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STUDY OF LOSSES DURING CONTINUOUS TRANSFER EXTRACTION LOSSES AT CERN PROTON SYNCHROTRON

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Abstract

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The proton beams used for the fixed target physics at the SPS are extracted from the PS at 14 GeV/c in five turns, using a technique called Continuous Transfer (CT). During this extraction, large losses are observed in straight sections were the machine aperture should be large enough to accommodate the circulating beam without any loss. These losses are due to particles scattered by the electrostatic septum used to slice the beam and defocused by a quadrupole used during the extraction. Simulations and experimental results are presented.

INTRODUCTION

The proton beams used for the fixed target physics at the SPS (Super Proton Synchrotron) are extracted from the PS (Proton Synchrotron) at 14 GeV/c in five turns using a technique called Continuous Transfer (CT) [1]. This technique is used to fill the SPS with two consecutive PS extractions, being the circumference of the SPS 11 times the circumference of the PS. The missing turn of the PS is necessary for the rising time of the SPS kicker. During this extraction, large losses are observed in straight sections were the machine aperture should be large enough to accommodate the circulating beam without any loss. These losses are due to particles scattered by the electrostatic septum used to slice the beam and defocused by a quadrupole pulsing during the extraction. These losses limit the maximum intensity deliverable to the SPS for fixed target physics, like for the CERN to Gran Sasso (CNGS) neutrino program, because of the large irradiation of the site outside the PS tunnel and at the CERN fence. Simulation and experimental results are presented as update of the study of [2].

CONTINUOUS TRANSFER: CT EXTRACTION

During the CT extraction, the horizontal tune of the PS is set to about $Q_x = 6.25$ to obtain a phase advance per turn of 90°, while the vertical tune remains fixed at $Q_y = 6.3$. In such conditions, a part of the proton beam, one fifth of the total initial intensity, is pushed by a slow and a fast bumps beyond the blade of an electrostatic septum. The sliced beam that receives the kick of the electrostatic septum is extracted during the current machine turn, while the rest is extracted with the same mechanism within the next 4 turns. The different bumps are set in such a way that the five beam slices feature the same intensity. According to ref [3], it is not possible to share the same intensity among the slices and at the same time have the same emittances.

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THE BEAM LOSS MONITOR SYSTEM

The PS beam loss monitor (BLM) system is composed by 100 ACEM detectors (Aluminium Cathode Electron Multiplier [4]) mounted on top of the main magnets. Due to the position chosen in the past (the system dates back to the middle ’80s) and the large variation of the signal with the primary proton energy, it is practically impossible to correlate the amount of protons lost in the machine with the signal recorded by the BLMs. Most of the losses in the PS are in the horizontal plane, whereas the BLMs are mounted on top of the bulky iron yoke of the main magnets. To complicate even more the picture, the BLMs are installed on different sides of the main magnets, in some sections facing the inside of the ring, sometimes the outside, following the pattern of the four magnet types which compose the PS lattice. For these reasons, the BLM system is used during operation to detect malfunctioning of the machine, more than as a real protection system, obtained by comparing online a given loss pattern with the reference one. The pattern of the losses observed with the system can tell something about the region where the losses occurs, whereas it is not possible for example to deduce the ratio of beam lost between two different sections of the machine. It is not even possible to deduce if a loss is produced in one of the main magnets or in the straight sections, being the BLM mounted at the entrance of the magnet unit. The aim of the simulations presented in the following is to reproduce qualitatively the observed loss pattern but not to quantify the beam loss detected by the BLMs. This would require a detailed simulation of the secondary shower developing in a large fraction of the main magnets, and goes beyond the purpose of this study.

SIMULATIONS

Aperture Model

One of the key elements that will drive the loss pattern in an accelerator is the acceptance of the machine. Because of this, special effort has be put in order to measure and establish it. The PS aperture model [5] was set based on the dimensions from the mechanical drawings for each element and, in some cases in measurements, made in-situ.

CT Optics and Simulation

Among the different elements of the PS, which is composed by 100 combined-function magnets arranged in a

FDODF lattice and interleaved by 100 straight sections (SS, numbered from SS00 to SS99), the ones used for the CT extraction and included in the simulation are:

1. a slow bump around the electrostatic septum, created by two magnets, and used together with the two fast kickers to push the beam beyond the electrostatic septum.
2. the electrostatic septum used to impart an extra kick to the beam slice for the extraction.
3. the slow bump used to direct the beam, together with a magnetic septum, in the transfer line towards the SPS.
4. two quadrupoles used to distort the optics of the machine between them hence having a large horizontal beta at the electrostatic septum and practically zero dispersion.

The tracking simulations is done with the Sixtrack code [7]. During the five-turns extraction process the fast bumpers increase the kick strength in order to place the beam in the correct position with respect to the septum foil to slice exactly $1/5^{th}$ of the beam at each turn. For simulations a bi-gaussian distribution in phase space in both planes is considered. The relative position between the beam and the septum needed for the equal intensity extraction is given in Table 1.

Table 1: Relative position between beam-septum in number of betatronic sigmas

Beam slice	**Relative position**
1^{st}	0.84
2^{nd}	0.67
3^{rd}	0.62
4^{th}	0.32
5^{th}	–

For the simulation, typical normalised emittances of $\epsilon_x = 12$ mm mrad and $\epsilon_y = 8$ mm mrad are chosen.

When the beam reaches the electrostatic septum, the sliced part receives an angular kick of $\theta = \arctan\left(\frac{E_0 l}{p\beta}\right)$ [6], where E_0 is the electrostatic field, l length of the septum, p particle momentum, β the particle velocity. Due to the kick of the septum, particles are displaced to a new closed orbit to be extracted by the magnetic septum of section 16. As the beam is shaved by the Molibdenum blade of the electrostatic septum, it is unavoidable that some particles undergo to scattering interaction with the septum material, simulated by the K2 code [8]. A septum like element has been included in the tracking in a parametric way that is possible to modify certain values (septum angle, half gap, kick) as in the real machine to optimise the extraction efficiency. In addition, during normal operation the radial position of the beam thus the energy is adjusted to match the injection energy of the SPS. A typical radial displacement is of the order of $\Delta x = -3mm$ giving a $\delta p/p = -0.001$. The real closed orbit is reproduced in the simulation using orbit correctors.

The flexibility of the tools used and changes made allows to perform easily beam loss studies of any kind injection or extraction configuration.

Simulation Results

Simulations have been performed in a 7 turn-basis. A first turn to establish the optics and the trajectory of the slow bump and six turns to slice and extract the beam. Each particle trajectory is compared with the aperture model to determine if the particle is extracted or lost in specific location of the machine. The maximum ever measured extraction efficiency for a PS CT extraction is $\eta = 96\%$. The simulation reproduces an extraction efficiency of $\eta = 96.3\%$, with an efficiency per turn shown in table 2, whereas the the efficiency per turn measured is about 20%±1%.

Table 2: Simulated extraction efficiency turn by turn

Beam slice	**% Beam Extracted**
1^{st}	20.0%
2^{nd}	18.5%
3^{rd}	19.2%
4^{th}	19.0%
5^{th}	19.5%

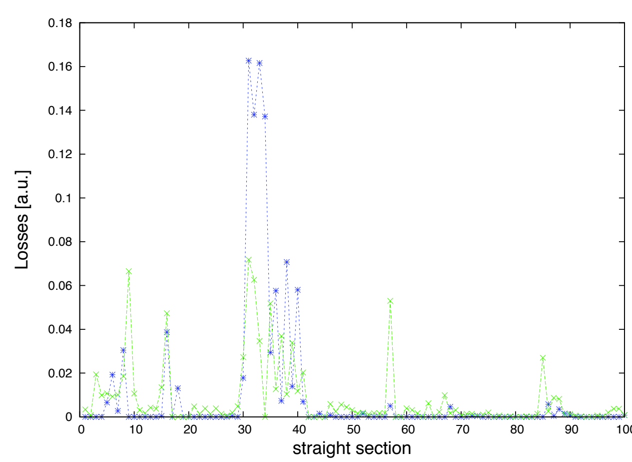

Figure 1: Beam loss simulations of normal CT operation. Green BLMs measurements, blue simulations.

The comparison between the BLMs signals and the simulated loss maps are shown in figure 1, with a very good agreement as all the loss locations in the accelerator are reproduced. In particular, losses in sections SS05-10 constitute a great concerns in terms of radioactivation as there is not enough shielding in that area to protect the building outside the PS tunnel. Those particular losses are created by one quadrupole installed in SS05 pulsing during the extraction which defocuses the particles scattered by the electrostatic septum. The main difference between simulation and measurements is in section 57, where the magnetic septum for a slow extraction is placed. Most probably, this difference is due to the fact that the simulation does not take into account the real shower development generated by the lost particles. Others issue that one should take into account is that the BLMs are mounted at the end of each straight section inside or outside the ring, while in the simulations all particles are grouped and counted considering the whole section. Figure 3 shows that most of the losses occur inwards the machine while in two septa areas occur outwards (s=100 m magnetic septum,s≈200 m electrostatic septum).

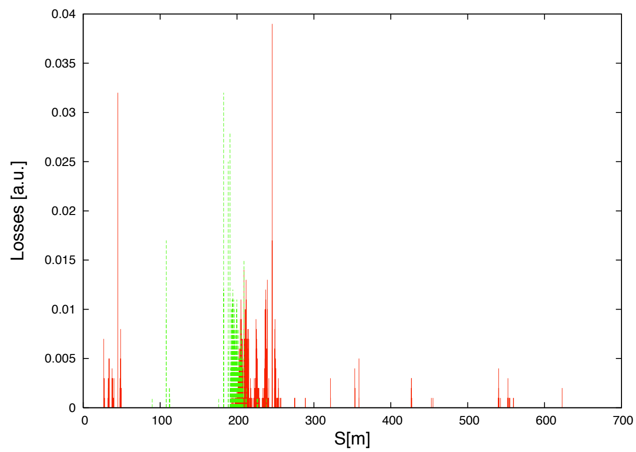

Figure 2: In red particles lost inwards the machine, in green outwards

Losses Displacement

It has been shown that simulations are able to reproduce the loss pattern, and in particular it is clear that is not possible to avoid the losses in SS05-10 without changing completely the extraction scheme. The only viable solution to reduce the radiological impact of the extraction losses is to displace them in a better-shielded part of the machine, where the tunnel radiation shield thickness is enough. This can be done by installing a new quadrupole 4π in phase advance before the quadrupole in SS05 and removing the latter. The new extraction scheme would be then unchanged, apart that the quadrupole producing the losses would be in SS73 and bring them in SS73-SS78. Once the new quadrupoles has been installed, the extraction tests confirmed the simulation prediction as shown in figure 3.

CONCLUSIONS

The CERN PS CT Extraction has been reproduced obtaining the nominal values for extraction efficiency. The beam loss pattern simulated predicts in an accurate way the measurements taking into account several aspects. The BLM system is not meant to provide precise data about the amount of proton lost, whereas the results of the simulation is a pure counting of protons which hit the machine aperture. Other discrepancies might be due to the fact

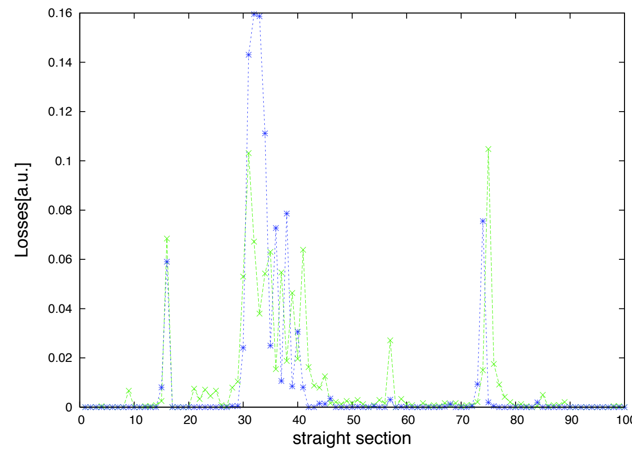

Figure 3: Beam loss simulations of CT operation with new quadrupole configuration. In green BLM measurements, in blue simulations results.

that in reality the scattered particles might re-interact with other aperture restrictions in the machine and being furthermore deviated, whereas in the simulation those supplementary restrictions are considered as pure absorbing surfaces. Moreover, the simulations do not take into account the propagation of the secondary particle shower, which might displace the maximum of the losses by one or two straight sections.

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