets. The beam loss is clearly lower than during comparable beam stops in the past, when CT extraction was used.

For efficient acceleration in the SPS, the beam has to be debunched in the PS, i.e. it fills the whole circumference of the PS without a kicker gap. The beam “filament” is physically crossing the 3 mm thick septum blade during the kicker rise time, where protons collide with the copper blade and are removed from the stable orbit. The magnetic septum blade is much thicker than the electrostatic septum blade causing beam loss in CT extraction. This explains why only relatively few particles “survive” the collision after a glancing incidence with the blade for a part of the accelerator’s circumference. The generation of ionizing radiation is concentrated in the region downstream of SS 16, in main magnet unit (MMU) 16, in SS 17 and in the first elements of the transfer line FT16. The crossing of the septum blade accounts for a loss of 1 – 2 % of the total beam. As long as the beam in the PS cannot be bunched, this has to be regarded as the irreducible loss for MTE transfer.

Instability during the island formation, occurring with periods between 5 minutes and 40 minutes, are a second source of beam loss. The MTE process, relying on separation of particle bunches in phase space without mechanical elements, is sensitive to minute variations of the nominal parameters of numerous electromagnetic and electronic components. The components at the origin of the orbit fluctuations are presently actively investigated. It is assumed that this effect causes another 2 % increase of the beam loss, bringing it to a total of 4 % (Figure 2-5).
Figure 2-5: Beam-loss monitor signals in the PS. Blue: during CT-extraction, Red: during MTE transfer. Small losses are observed for MTE also in other regions than SS16. Methods of further reduction are under study.

Figure 2-6: MTE extraction efficiencies during low intensity operation (left) and high intensity operation (right).
A number of other research programs request protons from the PS (namely the LHC, n-TOF, the Antiproton decelerator AD and in the East hall). These are of lower integrated intensity and their extraction modes work with smaller losses.

2.2.3.3 Technical options to reduce beam loss during MTE

Beam loss on the septum could be reduced with either of the following methods (or combination of them):

- **Dummy septum**
  A passive beam catcher is installed in the straight section immediately preceding the straight section 16. This location is determined by the fact that the islands should be sufficiently separated during the extraction process. The beam would impinge on a static object which does not need to be regularly maintained and which can be enclosed by local bulk shielding. This can considerably decrease stray radiation levels laterally and protect the critical septum from high activation levels. The magnet following the dummy septum would be irradiated by the secondary particle cascade, taking the role presently filled by MMU 16. A study of this option is currently ongoing.

  The difficulty, in this case, would be the displacement of the quadrupole and the dipoles installed in SS15. The dipole is used to create the MTE slow extraction bump, whereas the quadrupole is used during the Gamma Jump. Studies are ongoing to determine if it would be possible to renounce to the dipole and to change the Gamma Jump scheme.

- **Barrier buckets**
  During the extraction process, the beam has to be de-bunched and recaptured at 200 MHz to fit the constraints given by the SPS RF. There is hence no space in the longitudinal distribution to accommodate the kicker rise time. Using a barrier-bucket technique [BLASKIEWICZ], a hole in the longitudinal distribution could be created. Then the kickers have to be triggered synchronously with the gap. This solution could be used only for the CNGS-type beams, i.e. only for the beams which are not slowly extracted for the SPS: the resulting time structure would be incompatible with the needs of the experiments in the North Area. Studies of this solution will be launched in the near future, but important hardware modifications of the RF would be required. In particular, a new RF cavity and new systems to synchronize the kickers with the longitudinal gap will be necessary to change the longitudinal structure.

- **Combined operation with Septum 31**
  This scheme is based on a deviation of the beam by a kick in the electrostatic septum 31 with the aim of steering the beam away from the magnetic septum blade in section 16. Some tests will be done during the 2011 run, since most of the needed hardware is already present in the machine. The most challenging issue is related to the missing strength of the kickers used to deviate one of the islands beyond the blade of the SEH31. It needs to be studied in greater detail before an answer on its net benefits is possible.
• Thinner septum blade
Bunched Beam loss on the septum may be reduced by about 40 % by replacing the septum blade (3 mm thick) by a thinner model (1.6 mm thick). The septum blade is water cooled and in a thin blade, little margin is left for the tightness of the water pipes. Repair of a cooling water leak would necessitate a heavy intervention on the activated septum and this option must be considered carefully.

• New low frequency RF for the SPS.
A bunch-to-bucket transfer between the PS and the SPS with a proper gap in the longitudinal distribution to accommodate the kicker rise time would be the optimum solution to reduce the losses down to a possible minimum. It is known, however, that the SPS cannot have a low frequency RF system [SHAPOSNIKOVA] required for this kind of solution. A series of studies with the CT extracted beam were also carried out in the past to verify if the existing SPS RF could accelerate bunched PS beams [BOHL1,2] with losses comparable to the de-bunched case. The results of the studies proved that the de-bunched beam transfer minimize the SPS losses during acceleration.

• Faster PS kickers
The rise time of the existing kickers used to create the 5 turns long fast bump is 350 ns (10%-90% of the maximum kicker voltage), i.e. about 17% of a complete PS turn. Other kickers installed in the PS have a rise time of only 80 ns (10%-90% of the maximum kicker voltage). A net reduction of the kicker rise time had been considered too expensive to be feasible, with expected upgrade costs in the order of MCHF.

2.2.4 Loss during acceleration

Other beam losses at the injection section are produced for the fixed target beams in correspondence of the 3.5 GeV/c bunch splitting. These losses are produced by an imperfect tuning of the total RF cavity voltage during the harmonic change. Due to this, a net beam acceleration or deceleration at constant magnetic field induces a slow radial position drift. Losses occur at the location of the injection septum, which is one of the horizontal aperture restrictions of the machine. These kind of losses have been cured by: a) keeping the radial loop active during the bunch splitting; b) fine tuning of the bunch splitting, in particular of the phase offset between the two harmonics every time that these losses appear [GILARDONI3].

At transition crossing [AUMON4], fast pulsing quadrupoles are triggered to change rapidly the momentum compaction factor of the machine. This is done to avoid the development of different instabilities [METRAL2]. Losses are observed during this period due to three mechanisms:

a) The machine optics distortion creates zones where the beam envelope is too large for the available aperture. This has been fixed by changing the powering scheme of the fast quadrupoles [AUMON4].
b) The radial position of the beam is such that the beam it is no more centred with respect to the vacuum chamber. This was corrected in the past by programming a controlled energy error at transition. This, however, implied a fine trimming of the RF phase jump depending on the energy error. Recent studies [AUMON1] revealed that the beam position monitors which control the beam radial position were not in the optimum position with respect to the machine optics to detect fast energy errors. A better choice of the positioning location of the pickups could solve the problem of the radial position drifting at transition.

c) Beam instabilities have been observed already in the past, in particular for the single-bunch high-intensity beams delivered to n_TOF [METRAL2]. Studies are ongoing to improve the understanding of such instabilities and to minimize also the losses [AUMON2].

These, together with the continuous trimming of the machine done by the operation crews and the RF experts reduced the losses at transition from typically 2-3% of the circulating beam to less than 1% [GILARDONI3].

### 2.2.5 Beam loss summary

Upon injection into the PS, up to 4.9 \( \cdot \) 10^{11} protons per second are lost in the vicinity of the injection septum 42. When the injector complex is running at the present full intensity, injecting 8 \( \cdot \) 10^{12} protons per second into the PS, this corresponds to a loss rate of 6%.

When MTE is used for transfer of the beam out of the PS, practically all of these losses occur on the extraction septum SMH16. During CT extraction, 70 % of the losses are concentrated on SEH31, the rest is distributed over the PS ring peaking in straight sections 31 - 45 (42: Route Goward), 75 and 16. Table 2-4 summarizes the loss estimates during ejection from the PS.

Table 2-4: Approximate beam loss figures for the CT and MTE extractions in the PS. The typical intensities from Table 2-3 were used. In the annual figures, the availability of the PS and its injectors (75 %) was assumed.

<table>
<thead>
<tr>
<th></th>
<th>CT extraction: 10 % loss</th>
<th>MTE extraction: 4 % loss</th>
<th>Improved MTE extraction: 2 % loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per second (nighttime Supercycle)</td>
<td>6.4 ( \cdot ) 10^{11}</td>
<td>2.6 ( \cdot ) 10^{11}</td>
<td>1.3 ( \cdot ) 10^{11}</td>
</tr>
<tr>
<td>Per hour (nighttime Supercycle)</td>
<td>2.3 ( \cdot ) 10^{15}</td>
<td>9.2 ( \cdot ) 10^{14}</td>
<td>4.6 ( \cdot ) 10^{14}</td>
</tr>
<tr>
<td>Per year (2550 hours effective)</td>
<td>5.8 ( \cdot ) 10^{18}</td>
<td>2.3 ( \cdot ) 10^{18}</td>
<td>1.2 ( \cdot ) 10^{18}</td>
</tr>
</tbody>
</table>
3 Radiation effects

During beam loss, ionizing radiation is produced from the nuclear collisions between beam particles and nuclei of the surrounding materials. Cascades of secondary particles emerge from the interaction point, having a fourfold effect:

1. The activation of materials hit by the primary or secondary particles from the interaction. This concerns primarily objects which are close to the interaction point. Activation of material leads to two concerns:
   a. The radionuclides in the activated material emit decay radiation and thus create a radiation field. Depending on the degree of activity, ambient dose equivalent rates can be prohibitive for human intervention on the activated objects for a certain time. The time required for radioactive decay before a human intervention could take place may not be compatible with the goal of a high operational availability of the accelerator. The required decay time strongly depends on the ambient dose equivalent rates and the projected collective and individual doses for an intervention. In many cases additional spare parts must be kept, as the radiation level generated by the exchanged equipment excludes an immediate repair. Higher activation levels therefore increase the number of required spare parts. The required decay times for the work in the vicinity of radioactive objects must be optimized such as to keep personal dose to workers as low as reasonably achievable.
   b. At the end of its useful lifetime, all activated material must be eliminated as radioactive waste or stored for decay until it can be considered as non-radioactive, which both is inconvenient and costly. With higher activation levels the time and amount of material increases, which has to be stored for decay or considered as radioactive waste.

2. The penetrating components of the stray radiation (neutrons, photons and muons) propagate through the shielding of the accelerator. Stray radiation can be measured in a radius of a few hundred meters around the point of emergence due to multiple scattering of photons and neutrons on air nuclei. If the intensity of the stray radiation is exceeding the level for which the accelerator shielding was originally built, then formerly non-designated areas, usually accessible to the public, may be subject to dose rates in excess of the limits for such areas. Dose constraints and limits have strongly decreased since the construction of the PS, while beam intensities have been considerably increased. Despite of an overall much cleaner beam operation nowadays, the shielding has not been improved in the same amount as would have been required to cope with present-day legal requirements and dose constraints for justification and optimization.

3. Activated air may escape the accelerator tunnel into the environment. Radionuclides in air can be transported even further than scattered stray radiation. In an accelerator, predominantly radioactive gas containing $^{11}$C, $^{13}$N, $^{15}$O and $^{41}$Ar is produced. By their $\beta^-$-decay, these atoms are responsible mainly for external exposure of humans in the environment.
4. **Activation of fluids (mainly water):** Water and other fluids circulating in areas where beam losses occur are undergoing nuclear reactions with the secondary particles. Liquids found in the accelerator are mainly water (demineralised and tap water) for cooling purposes, oil and Fluorinert for insulation of high voltage connectors. Oil can also be widely found in the ventilation stations, vacuum pumps and motors. In addition, activation of soil water may occur outside the accelerator building. Within the tap water circuits, corrosion occurs. Water and suspended corrosion products are transported outside the accelerator perimeter or lost through leakages in the circuit. The undissolved corrosion products are captured by filters or deposited in the water conducts. The radionuclides in solution (mainly tritium, \(^3\)H) are released with the water and expose the public. A number of demineralised water circuits are in shared used between equipments in the accelerator and technical installations outside the tunnel. The activation products (\(^3\)H) can be therefore found in a large number of cooled devices in the surface buildings (e.g. power supplies).

The first of the three relevant effects is illustrated in more detail for Section 16 of the PS and for the change of a main magnet unit (MMU) in the following sections.

### 3.1 Activation of accelerator components

#### 3.1.1 Measurement of ambient dose rate equivalent

In the PS, eight dose rate monitors (air-filled ionization chambers, calibrated in the quantity ambient dose equivalent (H*(10)) for gamma-emitters) are installed to monitor dose equivalent rate from activated materials. They are installed in critical locations in the straight sections 9 (below the PS Bridge), 16 (magnetic septum SMH16), 31 (electrostatic septum SEH31), 37 (beam loss point), 39 (beam loss point), 42 (injection septum SMH42), 63 (East Area extraction) and 75 (beam loss point). These monitors deliver on-line information on dose rates at their location once the accelerator is turned off. They are also called “induced activity monitors”. Monitor data is stored by the ARCON system once per hour but available in real time in a higher time resolution. This data permits to extrapolate the present dose rates into the future, projecting the radioactive decay. To a certain extent, the dose rate at other locations can be estimated if the ratio is known, for example from a ring survey measurement.

At least once per year, at the start of the annual shutdown period, a complete ring survey measurement is performed. Dose rate measurements are performed at the inside upstream and downstream positions of each straight section. The main objective is to provide dose rate data with a better location-dependent resolution for the maintenance and repair activities of the personnel. In addition, these data are used to review the past operation period with respect to beam loss and relative changes of such to the years before. The dose rate measurements give an approximate picture on where losses occur in the accelerator.

Figure 3-1 and Figure 3-2 show the results of radiation measurements in the PS ring. The first graph gives values measured in the corridor of the PS ring at about 2 m distance to the beam line. The second graph represents the annual measurements up- and downstream of each straight section.
Figure 3-1: Ambient dose equivalent rate in the PS tunnel at about 2 m distance from the beam line; measured on 7/12/2010, about 2 weeks after the end of operations with beam. The maximum values reached 500 µSv h⁻¹, the average and median levels are at 25 and 6 µSv h⁻¹, respectively.

Figure 3-2: Ambient dose equivalent rate in the PS at 40 cm distance from the beam line; measured on 07/12/2010, about 2 weeks after the end of operations with beam. The maximum values reached up to 5 mSv h⁻¹, the average and median levels are at 200 and 48 µSv h⁻¹, respectively.
Figure 3-3 shows the results of the radiation survey measurements from the last ten years inside the PS ring. The activation pattern reproduces very much the measured pattern of beam losses from the high intensity beams in CT extraction mode (see Figure 2-5). The activation pattern remains similar over the years and changed only in a few sections due to voluntary changes in the beam operation. Figure 3-4 shows the box plots of the results from the surveys of the last ten years.

For a more detailed analysis, two critical positions have been chosen in this report: The injection location at SS42 and the extraction region for most of the accelerated protons in SS16. Both areas show high activation levels, but they are not the only areas with such levels. High radiation levels are also observed in areas affected by beam loss induced by the CT extraction scheme. Replacing the CT by MTE would therefore drastically reduce activation and radiation levels in these sections while the injection and ejection will remain critical locations.

Figure 3-3: Results of the annual radiation survey measurements done in the PS ring over the last 10 years. Each campaign includes 200 positions measured 32 hours after the end of operations with beam, two at each PS straight section at 40 cm distance from the vacuum chamber.
Figure 3-4: Evolution of measured ambient dose equivalent rates in the PS ring over the last 10 years. The year 2005 is missing as there was no beam operation in the PS. The box plots give information about the distribution of the 200 measured dose rate values. The box comprises all values between the upper and lower quartile (=50%). The line inside the box gives the Median value. Extreme values which exceed 1.5 times the interquartile range are displayed as circles.

3.1.2 Extraction region SS16 and FT16

The beam loss on the septum blade in the upstream end of section 16 is leading to a sizeable activation of the accelerator components downstream of it. These include:

- The extraction septum itself;
- Main magnet unit 16 and its special, Y-shaped vacuum chamber;
- The first quadrupole in the TT2 line, FT16.QFO105.

Should any of these items fail for any reason, the CERN accelerator complex would have to be stopped until the repair of the faulty component. The availability of the CERN accelerator complex depends on an acceptably long waiting time after the stop of the beam for repairs. Figure 3-5 shows the result of two surveys of this area in December 2009 and in June 2010.

The next section deals with the estimation of dose equivalent rates close to the magnetic extraction septum SMH16.
Figure 3-5: Top: Plan view of the section of the PS tunnel between MMU 15 and MMU 19. The beam is circulating in the sense of increasing magnet numbers. A straight section always precedes the MMU with the same number. Bottom: Ambient dose equivalent rates at different measurement positions are indicated on the survey map for 1/6/2010, 26.5 h after the end of operations with beam. On the lower graph, this survey is reproduced in red, whereas the blue line indicates the results obtained during a survey on 17/12/2009, 4 weeks after the beam stop. The distance between accelerator vacuum chamber and measurement point was 10 cm.
3.1.3 Extrapolation of ambient dose equivalent rates

Build-up and decay of the concentration or the activity of a single radionuclide and thus of the dose rate emitted by it are described with a simple relationship containing the physical half-live of the nuclide. In the case of an accelerator, the situation is more complex, because of the presence of a mixture of different radionuclides with different production cross-sections and half-lives. In exact terms, the time-dependence of ambient dose equivalent rate after the stop of the activation at time \( t = 0 \) is the sum over the exponentials of all transitions \( i \) of as many radionuclides \( N \) present in the activated material.

\[
H^*(10) = \frac{1}{\tau^2} \sum_{i=1}^{N} A_0(N) \exp \left( -\frac{t}{\tau_N} \right) \Gamma(N)
\]

In this equation, \( A_0(N) \) is the activity of radionuclide \( N \) immediately after the stop of the accelerator and \( \Gamma(N) \) is the conversion coefficient between activity and ambient dose equivalent rate at a standard distance from the emitter. In practice, this relation has too many unknown parameters (\( A_0 \) for \( N \) different radionuclides) to be of practical use. An empirical relationship for the ambient dose equivalent rate of activated material has been developed by Sullivan [SULLIVAN]. It is based on the observation, that ambient dose equivalent rate emitted by activated accelerator components is approximately a linear function of the logarithm of the decay time,

\[
H^*(10) \equiv H_1 \left( 1 - \frac{B}{H_1} \ln(t) \right)
\]

where the parameter \( H_1 \) is the dose rate one day after the stop of activation and \( B \) characterizes the radiation source and its irradiation history. These two parameters are best fitted to a limited data set (for example, dose equivalent rates spanning a few days) in order to make predictions for longer time ranges. The relation has shown to be valid for decay times from about 1 day to 100 days. Figure 3-6 shows the decreasing ambient dose equivalent rate at SS 16, for decay times from 1 hour to 95 days and the fitted decay curve. The values were measured in the shut-down between November 2008 and February 2009. It can be seen that the equation above describes very well the radiation levels during decay of the complex radionuclide mixture in an accelerator component. In this case, the ambient dose equivalent rate measured immediately after turning off the accelerator was significantly lower than measured today, because at that time, most of the protons were extracted in CT transfer, with a much smaller impact on the magnetic septum in SS 16.
3.1.4 Possible evolution of the activation of the septum in section 16

It is not possible to measure the time-evolution of activity (and thus of dose rate) during the build-up phase, because the induced activity monitors are saturated with the prompt radiation from beam loss during accelerator operation. For an estimation of future dose rate levels from activated materials, one must resort to a Monte-Carlo radiation transport calculation coupled to a nuclear model [FLUKA] to estimate the evolution with time of radionuclide concentrations and ambient dose equivalent rates from activated accelerator components.

For the following study of activation and ambient dose rates at septum SMH16, a simplified model of the extraction septum and two main magnet units is used in the simulation code. The septum is represented by a copper block for the yoke and a 3 mm thick copper slab for the blade. They are placed in a hollow stainless steel cylinder with 10 mm thick walls, representing the vacuum vessel (“tank”). The “tank” is closed on its ends with 20 mm thick cylindrical discs for the vacuum flanges. The additional material of the thicker-than-real tank walls compensates for omitted details in these explorative calculations. Four stainless steel slabs of the approximate size and mass of ionization pumps are arranged at their approximate real locations under the septum tank.

Figure 3-6: Ambient dose equivalent rate measured at PMIPS16 (blue dots), 18 November 2008 – Spring 2009. In red is a fit according to the Sullivan relationship described in the text.

\[ y = -0.74 \ln(x) + 4.2 \]
Figure 3-7: Two projections of the lay-out of the magnetic septum SMH16, simplified for the Monte-Carlo radiation transport simulation with FLUKA. Left: view in beam-direction. Right: view from the inside of the PS ring, longitudinally cut in the plane of the septum blade. The beam moves from left to right. At the left of the image the stylized representation of the downstream end of main magnet unit MMU 15 is visible. Under the septum, an ionization pump can be recognized.

It has been stated above (Table 2-4), that the losses of a well-tuned MTE extraction scheme without the possibility of bunching the beam will amount to 2 % of the intensity [MTE]. Applied to the maximum required intensity (night-time cycle, Table 2-3), this corresponds to $1.3 \times 10^{11}$ protons per second. Simulations of the MTE suggest that half of the beam loss occurs on the 3 mm thick blade of the magnetic septum with a beam momentum of 14 GeV/c. A series of activation and decay calculations were performed with different durations of the irradiation time and with a beam intensity of $6.4 \times 10^{10}$ s$^{-1}$ impinging on the septum blade. It was assumed that the septum was not radioactive at the beginning of the irradiation. For each run, ambient dose equivalent rate was scored after a series of decay (waiting) times. Because present beam intensity and beam loss monitors do not allow to quantify the losses with very high precision, Figure 3-8 shows the evolution of ambient dose equivalent rate $H^*(10)$ at the most exposed location of the septum after a run of 160 days duration with a beam loss of either $6.4 \times 10^{10}$ s$^{-1}$ or $1.3 \times 10^{11}$ s$^{-1}$. The similarity to Figure 3-6 is evident. Figure 3-9 shows a family of decay curves for different irradiation times, plotted as a function of the logarithm of the decay time. Figure 3-10 uses the same data as represented in Figure 3-9, but here, the ambient dose equivalent rate is represented as a function of irradiation time and parameterized by the decay time (waiting time) after the stop of the accelerator. Thus the figure permits to estimate the build-up of dose rate with continued operation of the accelerator.
Figure 3-8: Simulated decrease of ambient dose equivalent rate $H^*(10)$ at the magnetic septum SMH16 for an irradiation period of 160 days for waiting times between 1 hour and 200 days. The beam intensity hitting the septum blade is $6.4 \times 10^{10}$ p s$^{-1}$ or $1.3 \times 10^{11}$ p s$^{-1}$. The vertical line indicates a waiting time of 14 days.

Figure 3-9: Simulated decrease of ambient dose equivalent rate $H^*(10)$ at the magnetic septum SMH16 for different irradiation periods and for waiting times between 1 hour and 200 days. The beam intensity hitting the septum blade is $6.4 \times 10^{10}$ p s$^{-1}$. The vertical line indicates a waiting time of 14 days.
Figure 3-10: Build-up of ambient dose equivalent rate at septum SMH16 as a function of irradiation time for a loss of $6.4 \times 10^{10}$ protons per second on the septum coil. Curves ordered by the parameter waiting time. The same parameters and results as in Figure 3-9 are used.

3.1.5 Personal dose during interventions on septum 16

As noted earlier, a failure of Septum 16 would lead to a standstill of all experiments relying on the delivery of high-energy beams from the CERN accelerator complex. This situation is considered as acceptable for a duration not longer than 14 days [COLLIER]. A longer waiting time is not very efficient, the logarithmic nature of the decay curves makes that a waiting time of 4 weeks would reduce the ambient dose rate only by further 10%.

From the estimated decay curves and from operational experience, an estimation of the necessary waiting time during a standard PS run can be made. As one scenario, a situation is assumed in which the whole septum must be exchanged against a spare. This is a routine operation, repeated every 2 to 3 years during a shutdown of the PS, and the technical personnel involved is trained to exchange the septum reliably in a short time.

From the records of the past exchanges of the septum, the following heuristic relation between the ambient dose rate, the collective personal dose and the maximal personal dose can be inferred: For an ambient dose equivalent rate of $H^*(10) = N \text{ mSv h}^{-1}$ at the highest exposed position (at the upstream end of the septum on the inside of the ring), the collective personal dose received during the septum exchange will amount to $H_{\text{coll}} = 0.275 N \text{ person-mSv}$ and the highest exposed individual will receive a personal dose of $H_p(10) = 0.025 N \text{ mSv}$. These values apply for smooth exchanges of the septum without
any technical problems. In the case of repeated vacuum intervention or alignment issues, the individual doses can increase considerably by factors between 2 and 5, as seen in the past.

Radiation protection regulations at CERN stipulate that the personal dose received during a planned intervention, must not exceed $H_p(10) = 2 \text{ mSv}$. Assuming a factor 4 as safety margin for unexpected complications during the septum exchange, the ambient dose equivalent rate at the beginning of the intervention shall be lower than $H^*(10) < 20 \text{ mSv h}^{-1}$. In this case, the highest personal dose will very likely remain below 2 mSv and the collective dose below 5.5 person–mSv. From Figure 3-6 and Figure 3-9, one can read that for a PS run of 160 days and for optimized beam loss on Septum SMH16, an ambient dose equivalent rate of 20 mSv h$^{-1}$ will be attained after a waiting time of up to 14 days after a stop of the beam.

The statement made here is approximate for three reasons:

- Although the quoted simulation results reproduce dose rate measurements at short decay times reasonably well, the accuracy of the simulated long-time behavior of activity and dose rate is affected by uncertainties of the Monte-Carlo simulation code and of the approximate representation of materials and structures;

- The number of protons hitting the septum blade is unknown within a factor of two; Figure 3-8 shows the variability of the resulting dose equivalent rate;

- A bias arises from the policy to operate between long shutdowns in 2013 and in 2017 with extended technical stops with a duration of about 2 months. From Figure 3-9 one can see that after a decay period of 60 days, the ambient dose rate on the septum will decay only to a value of $H^*(10) = 10 \text{ mSv h}^{-1}$. This bias may prolong the waiting time after a septum failure.

Naturally, the decision to start the septum exchange must be based on a dose rate measurement. A first indication is given by an induced activity monitor at a representative location at the upstream end of Septum 16. Its measurement must be confirmed by a radiation survey around the septum. With the safety margin above, one can conclude that a septum exchange, with a highest personal dose $H_p(10) < 2 \text{ mSv}$ is possible within 14 days from the stop of the PS accelerator, if beam loss on septum 16 is limited to approximately $6.4 \times 10^{10} \text{s}^{-1}$.

These estimates have been made for an optimized MTE transfer with the present technical equipment in the PS ring. Technical options to further reduce beam loss on the extraction septum SMH 16 are discussed in section 2.2.3.3. A possibility to reduce the time of a septum exchange and thus the personal dose during interventions on SMH 16 and downstream of it would be a reconstruction of the components with the possibility for rapid removal, installation and alignment (plug-in / plug-out). An example for this construction method has been used in the LHC collimator regions.

**3.1.6 Exchange of a PS main magnet unit**

Among the scenarios of urgent interventions during a PS run, the replacement of a main magnet unit would require a long intervention time for a considerable number of persons. During the long shutdown
in 2005 and two further shutdowns in 2007/8 and 2008/9 a total of 56 magnets had been exchanged and renovated. The required time and procedure to replace a faulty magnet by a ready spare magnet is therefore well known. For the removal as for the reinstallation, a total of 8 hours for four experienced transport specialists is considered. This does not include the potentially required removal of equipment from adjacent straight sections, which would even further increase the intervention time for the same transport team. Rather short interventions by magnet and vacuum specialists are required to prepare the magnet. In this simple approach, where all steps are considered to be optimized, one can easily deduce the maximum admissible dose rate before starting such an intervention. Given the maximum individual dose must not exceed 2 mSv per individual for one intervention, an ambient dose rate of roughly 250 µSv/h on average must not be exceeded. Increasing this value by means of dose sharing is difficult to envisage for the main magnet manipulations, considering the few experienced transport specialists currently available.

A complete intervention includes a possible removal of equipment from straight sections to allow access, disconnection and reconnection of vacuum, power, cooling and beam instrumentation, the alignment measurements and testing. At a dose rate of 250 µSv/h one can expect a collective dose for the whole intervention of about 30-40 person-mSv distributed among 10-15 persons with maximum doses of 2 mSv for some individuals. These values have been determined by averaging over a number of removal interventions done in 2005.

Figure 3-11 illustrates ambient dose rate levels in the PS tunnel for three different decay periods. The sectors shown represent the most activated sectors in the PS tunnel. The high levels are due to CT extraction losses. Given the measured dose rates, one would require at minimum a decay time of 7 days for a number of magnets in this sector before starting a still quite costly intervention in terms of doses. For a total decay time of 14 days, one can expect a further decrease of the dose rate by 20%.
Figure 3-11: Ambient dose equivalent rates along the PS, at 2 m distance from the beam line, going from section 29 to 52; measured 1 hour after beam stop (20/09/2010) and extrapolated for decay times of 24 hours and 7 days. 14 days of decay time would further reduce the levels by approximately 20%.

3.1.7 Other scenarios

There are a number of scenarios that have not yet been planned or executed within the last ten years. In prospective of a complete risk analysis and optimization approach, a removal, repair or replacement procedure shall be established for each of the installed equipments. In the list below, a non-exhaustive list of possibly critical equipment is given.

- **Other septa**
  Besides Septum SMH16, the septa SMH42 and SEH31 have been already exchanged several times in the past. Quite reliable data is available to estimate the dose impact for such interventions. Other septa in sections 23, 26 and 57 are less of concern, as dose rates usually are much lower compared to first ones, while not being more complex for the removal.

- **Dumps**
  The two internal dumps in sections 47 and 48 have been designed to allow a quick removal. Although highly active, disconnection, removal and replacement by a spare have not been of major concern in past interventions. The activation levels depend heavily on the use of the dumps before the intervention.
\begin{itemize}
\item **RF cavities**
Most of the RF cavities are located in low activation sections. However, the removal, repair or replacement of different types of cavities can be very time consuming and difficult in terms of handling and transport. There is no experience available for replacement of such devices from the last ten years. Depending on the evolution of activation in the PS tunnel, this might become critical for some sections and shall be studied more in detail.

\item **Kicker magnets**
As for the RF cavities, not much experience is available in the replacement of kicker magnets. Depending on the installation position and the activation levels the dose impact is unknown at the time being; hence no limiting dose rate can be given.

\item **Main magnet bus bars**
The main magnet bus bar represents a critical element due to expected frequent failures. The removal of such a bus bar can be quite delicate, requiring the displacement of other equipment within straight sections or a full main magnet. Personal doses are mainly determined by the preparatory work, before being able to remove a bus bar.

\item **Zero-spare equipment**
There may exist a number of equipments for which no operational spares are available. In case of a failure of such equipment, it has to be removed from the tunnel and immediately repaired. Depending on the activation level, this can be costly in terms of doses.
\end{itemize}

### 3.1.8 Beam loss constraints

Based on the scenarios for the removal of the septum SMH16 and the removal of a main magnet unit in a highly activated sector, constraints for beam loss in the PS can be given. Given a maximum acceptable time of 14 days between the failure of an equipment and the start of repair, and an ambient dose rate averaged around the main magnets of 250 μSv h⁻¹, the beam loss at full energy must not exceed $10^{10}$ protons per second in any location of the PS ring. In the case of extraction septa, which can be exchanged more rapidly than MMUs, a maximal beam loss rate of $10^{11}$ s⁻¹ is acceptable. The beam loss integrated over all 100 sections of the PS shall not exceed $10^{12}$ s⁻¹. If technically feasible, and not in contradiction with other requirements put on the beams (e.g. energy, intensity, time structure), beam loss shall be further optimized below the constraint.

These constraints for continuous, routine operation are expressed as orders of magnitude, reflecting their limited precision: They have been derived from simulation calculations (albeit based on measurements) and from simplified intervention scenarios in the PS. Both simulation calculations and scenarios are subject to uncertainties that are difficult to quantify. The scenario for septum exchange contains a safety margin contributing a further factor of uncertainty.

The authors believe that the implementation of the inherently conservative constraints guarantees the possibility of repairing major failures in the PS with acceptable, optimized personal doses within a fortnight of the breakdown. Introduction of the constraints will reduce the present uncertainty in intervention planning considerably.
3.2 Stray Radiation

3.2.1 General considerations

Stray radiation produced by the PS has an important impact on its environment as the accelerator is built close to the surface. Sufficient shielding between accessible areas and the accelerator enclosure is elementary to comply with the regulations for dose limits and dose constraints to the personnel and public. As beam loss inevitably occurs during accelerator operation, a minimum of such passive protection is required to maintain the flexibility for beam setting up and operation without exposing personnel and public above the legal limits.

Since its construction in 1959 the PS has seen a large increase in beam intensity. While the first maximum intensities were in the order of \(10^{10}\) protons per pulse, record intensities achieved recently during short periods exceeded the figure of \(3 \times 10^{13}\) protons per pulse. These increases have been achieved continuously thanks to improvements in the beam control, the addition of Linac 2 and the Booster which increased injection energy to the PS (see Figure 3-12).

![PS Proton Intensity Evolution Over 50 Years](image)

**Figure 3-12:** Evolution of the typical and maximum intensity delivered by the PS since its first operation.

In the past, the PS has certainly been well shielded for the operated beam power considering that internal targets had been used and that the major part of the beam power was lost inside the PS tunnel. Nowadays, with a more than a 1000 fold increase in intensity, the shielding would be no longer sufficient for such large losses, even after the two upgrades of the shielding which took place in the late 60s and the late 70s. Indeed, the beam control has been improved considerably as it can be seen in the decrease of the induced activation levels. With the removal of internal targets, a large part of the beam power is transferred outside the tunnel to specific target areas, further accelerators or dumps. But with today’s beam intensities in the order of \(1 \times 10^{18}\) s\(^{-1}\), losses of less than 1% would still be a factor of ten higher than the initial full beam intensity of the PS.
During the 50 years of PS operation, the radiation protection approach, limits and constraints have changed drastically. The perception of radiation risk, by the public as well as by the personnel, has evolved considerably. Newly introduced constraints above which justification and optimization of the exposure is required force to further optimize levels which have been acceptable only a few years ago without any further action. Safety Code F “Radiation Protection” (2006) [CODEF] stipulates in paragraphs 2.2.2 and 2.3.4 the justification and optimization of any exposure of personnel above 100 µSv per year and 10 µSv per year for the exposure of the general public. The code regulates as well, complemented by its underlying safety instructions, the classification of radiation areas where annual limits for non-exposed workers are possibly exceeded.

### 3.2.2 Top shielding on the PS ring

In September 2010, a survey campaign was performed in order to determine the top shielding level of the PS. The PS tunnel floor is situated at the 432.40 m (above sea) level, the beam line is passing at 1.26 m height from the tunnel floor. The PS tunnel internal height is about 4 m in a standard section. The level of the top shielding varies between 438 m (close to B.151) and 443 m (close to B.157). The largest part of tunnel top shielding is uniformly at a level of 441.2 m. This leads to different shielding thicknesses for different sectors of the PS. Table 3-1 gives the details on the levels of different positions at the PS, including the distance to the beam and the present shielding thickness. The weakest shielding thickness is found in B.151, where the PS is enclosed by the PS Bridge. The shielding thickness (concrete) varies there between 1.8 m and 3.4 m. The PS Bridge top area is inaccessible during beam operation and the personnel access safety system to this area is interlocked with the beam. The impact of stray radiation from the PS Bridge has been thoroughly studied in the framework of the BLRWG (Beam Loss and Radiation Working Group) in 2005 [BLRWG, OTTO].

Usually, no access is allowed on top of the PS during beam operation, with exception of the three crossings. The main impact from stray radiation emerging through the top shielding is coming from skyshine effects on the surrounding buildings on the Meyrin site. This impact will be addressed in section 3.2.6 for the specific case of SS16 (corresponding to position 9 in Table 3-1).

Unfortunately, the weakest thickness of top shielding coincides with those accelerator sections in which the losses are the highest – injection and extraction. In addition, it seems that these areas have been overlooked in the efforts of shielding improvements in the 1960s and the 1970s.
Table 3-1 Different positions at the PS with their corresponding levels above sea. For positions on top of the PS tunnel, the distance to the beam and the present shielding thickness is given.

<table>
<thead>
<tr>
<th>Position</th>
<th>Altimetry level</th>
<th>Distance to beam</th>
<th>Shielding thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PS tunnel floor</td>
<td>432.40 m</td>
<td>1.26 m</td>
<td>-</td>
</tr>
<tr>
<td>2 PS beam</td>
<td>433.66 m</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 PS tunnel ceiling (most parts)</td>
<td>436.40 m</td>
<td>2.74 m</td>
<td>-</td>
</tr>
<tr>
<td>4 PS Bridge (B.151)</td>
<td>438.90 m</td>
<td>5.24 m</td>
<td>1.8 m</td>
</tr>
<tr>
<td>5 Route Goward crossing</td>
<td>440 m</td>
<td>6.34 m</td>
<td>3.6 m</td>
</tr>
<tr>
<td>6 Close to B.157</td>
<td>443 m</td>
<td>9.34 m</td>
<td>6.6 m</td>
</tr>
<tr>
<td>7 Pathway B.561 to B.289/400</td>
<td>441.80 m</td>
<td>8.14 m</td>
<td>5.4 m</td>
</tr>
<tr>
<td>8 Pathway B.367 to B.152</td>
<td>441.20 m</td>
<td>7.54 m</td>
<td>4.8 m</td>
</tr>
<tr>
<td>9 On top of SS16</td>
<td>439.40 m</td>
<td>5.74 m</td>
<td>3.0 m</td>
</tr>
<tr>
<td>10 Top shielding PS (large part)</td>
<td>441.20 m</td>
<td>7.54 m</td>
<td>4.8 m</td>
</tr>
<tr>
<td>11 Buildings PS centre</td>
<td>437 m</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3-13: Top view of the PS with geodetic altimetry data and the positions as listed in Table 3-1.
3.2.3 Side shielding of the PS ring

The side shielding against stray radiation towards accessible areas is more difficult to assess: no profile drawings exist that would represent the true shape of the inclined site surface and the building positions with respect to the PS tunnel. The buildings in the centre of the ring are slightly above the beam level (437 m), but lower than the top shielding of the PS. As the site surface is elevated towards the NW-N direction, all buildings in this direction outside the ring are situated above the top shielding level. These buildings are therefore mostly affected by radiation emerging through the top shielding – direct or via shelter shine. Buildings situated outside the PS ring along the Route Democrite are at about the same level as the PS centre (Building 356: 436m) and fall off to approximately the level of the beam (Buildings 157, 2003 to 355). The buildings on the S-SW side (B.150) are similarly situated at the level of the beam.

The minimal thickness of side shielding at the PS can be found inside the buildings 150 and 151. Along the PS Bridge, the concrete walls towards the PS have a thickness of about 5 m (inside) to 5.5 m (outside). It is expected that the side shielding in other locations is larger than 6-8 m. The shortest distance between buildings and the PS is 10 – 15 m, but usually more for most of the buildings situated at the beam level.

There is a possible effect of muons emerging from beam loss locations in forward direction leading to higher radiation levels in buildings located at beam level. This has been observed in B.150, where exceptional losses occasionally occur on extraction kickers in SS75. The same has been seen in B.157, where losses inside the PS are detected by the radiation monitors installed in the East Area. In forward direction of the PS internal dumps in SS47 and SS48, additional iron and concrete shielding was put in place behind B.356, most likely for the same reason.

Apart from the fixed radiation monitoring systems in the East Area, at CTF3 and in the PS South hall, no measurement data are available for other buildings situated at the beam level in the N-E-S-SW sector. Beam losses in the sections SS50 to SS01 (N → S) are rather low and exceptional losses are not observed very frequently in e.g. the East Area or the PS South hall. This makes it difficult to acquire data with mobile systems. With RAMSES2 light, the fixed monitoring of these sectors has been improved by adding radiation monitors at critical locations.
Figure 3-14: Radiation monitors installed at fixed locations around the PS accelerator. For the monitors in green, being connected to the ARCON system, data is available since about 1995. The monitors in blue have been recently installed for RAMSES at CTF3 (2008) and RAMSES2 light (2011). With exception of the monitors at ISOLDE and in the East Area, all remaining ARCON monitors have now been replaced by RAMSES2 light monitors.

For a comprehensive picture of the implementation of the PS tunnel on the Meyrin Site with respect to all buildings in proximity, a complete 3D model shall be established based on as-built drawings and survey measurements where required. This would be helpful to estimate the radiation impact on buildings situated at the level of the beam by a generic study of beam losses and a subsequent estimation of radiation levels behind thick shielding in forward direction.

3.2.4 Stray radiation streaming through ducts or other openings

The PS tunnel is equipped with an enormous number of openings for personnel access and for the supply of cooling water, air, electrical power and control cabling into and out of the tunnel.

Access doors

Four regular access doors exist. Two of them, D.102 and D.111, include an access chicane and a mobile shielding block that represents a reduction in effective shielding thickness compared to the shielding present left and right of the access point. One access door, D.121, is situated at the end of a bent access tunnel, where stray radiation may easily stream through. At that part, one of the radial technical galleries passes, possibly functioning effectively as a neutron trap. The effectiveness of the bent tunnel, the ‘neutron trap’ as well as the distance towards the PS, has not been studied yet.
Emergency exits
There are several emergency exits representing more penetrations through the shielding. The resulting reduction of the shielding capability was thoroughly studied for D.122, which is situated at the end of the bent access tunnel towards SS16 [DAMJANOVIC2]. Due to important beam losses in SS16, significant radiation levels have been measured in the court yard in front of D.122 and B.151. An additional shielding wall has been installed in front of D.121 at the beginning of the run in 2010 as a compensatory measure.

The exit door D.113 towards B.157 also represents a shielding weakness towards the PS. In 2007 an important loss point has been moved from SS09 to SS75 to reduce the stray radiation impact in the PS South and North hall. This loss point is now situated in the proximity of D.113. A new fixed radiation monitor has been installed in 2011 for the permanent surveillance of this position to gain additional data of the radiological situation.

The emergency exit doors D.130 (LEIR) and D.133 (Linac3) are close to the ejection towards the TT2 tunnel. A quite complex geometry of beam lines, brick shielding, chicanes and technical galleries increases the difficulty to assess the shielding effectiveness in a generic study or with simulation calculations. The doors D.220 and D.120 lead to the tunnels TT2 and PS Booster. During proton operation, the PS Booster remains inaccessible. The radiological separation between TT2 and the PS tunnel needs to be assessed, as the current shielding thickness and the effectiveness of the connecting chicane are unknown. For any operation with light ions, in which the PS Booster is not involved, an eventual impact from the PS on the Booster area needs to be assessed.
Figure 3-15: Access and emergency exit doors at the PS. D.109, 112 are located underground, inside technical galleries. D.101 is inside the surface building B.353; all other doors are situated at the level of the beam.

**Ducts**
A number of other locations where cabling ducts enter the PS tunnel may represent a pathway for stray radiation. The presently known locations are:

- B.362 (Kicker supply building) on top of SS45, vertical duct;
- Power supply cabling and water supply towards B.356 (see Figure 3-16), 2 horizontal technical galleries;
- Openings for survey measurements or other experiments in the past (on top of ejection area FT61);
- A technical gallery, partially shielded between SS16 and the Linac 3 area, crossing on top of the LEIR injection/ejection tunnel (see Figure 3-16);
- Former beam line passages towards TT70 and B.2003 (CTF3 DL/CR, former EPA);
- Technical gallery from B.6 and 355 towards PS SS01 via D.109;
- 8 ventilation shafts all around the PS ring;
- 4 radial technical galleries towards the ring centre;
- 4 ovoid ducts towards the ring centre; one ovoid is cut and open at the level of B.151 and door D.122.
Figure 3-16: Technical gallery towards B.356, partially closed with lead bricks and sand bags (upper two images). Brick shielding below PS Bridge towards B.150 (lower left) and technical gallery opening towards Linac 3 (lower right).
The following two chapters will focus on the two most important weak shielding points, where considerable stray radiation levels are present during routine operation. The first position is where Route Goward crosses the PS tunnel. At this position, several conditions merge, leading to a non-compliant situation with respect to radiation protection regulations. While the top shielding is lower than on the inaccessible rest of the PS ring, this part remains paradoxically accessible during beam operation. At the same time, the crossing is located close to the injection section of the PS, where increased beam loss occurs. This leads to permanently high radiation level on the road, an area which should be classified as a non-designated area. The second position is located on top of the ejection section SS16. Again, less than the average shielding thickness on top of the PS ring leads to high dose rate levels coming from beam losses during ejection towards TT2. Although the area remains inaccessible during beam operation, the stray radiation levels are so high that a considerable exposure from skyshine can be observed in the surroundings of the PS and even outside of the CERN site.

3.2.5 Stray radiation on Route Goward

Route Goward crosses the PS to allow vehicle access to the centre of the PS Ring (see Figure 3-15). The shielding thickness at this position is reduced compared to the rest of the ring top shielding and represents one of the weakest shielded areas. The road crosses the PS at the 440.0 m level, while the rest of the ring is covered up to 441.2 m. The PS beam level is situated at 433.66 m. At the Route Goward this results to approximately 3.6 m earth/concrete shielding.

The road crossing is situated on top of MU43 and SS44, only a few meters downstream of the injection point into the PS (SS42), where losses are observed mainly at injection and during the CT extraction under normal operating conditions.

Radiation measurements on the road crossing showed that the ambient dose equivalent exceeds by far 2.5 $\mu$Sv·h$^{-1}$, which is the applicable limit for non-designated non-permanent stay areas on CERN sites. After the identification of this situation in August 2006, the area has been classified as a supervised radiation area as a temporary solution. As a warning measure, the street level has been painted with a yellow-black pattern and a barrier has been installed. However, the permanent classification of a freely accessible area is not foreseen in the Safety Code F [CODEF]. Hence, a structural solution has to be found which inevitably includes additional shielding measures, as access to the area cannot be avoided because it represents the only access for vehicles into the PS Ring centre.

The current situation with a light barrier is not satisfying and not according to the rules in force. On one hand the barrier is an obstacle to free passage into the centre of the PS for those who have their workplaces there (BE-RF, TE-PC, DGS-RP groups), on the other hand it cannot prevent unauthorized persons (members of the public) from crossing on foot or as guests in a vehicle and thus being unduly exposed.

3.2.5.1 Stray radiation measurement

Since 2006, frequent radiation measurements have been performed on the Route Goward. A fixed radiation monitor (PAXS51, Figure 3-14) had been installed in order to permanently monitor the
radiation level and to prevent excessive radiation levels over longer periods in case of increased beam loss.

A mobile monitoring system has been employed to measure the spatial distribution of stray radiation on Route Goward. The first measurement was conducted in August 2006 with beam extracted by the CT process. It was found that the radiation was not very localized but distributed across the road with a rather low gradient. A second, higher resolution mapping was carried out on 10 March 2010 in order to validate Monte-Carlo simulation results [DAMJANOVIC01]. The measurement has been performed during a period where only the MTE transfer, which does not generate beam loss downstream of MMU 16, was in use. This means that losses under Route Goward originated exclusively from the injection process. The average intensity of the beam injected into the PS amounted to $2.25 \times 10^{12}$ protons per second during the measurement. It should be noted that this represents less than a third of the intensity injected under full intensity operation conditions of the PS, when up to $8.2 \times 10^{12}$ protons per second are currently injected. Figure 3-17 shows a two-dimensional distribution of the losses on the road surface and adjacent areas as measured in 2010.

Figure 3-17: Measured 2-dimensional distribution of net ambient dose rate $H^*(10)$ in $\mu Sv\cdot h^{-1}$ at 50 cm height in the region of Route Goward crossing the PS. The PS was operated with an average beam intensity of $2.25 \times 10^{12}$ protons per second and MTE extraction only. The MTE extraction was operating without island extraction. The measured dose rate originates mainly from the losses during injection at $E_i = 1.4$ GeV.
3.2.5.2 Simulation of beam loss upon Injection

A Monte-Carlo simulation of the transport of secondary particles and radiation from an assumed beam loss in the PS injection region has been carried out with the code Fluka2008. In the calculation, beam loss is supposed to occur with an energy of 1.4 GeV at seven defined points along the beam line in the injection region. The intensity of beam loss at these points has been determined such, that the readings of three beam loss monitors (BLM 43 to BLM 45 mounted on top of the MU43, MU44 and MU45) is reproduced. The reading of a fourth BLM (BLM 42 on MU42) has to be reduced by a factor of 2 in order to match the simulated data. The cause of this must be investigated. With the distribution of beam loss defined in this way, the dose rate profile on the road level behind approximately 3.6 meters of shielding can be very well reproduced (Figure 3-18). Based on the results of the simulation, the ambient dose equivalent on the Route Goward determined with this loss scenario amounts to \((5.3\pm0.03)\times10^{-8}\) pSv per lost proton. The absolute value of ambient dose equivalent rate matches that of the measurement if one assumes a loss of 1.4 % of the injected beam intensity. Due to the large measurement uncertainties of the beam transformers, this result cannot be confirmed by beam intensity measurements (see section 2.2.1.2).

![Dose Rate Chart](image)

Figure 3-18: Measured (open circles) and simulated (filled circles) profile of ambient dose equivalent rate above route Goward during a test with \(2.26\times10^{12}\) protons injected into the PS per second. The good correspondence between simulation and measurement could only be obtained by reducing the reading of BLM 42 by 50 %.

3.2.5.3 Present radiation levels on Route Goward

Radiation levels on the crossing of Route Goward with the PS exceed routinely and by a large margin the ambient dose rate limit for publicly accessible areas (2.5 \(\mu\text{Sv} \cdot \text{h}^{-1}\) for non-permanently occupied public locations). When the CNGS and fixed target programs are running at full intensity with CT extraction, then the ambient dose equivalent rate attains values above 15 \(\mu\text{Sv} \cdot \text{h}^{-1}\) (see Figure 3-19). The use of the
MTE scheme will eliminate beam loss upon extraction in this sector, but even after implementing the MTE transfer, a further reduction of ambient dose equivalent rate is required to comply with the current radiation protection regulations.

Figure 3-19: Ambient dose equivalent rates measured in 2010 of PAX51, situated at the crossing of Route Goward over the PS tunnel.

From the results of measurements in 2006 and 2010 on Route Goward, one can relate the measured dose rate to the injected beam intensity. It was found that the value amounts to about 0.025 μSv·h\(^{-1}\) per 1·10\(^{10}\) s\(^{-1}\) injected into the PS for an intensity of (2-2.2)·10\(^{12}\) protons per pulse. Surprisingly, the same value was found independently if the beam was ejected in fast extraction mode or CT mode. In 2006 it was found that about half of the measured ambient dose rate was originating in beam loss at injection, while the other half could be contributed to beam loss during the CT extraction. While it was confirmed that MTE beam, even when extracted fast, does not cause beam loss in this section, the reason underlying the discrepancy is presently unknown. Further investigations will be done once the new radiation monitoring system is operational as it allows a cycle by cycle measurement.

Table 3-2: Correlation factors between dose rate measured on the Route Goward and the injected beam intensities for the two extraction methods. The last two columns give the maximum permissible injected beam intensity to comply with the dose rate limits for the current loss situation.
3.2.5.4 Reduction of radiation levels on Route Goward

The most straightforward solution appears to be a reinforcement of the shielding of the PS at the crossing point. A series of beam dynamics studies so far did not show any margin to significantly reduce the existing losses, at least not by the factor required to change the classification of the road. Even in a scenario where the injection point into the PS would be moved further upstream, this region will remain very sensitive to beam loss due to the lack of shielding. Without additional shielding of the PS at the crossing, frequent excesses of the ambient dose rate limits would occur and have an impact on the beam operation efficiency.

Simulations, validated by measurements of the dose rate profile on Route Goward (see 3.2.5.2), indicate that 40 cm of ordinary concrete would reduce the ambient dose rate by a factor of 2.0 for beam loss at an injection energy of $E=1.4$ GeV and 80 cm by a factor of 4.7. An additional shielding of at least 120 cm of ordinary concrete would be required to attain an acceptably low ambient dose equivalent rate level on Route Goward under the present operation conditions. The shielding thickness missing as compared to the rest of the PS ring is about 120 cm; this shall therefore be the minimum amount to be added. The final recommendation for the addition of shielding on the Route Goward shall take into account future intensities and energies. This topic is addressed in section 4.1.

A part of the injection beam loss is due to the extended physical beam size at the septum location. Its influence on Route Goward could be reduced by displacing the injection septum to an upstream location, for example to SS41.

As a general remark, the presently available beam instrumentation is not sufficient to conduct investigations into the different loss mechanisms. A fast transformer, fast pick-ups and beam loss monitors with a dynamic range larger than the current one would represent the minimum equipment necessary to study the loss mechanism and to devise countermeasures. In this perspective, a series of studies it is planned, like re-establishing an updated impedance model (transverse and longitudinal) and re-measuring the machine dynamical aperture to redefine the machine acceptance at low energy.

It is worth to mention that an important reduction of the integrated losses has been reached thanks to the continuous monitoring of the injection efficiencies and the subsequent optimization done by the operation crews.

3.2.6 Stray radiation from Straight Section 16

Straight section 16 houses the magnetic septum where most of the beam loss occurs during MTE extraction and considerable losses take place for other extraction modes. The secondary radiation cascade penetrates the roof shielding in the area. “Skyshine” (radiation diffusion by multiple scattering in air) is the cause for measurable levels of ambient dose equivalent on the Meyrin Site in proximity of the PS ring. Figure 3-20 shows the position of Straight section 16 with locations of the environmental monitor stations and with distances to the surrounding buildings.
Figure 3-20: Distances (m) between the loss point in SS16 of the PS (star in the centre) and the surrounding buildings. “PMS” indicates the environmental monitor stations in the vicinity of the PS.

Table 3-3: Correlation factors between the ambient dose rate measured on top of SS16 (PAXS35) and the ejected beam intensities for the two extraction methods MTE and CT. The last two columns give the maximum permissible ejected beam intensity to fall below the 100 µSv per year criteria for personnel in the buildings on the CERN site.

<table>
<thead>
<tr>
<th>MTE only (03/2010) (with ~ 2.0·10^{13} ppp)</th>
<th>CT only (08/2006) (with ~ 2.2·10^{13} ppp)</th>
<th>Dose rate limits</th>
<th>Derived max. permissible injected beam intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>[µSv·h^{-1} per 10^{10} protons per second]</td>
<td>[µSv·h^{-1}]</td>
<td>[10^{10} protons per second]</td>
<td></td>
</tr>
<tr>
<td>0.43</td>
<td>0.08</td>
<td>30</td>
<td>CT: 380 / MTE: 70</td>
</tr>
</tbody>
</table>
3.2.6.1 Correlation of stray radiation from SS16 to site monitors

The dosimetric impact of stray radiation on the Meyrin site and beyond of the different CERN accelerator installations on the Meyrin site is permanently monitored by active and passive area monitors. In order to visualize the contribution of the PS to the exposure on site, ambient doses from stray radiation caused by beam loss in the PS have been correlated with the readings of the environmental site monitors. As shown in Figure 3-21, there is a strong correlation between the ambient doses measured on top of SS16 and the neutron radiation doses at some distance from the PS. Clearly visible as well are the different loss positions for CT and MTE extracted beams. While for CT, the main losses occur in straight sections 31 and downstream (close to PMS128), the MTE losses are concentrated in SS16. In order to reduce the dosimetric impact on the site, limiting the losses in SS16 is mandatory.

Figure 3-21: Correlation between ambient dose rates measured above SS16 and the dose rate from neutrons measured by the environmental site monitors in proximity of the PS. The horizontal axes show the values measured by the monitor PAX35 on top of SS16; the vertical axis the readings of the different site monitors. The red dots represent data measured during operation with high intensity beams extracted mainly in CT mode between July 2009 and November 2009. The blue dots are from the period February 2010 to May 2010 with MTE only operation. The vertical and horizontal bars show the measured average values over the displayed periods.
For the Skyshine effect, empirical formulae exist, describing the decrease of ambient dose rate with increasing distance from a large surface source. The exponential functions given in literature could not reproduce the measured values satisfactorily because several parameters could only be insufficiently estimated. Therefore, a similar empirical exponential function was plotted, based on the measurements performed in the surroundings of the PS. Although the monitoring stations are not aligned with respect to the main source in SS16, this simplified approach results in a reasonable representation of the dose rate gradient from Skyshine. Two positions do not fit to the obtained curve, which can be explained by their specific location (situated at a lower altitude and partially shielded). Positions too close to the source (B.561) do not follow the fitted function either.

This simplified approach neglects all other possible radiation sources (PS Booster, TT2 tunnel) and other major source contributions from the PS (Route Goward). However, the obtained relation allows to determine the dose rate level on top of SS16 which correlates with ambient dose levels in the closest office buildings below the justification and optimization thresholds. The value thus determined is about 30 µSv·h⁻¹ on PAXS35, being situated on top of the ejection region SS16/FT16.

3.2.6.2 Stray radiation on top of SS16 and in the PS ring centre

A mobile monitoring system has been employed to measure the spatial distribution of stray radiation in the south-western corner of the PS Ring during a period of machine operation with beams extracted exclusively by the MTE scheme (Figure 3-23). To compensate for variations in beam intensity, the data have been normalised to the reading of the radiation monitor PAXS35. This monitor measures beam loss on SS16 as it is placed on top upstream of the ejection region (see Figure 3-14). Normalisation to beam intensity monitors may induce error, not only of the uncertainty of these measurements but because
beam loss is not proportional to beam intensity. This depends to a certain extent on the skill of the accelerator operators, who strive to achieve the highest possible transfer efficiency.

At the time of the measurement, the highest ambient dose rate measured was $H'(10) = 250 \, \mu Sv \cdot h^{-1}$ in a small area above and slightly downstream from SS 16 (east of the PS North Hall, Bld. 151). Under these circumstances, the ambient dose equivalent rate measured in Bld. 561 and 587 is between 0.1 $\mu Sv \cdot h^{-1}$ and 0.3 $\mu Sv \cdot h^{-1}$. The annual personal dose equivalent of a worker in either of these buildings would be between 200 and 600 $\mu Sv \cdot y^{-1}$. Installing in one of these buildings offices for personnel other than those directly affected to accelerator operation and maintenance is not justified. Independently of the justification, the situation demands optimization, so that an acceptable annual personal dose of 100 $\mu Sv$ is not exceeded.

![Figure 3-23: Ambient dose equivalent rate $H'(10)$ in the south-western corner of the Centre of the PS ring. Data was measured over a period of about 4 hours and while the radiation monitor PAXS35 was measuring about 112 $\mu Sv/h$.](image-url)
3.2.6.3 Reduction of Skyshine

A straightforward measure to reduce the environmental impact of Skyshine would be the local reinforcement of the PS tunnel’s roof shielding. Installation of a 100 cm thick concrete slab would reduce the ambient dose equivalent rate by about a factor of 10, allowing sufficient safety margin for potential intensity increases in the PS. An equivalent shielding thickness made of earth would be in the order of 130 – 150 cm.

From the geodetic measurements performed in September 2010, the thickness of the shielding above SS 16, composed of concrete and earth, is estimated to be about 3 m (Figure 3-13 and Table 3-1). As the shape of the surface in this area is very irregular and in the underground is the area where the tunnels of PS, Linac, LEIR and TT2 join, modelling the structure for radiation transport calculations is difficult to implement. A proper 3D model of the ejection region could help to correctly produce a model for Monte Carlo simulations. The simulation can then be used to design the optimal lateral extension of a shielding plate to reduce the dose rate from radiation penetrating through the PS roof shielding.

3.2.6.4 Stray Radiation in other areas.

Beam loss in the magnetic septum in SS 16 leads to unacceptably high radiation levels in Linac 3 and in front of door D.122. These phenomena were observed at the end of 2009 when ambient dose equivalent rates reached unacceptably high levels due to high intensity beam operation (Fixed target beams for CNGS and SPS). During the technical stop in Winter 2009/2010, shielding measures were taken. An 80 cm thick concrete wall was built inside the PS tunnel, attenuating the secondary radiation from the septum to LINAC 3. It has led to a reduction of ambient dose equivalent rate by a factor of 2.5. Long-term workplaces in LINAC 3 are now subject to an ambient dose equivalent rate of less than $H^*(10) = 10 \, \mu Sv \cdot h^{-1}$ and remain classified as simple controlled radiation area.

The exit of the curved tunnel towards door D.122 has been blocked with a concrete shielding wall ($d = 80 \, \text{cm}$) which has reduced the ambient dose equivalent rate to less than $2.5 \, \mu Sv \cdot h^{-1}$ in the court yard in front of B.151.
3.3 Air activation and Release

3.3.1 Description of the ventilation system

Air exchange and circulation in the PS is achieved by 8 air handling units. Figure 3-24 gives an overview of air flow in the PS. Schematically, each station is injecting 40,000 m$^3$ of air per hour in the PS tunnel. Of these, 36000 m$^3$·h$^{-1}$ are taken from the tunnel itself and 4,000 m$^3$·h$^{-1}$ are aspirated from the environment. Given the estimated volume of the PS tunnel of about 24,000 m$^3$ [OTTO], the whole air in the tunnel is renewed about 1.3 times per hour. The air is treated and brought to a predefined temperature with heat exchangers cooled with chilled water before being re-injected in the tunnel. This scheme of air management leads to an overpressure in the PS tunnel with respect to the environment and neighbouring premises. With the above parameters and the dimensions of the PS tunnel, an average air speed of 0.4 m s$^{-1}$ can be derived. The actual air speed may differ strongly from the average value for two reasons: with about 630 meters circumference the PS tunnel is rather small and it has numerous openings to other tunnels as well as to buildings and technical galleries, as will be seen below. A laminar air flow cannot be guaranteed under these conditions and the air flow is influenced by local particularities.

![Figure 3-24: Schematic view of the air flow in the PS tunnel](image-url)
Figure 3-25: PS tunnel close to SS14. The ventilation duct running along the accelerator and the connection to the ventilation station no. 2 (close to SS16) is shown on the upper part.

3.3.2 Air-flow in the PS

The PS accelerator is one link in the chain of CERN injector accelerators. It receives particle beams from two other accelerators, the PS Booster and LEIR and it ejects beams into the transfer tunnel TT2 towards AD, n_TOF and SPS and in the East Hall experimental area via the FT61 line. None of these connections is air-tight and affects local airflow in the PS. The main entrances to the PS, doors D.102, D.121 and D.122 and the radial tunnels leading to the centre of the ring and door D.101 present further openings in a hypothetical “envelope” of the PS. Finally, leaks are found in the construction traversing the former experimental areas in building 150/151 (the “PS Bridge” including its shielding) and in the cable passages from the magnet power supplies to the tunnel. Figure 3-26 shows the location of the estimated major leaks, which affect air flow in the PS accelerator. It can be noticed, by comparison with Figure 2-4, that large beam losses occur in zones with large air leaks.
A reversal of the ventilation system of the PS, in which the air would be aspired through the tunnel openings and extracted in a controlled way, thus creating a dynamic confinement in the ventilated volume with moderate leaks, cannot be envisaged in the PS in its current configuration. The location and size of the leaks is such that the aim of dynamic confinement, a controlled air flow to an identified release point, could not be realized. Two costly alternatives are available:

1. Identifying all components where air cooling is critical and bringing fresh air to the location through ducts. A second set of ducts would transport the air to the release point. This involves the installation of ducts, and it is not guaranteed that sufficient space is available in the PS.

2. Tightening all access points to the transfer and radial tunnels, all doors, and all other locations in the PS. This would represent a major civil engineering project. Likely during its course, other leaking locations would emerge which are at present negligible. The successful outcome of the effort could not be ascertained.
The recommendation of installing a dynamic confinement in radiation areas is not a goal in itself. Its purpose is mainly the ability to control the flow of activated air. The effort required to achieve it must be compared with its benefits. A directed air flow is generally desirable to:

1. Protect workers from locally high radioactivity concentrations.
2. Avoid leaks of activated air in other working areas
3. Ensure a full accounting of releases by assessing them at a unique release point to which the major air volume is directed.

In the PS tunnel itself, point 1 does not apply. Radioactive air is exclusively produced by spallation of air nuclei during accelerator operation, when the area is inaccessible for personnel. After the stop of the beam, a waiting time of 15 to 30 minutes is needed, during which short-lived induced activity is decaying. Point 2, this is an existing hazard and dealt with in Section 3.3.4.2. Point 3, a full accounting of releases is desirable, as a measurement has a strong weight in public debate, which cannot be matched by estimates, however sophisticated they may be. Therefore a study shall be conducted, detailing costs, risks and benefits of a modification of the ventilation system to allow full accounting of the releases from the PS. The case of a major accident (fire or other incidents leading to a possible activity release) shall be taken into account. A crude but useful estimate of released activity during normal operation is already possible, enabling a judgment of the environmental consequences. This estimate is explained in the following section.

3.3.3 Environmental impact of air releases from the PS

As before, it is assumed that 2% of the 5.8·10¹⁹ protons extracted per year from the PS in the loss-prone FT and CNGS beams are lost during extraction. In the optimized MTE scheme, the loss is occurring predominantly in the magnetic septum in SS16. If CT extraction is used, the fraction of total protons extracted in this scheme will suffer 10 % loss, predominantly in SS31 (electrostatic septum) and the following sections. In both cases, the septum tank is the only barrier between the loss location and the air in the PS. The situation is similar to an unshielded particle loss. Air activation produced by a loss of a beam with \( p = 14 \text{ GeV/c} \) on an iron rod has been estimated [VINCKE]. This simulated geometry approximates an unshielded loss and the resulting activation figures are used here. The estimation of released activity is taking into account radioactive decay, determined by the physical half-lives of the radionuclide during the removal time of a random infinitesimal air volume, determined by the ratio of the fresh air volume injected into the tunnel and the tunnel volume. The estimate is based on an assumption of total mixing of air in each ventilation sector.
Table 3-4: Annual release of radionuclides produced by activation of air from the PS. It is assumed that $1.2 \times 10^{18}$ protons are lost in one year during extraction at a momentum of $p = 14$ GeV/c. The loss occurs in an unshielded location of the beam line (as for example the magnetic septum in SS16)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Radioactive half-life</th>
<th>Annual release (Bq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$C</td>
<td>20.38 m</td>
<td>$1.64 \times 10^{12}$</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>9.96 m</td>
<td>$1.97 \times 10^{12}$</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>70.59 s</td>
<td>$1.66 \times 10^{11}$</td>
</tr>
<tr>
<td>$^{17}$O</td>
<td>2.03 m</td>
<td>$1.58 \times 10^{12}$</td>
</tr>
<tr>
<td>$^{41}$Ar</td>
<td>1.83 h</td>
<td>$8.24 \times 10^{10}$</td>
</tr>
</tbody>
</table>

Table 3-4 shows the most critical radionuclides released from the PS and the estimated annual release. These release figures are used to calculate the dose to a member of the reference population group with the model described in [OTTO]. The reference group for the CERN Meyrin Site has been identified as the Swiss border guards, working and living in the direct vicinity to the site. The distance of their workplace is 350 meters from the centre of the PS Ring. The contribution to their annual dose of radioactive air releases from the PS is estimated to be 0.28 μSv. This estimated environmental impact of radioactive air released from the PS is much lower than the justification threshold of 10 μSv/year adopted at CERN. If the CT extraction would be used exclusively, this figure would rise to 1.4 μSv/year, which is still low in comparison with limits and guidelines. However, the contribution of other sources of activated air on the site, like the transfer tunnel TT10, ISOLDE and n-TOF, as well as the contribution of stray radiation must be taken into account.

It is found that the major part of effective dose is currently coming from stray radiation emerging through the top shielding of the PS. Less than 10% of the total effective dose to the reference group can be attributed to activated air.

### 3.3.4 Local improvement of air management in the PS

#### 3.3.4.1 Assessment of releases

The concentration of four categories of air-bound releases ($^3$H), short-lived gases ($^{11}$C, $^{14}$N, $^{14,15}$O, $^{18}$F, $^{41}$Ar), aerosol with $^7$Be and aerosol with beta emitters) is measured at one point in the PS close to straight section 55. The activity concentration is then multiplied with the volume of air expelled from the PS by the air-exchange system in order to estimate the radioactive releases. When comparing the releases estimated in this way with figures calculated according the model above, one finds that the calculation exceeds the measurement by a factor of 5 for short-lived gases and a factor of 10 for $^7$Be. Given the irregular ventilation flow in the PS, this result is not surprising. In the RAMSES 2 Light upgrade program of the radiation monitoring system, a displacement of the ventilation monitor is envisaged. In future, it will sample tunnel air from close to straight section SS16, where most of the beam loss and thus air activation takes place during multi-turn extraction. Choosing this location for air sampling will likely lead to a conservative estimation of the true releases.
### 3.3.4.2 Protection of workplaces

A number of workplaces are likely affected by the uncontrolled release of air activated at the major loss point in SS16. These places include Buildings 150/151, the yard outside of building 151 and the RF building in the ring centre, buildings 353 and 359. A local improvement of the air quality in these locations could be achieved with more modest means of tightening the major leaks around SS 16. A campaign of air activation measurement by mobile monitoring stations has been delayed due to a late delivery of the required measuring equipment. The devices becoming available in the beginning of 2011 will allow delivering results during the run in 2011. A few measurements, which still were performed in 2010 in B.353, have shown presence of air borne activity being at levels at about 0.1-0.2 CA, but these values include a number of uncertainties. More reliable results can be expected by employing a number of parallel measurements and the correlation with the newly monitored activation levels in SS16.

At locations where the activity concentration in air exceeds guideline values, local improvements of air flow control can be undertaken. One has to be aware, however, that local measures in one area of the PS will have unpredictable consequences in other areas. This fact can be accepted in the specific case if the ‘other’ areas are far from workplaces.

### 3.4 Water activation and release

Measurements have shown in the past that activation of liquids, while present, is not causing a radiation risk. The evaluated activity concentration has consistently been lower than the relevant limits and guidelines. Demineralization cartridges for demineralized water, where most of the activation products accumulate, are installed in radiation areas. The remaining demineralized water still contains varying amounts of H-3 and short lived emitters. The fact that both the demineralized water circuits and the chilled water circuit supply water to other equipment and areas than the PS tunnel, leave a potential risk of contamination of non-radioactive equipment. In a future upgrade, the separation of water supplies for activation risk areas, such as the PS accelerator tunnel, and other technical infrastructures shall be implemented.

Ground water activation does not present a hazard for the water supply because around the site, ground water is not used for drinking or irrigation purposes.
4 Possible future beam parameters and associated radiation effects

4.1 Consequences of the PSB Energy Upgrade

In 2010, an upgrade of the PS Booster has been studied with an aim to extract protons at an energy of 2.0 GeV (instead of 1.4 GeV) [GIOVANNOZZI, HANKE]. This would allow to increase the intensity per LHC bunch from $1.1 \cdot 10^{11}$ protons to approximately a maximum of $2.7 \cdot 10^{11}$ protons. During the study, the possibility has been prospected that also all other proton beams would be injected at the higher energy. The influence of the increase of the injection energy on beam loss and therefore on radiation effects can be described as follows:

Increasing the energy of a particle beam results generally in a reduction of its physical emittance (in other words, of its physical dimensions). Assuming constant beam intensity, this would in principle reduce beam losses if the same mechanical vacuum pipe aperture is kept as today. However, as outlined in section 3.2.5.4, the part of the total beam loss due to beam size cannot be measured accurately and it may be as small as one fifth. An estimation of ambient dose equivalent rate on Route Goward for a beam with reduced emittance is not straightforward because the locations of beam loss may be different depending on the physical beam size.

On the other hand, the intensity of the secondary radiation cascade, and thus the ambient dose rate equivalent caused by it, increases with increasing energy of the primary particles. At high energies ($E \gg 1$ GeV) a dependence of $H = E^{3.8}$ for the ambient dose equivalent rate under $90^\circ$ from the point of beam impact can be observed. At the level of injection energies (1.4 GeV, 2.0 GeV) this dependence is not valid; furthermore, the Route Goward crossing lies in the forward solid angle seen from the injection septum. A Monte-Carlo radiation transport calculation on the basis of the one described in section 3.2.5.2, assuming the same distribution of the beam loss, suggests that the ambient dose equivalent rate will be a factor of 1.6 higher for the same intensity of losses.

The conclusion from the two preceding paragraphs is, that for a beam injected into the PS at $E = 2.0$ GeV with the identical intensity as at $E = 1.4$ GeV, the reduction of losses due to the lower emittance will not compensate for the higher ambient dose equivalent rate due to the increased primary proton energy. Then, the shielding of the road with 1.2 metres of concrete would be no longer sufficient. Depending on the estimated amount of beam loss, the required additional shielding thickness may increase to 1.8 meters.

The preceding argument is even more valid, if the emittance gains in the injected beam would be used for an intensity increase of the beam circulating in the PS. Then, protection of Route Goward from losses at injection would require even more effort, but also the ejection region (probably the region downstream from SS16) would suffer a higher impact of beam loss with consequently higher activation and higher ambient dose equivalent rates from stray radiation.

The required loss reduction and shielding measures in the PS injection regions must be studied in the next phase of the PSB energy upgrade study. For this purpose, manpower for beam dynamics calculations and for shielding estimates has to be foreseen within the project.
Figure 4-1: Distribution of ambient dose equivalent (pSv) in the injection region of the PS per lost proton. The loss points have been chosen so that the ratio of signal strengths on the beam loss monitors during injection at $E_{k}=1.4$ GeV are reproduced. Top: Dose distribution for $E_{k}=1.4$ GeV, Bottom: Dose distribution for $E=2.0$ GeV.
4.2 Estimation of future beam intensities

A few other options for increasing the number of protons available for experiments have been discussed. Among these are a shortening of the basic PS period to 0.9 s or even 0.6 s, using the higher proton intensity from LINAC 4 and others.

As seen in the example of the PSB energy upgrade, neither is beam loss exactly proportional to the beam intensity, nor is the ambient dose equivalent proportional to the number of accelerated protons. The conclusion is, that any upgrade of the accelerator complex, potentially resulting in higher numbers of protons injected and accelerated in and extracted from the PS, must be studied for its potential impact of radiation levels in and around the accelerator. Suitable measures must then be planned and implemented in order to keep personal doses and releases to the environment as low as reasonably achievable.

4.3 Beam intensity and beam loss limitation in the PS

In the preceding chapters several aspects of the radiological impact of beam losses have been discussed. Limitations for beam losses from radiation protection considerations arise both from activation and stray radiation. The limitations by stray radiation are mainly driven by weak shielding paired by localized high losses. The limitations derived from induced activity levels are linked to the requirement of urgent repair or equipment replacement interventions. While the exceedance of the limitations of the first category leads inevitably to an exposure of a large amount of persons to a low level of dose, the second involves a potentially high exposure of a small group of individuals.

From both cases, operational limits for beam losses can be deduced. The operational limitations of beam losses as determined in chapter 3.1.8 from the activation cases shall at least correspond to the limitations set by a stray radiation impact, after having increased the shielding at critical locations. While limiting losses, the maximum beam intensities put into operation now or in the future shall be guided by realistic loss scenarios respecting the operational guideline values. No beams with losses exceeding the beam loss constrains shall be put in regular operation. In the case that “virtually loss free” operation of very intense beams is envisaged, accident scenarios for full beam losses shall be considered.

Apart from the ongoing increase of intensities per acceleration cycle, the aspect of optimization shall be always considered. It is known that relative losses increase in a non-linear way while increasing the number of protons per pulse or bunch. The working group recommends establishing a cost-benefit analysis for the overall efficiency of the high energy proton production chain as a part of an ALARA approach for the operation of CERN’s high energy accelerators.
5 Recommendations

5.1 General Recommendations

- **Study the impact of all planned changes of the PS operational parameters**
  Any change of operational parameters of the accelerators causing altered conditions of beam loss and secondary radiation cascades, notably changes of beam intensity and beam energy, shall be accompanied by a study of their consequences for radiation protection and environmental protection. The CERN safety policy requires that such changes are at least neutral with respect to safety risks, and preferably entail a net improvement of safety and environmental performance.

- **Integrate beam operation into optimization processes**
  Due to non-linear increase of losses with peak intensity per pulse, accelerator operators shall optimize or minimize beam loss at peak intensities wherever and whenever possible. Changes in beam operation shall take into account potential and real exposure. In general, beam operation shall be integrated in the optimization efforts undertaken to reduce collective and individual doses to workers and the public. As for all optimization approaches, areas for possible improvements shall be identified and these efforts and achieved results shall be documented.

- **New equipment**
  Any new equipment which is going to be installed or which will replace existing equipment shall be designed bearing in mind the quick removal and reinstallation.

5.2 Before the shutdown LS1 in 2013

- **Establish a complete 3D model of the PS as-built and its implementation on the site**
  This model is required both for further radiological impact studies such as simulations and measurement campaigns as well as for civil engineering studies to reinforce the shielding of the PS at various locations.

- **Study additional shielding above SS 16**
  Evaluate the technical possibility to increase the roof shielding of the PS accelerator downstream of the North/South hall (B.150, 151). The objective of additional shielding is to protect the personnel in offices in the vicinity of the PS Ring. The thickness of additional shielding shall include a safety margin for potential increases of the PS beam intensity. The recommended thickness is in the order of 180 cm of earth.

- **Study additional shielding above Route Goward**
  A civil engineering solution for increasing the shielding thickness on Route Goward must be found and implemented. The objective is to limit the ambient dose rate on Route Goward, a typical passageway with access for the public, to 2.5 $\mu$Sv·h$^{-1}$. The additional shielding shall make provisions for additional beam loss and stray radiation of a potential increase of injected beam
intensity and beam energy from the PS Booster. The recommended additional thickness is 180 cm of concrete.

- **Constrain and optimize the local and integral losses in the PS**
  It is recommended that constraints for local beam loss (affecting the activation of one part of the accelerator and thus maintenance of this part, affecting stray radiation effects) and for integral beam loss (affecting the average ambient dose equivalent rate and thus maintenance of a general nature in the PS, affecting stray radiation effects) are implemented.

  Constraints based on arguments given in this report are:
  
  - Beam loss in an arbitrary location in the PS is limited to $10^{10} \text{ s}^{-1}$ at extraction energy
  - Beam loss in the extraction septa of the PS is limited to $10^{11} \text{ s}^{-1}$ at extraction energy.
  - Total beam loss in the PS is limited to $10^{12} \text{ s}^{-1}$.

  If these constraints are implemented, it will be possible to undertake major repairs in the PS after a waiting time of no longer than 14 days. It must be noted, that, due to the logarithmic nature of the decay curves, lengthening of the decay time would not permit substantial loss increases.

- **Beam instrumentation**
  It is recommended that the existing beam instrumentation systems shall be reviewed to determine the actions which must be taken to improve the accuracy of measurement and cross calibration, in particular for the beam current transformers. It is understood that a renovation of the BLMs shall take place in the next few years. In this case, it is recommended that the new system shall be able to provide, as the one of the LHC and the SPS, calibrated measurements with a sufficient dynamic range. Beam loss at a rate below $10^9 \text{ s}^{-1}$ shall be measured accurately.

- **Measure of local air activation**
  The concentration of radioactive gas in work areas around the PS accelerator shall be measured and the possible dosimetric impact shall be assessed.

- **Study monitoring of average air activation in PS tunnel**
  The monitoring of the average air activation in the PS tunnel is eliminating one unknown in the estimation of the environmental impact of releases from the PS. It can be achieved by placing more than one radioactive air monitor at representative places in the tunnel. However, as in all assessments of environmental impact by calculation, a second source of uncertainty is the time that radioactive air needs to escape from the PS. A combination of the measurements of local air activation (see above) and the average activity concentration in the PS tunnel will allow an estimate of the typical escape time of air with reduced uncertainty.
• **Feasibility study for the modification of the PS ventilation system**
  For the purpose of accounting releases of radioactive air and demonstrating compliance with environmental regulations and in order to reduce the risk of potentially exposing CERN personnel to radioactive air during beam operation or in accident cases, a study of the modification of the PS ventilation system from an overpressure mode going to a controlled extraction mode, optionally aiming at a dynamic confinement, shall be conducted. The study shall detail the technical feasibility, the associated financial costs as well as the expected collective dose for the modification works. The study shall be accompanied by an evaluation of the expected reduction of the dosimetric impact on CERN personnel in the surroundings of the PS as well as on members of the public.

• **Study the possibility to separate water circuits from activation and non-activation areas**
  A study shall be launched to evaluate the possibility to separate cooling water circuits supplying currently both activation areas and non-activation areas. Technical feasibility and impact as well as financial costs shall be assessed.

• **Study of hybrid MTE (use of SEH31)**
  It is recommended to continue the studies and the tests of the hybrid extraction, i.e., MTE using the CT elements, with the goal to reduce the losses at the SMH16.

• **Determine the non-linear relation between peak-intensity increase and beam loss**
  It is recommended to study the non-linear relationship between beam loss and increasing peak intensity. Following this study, a decision shall be taken where to limit the maximum peak intensity for standard beam operation.

• **Linac 3 permanent work places**
  The Linac 3 area is affected by beam loss occurring during beam ejection from the PS in SS16. It is particularly challenging to improve the shielding in this sector and the easiest solution might be to displace the permanent workplaces in the Linac 3.

• **Catalogue of intervention and dose planning for accelerator equipment**
  In the framework of the preparation for Radiological Work Permits and the optimization of future interventions, all equipment owners shall plan the work and estimate collective personal doses for all planned and the most likely exceptional interventions on their equipment installed in the PS tunnel. This catalogue shall complete the view on all possible intervention scenarios and their potential dose impact and thus form the base for decisions on further consolidation programmes.

### 5.3 During and after the shutdown LS1

• **Install additional shielding (SS 16, Rte. Goward)**
  Following the civil engineering studies, the Long Shutdown 1 should give sufficient time to install the additionally required shielding on the areas of Route Goward and of the Straight Section 16.
• **Installation of a dummy septum in SS15 for MTE**
  Following the recent simulation studies [DAMJANOVIC3], it appears that the installation of a dummy septum in SS15 to protect the septum SMH16 would considerably reduce the ambient dose rate levels at the septum itself. Following the results of a study to liberate the SS15 by displacing its present equipment to other straight sections, the dummy septum could be installed during the LS1.

• **Installation of a longitudinal kicker for the MTE barrier bucket**
  Following the PS-LIU upgrade related studies, a longitudinal kicker should become available for the RF feed-back systems. Studies shall be carried out to understand the possibility to implement a barrier-bucket in the PS during the MTE extraction and the impact of a spill with a hole in the SPS transmission efficiencies.

6 **Acknowledgement**

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The information contained in this document reflects only the author's views and the Community is not liable for any use that may be made of the information contained therein.
7 References

[AUMON1] S. Aumon et al., Optimization of the position of the Radial Loop Pickups in the CERN PS, CERN-ATS-2010-031

[AUMON2] S. Aumon et al., Transverse Mode Coupling Instability Measurements at Transition Crossing in the CERN PS, CERN-ATS-2010-030


[BARRANCO] J. Barranco, S. Gilardoni, Simulation and optimization of beam losses during continuous transfer extraction at CERN Proton Synchrotron, accepted for publications in Phys. Rev. ST Accel. Beams

[BENEDETTO] E. Benedetto et al. Results from the 2009 beam commissioning of the CERN multi-turn extraction, CERN-ATS-2010-052


[BLRWG]: http://blrwg.web.cern.ch/blrwg/

[BOHL1] T. Bohl, Observations in the SPS of beam with various longitudinal parameters and extracted from the CPS using CT, CERN-BE-Note-2009-013

[BOHL2] T. Bohl, Low intensity beam extracted from the CPS via CT or MTE with various longitudinal parameters, CERN-BE-Note-2009-014

[CHAMONIX] S. Gilardoni et al., PS potential performance with a higher injection energy, to be published in proceedings of the Workshop Chamonix 2011- LHC performance Workshop


[COLLIER] P. Collier, BE Department Head, private communication, 03/2011


[DAMJANOVIC1] S. Damjanovic, T. Otto, M. Widorski, Radiation levels on Route Goward, publication pending


[GIOVANNOZZI] M. Giovannozzi, Possible improvements to the existing pre-injector complex in the framework of continued consolidation, presented in LHC Performance Workshop - Chamonix 2010

[GILARDONI1] S. Gilardoni et al., Installation and Hardware commissioning of the Multi-Turn extraction at the CERN proton synchrotron, CERN-ATS-2009-139


[MANGLUNKI] D. Manglunki et al., First conclusions of the losses management working group, PS/OP/Note 2001-009


[SHAPOSHNIKOVA] E. Shaposhnikova, private communication

[STEERENBERG] PS MD: Transverse emittance as a function of protons beam intensity, PS/OP/Note 2000-13 (MD)