



TT20 beam loss reduction

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Abstract

The beam losses at the TT20 beam splitter are studied and different schemes for reducing these losses are performed. Beam losses induce radioactivation of the accelerator equipment and surrounding environment. By reducing the losses, the radiation dose, to personnel who carry out hands-on maintenance, is reduced and the machine availability and reliability is improved. To do so, three schemes are studied: Passive scatterer, Electrostatic Septum and Silicon crystal, and two distributions at the start of TT20 are considered, COSE and Octupole distributions. For COSE, loss reduction by a factor 5.7 was achieved with both the crystal and the ES, while for the Octupole distribution a factor 18.3 was achieved with the ES.

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1 Introduction

1.1 SPS and North Area experiments

At CERN, the SPS (Super Proton Synchrotron) is the last injector in the chain before the LHC (Large Hadron Collider). A 400 GeV proton beam from the SPS is also delivered to fixed target experiments in the North Area [1]. Particles are extracted from the SPS to the TT20 (Transfer Tunnel 20) transfer line. A continuous beam is achieved using slow extraction [2]. The disadvantage of slow extraction is that it requires a septum to split the beam, and such a process is intrinsically lossy. The lost protons activate the septum and its surrounding material. This may degrade the machine performance and increase the risk of radiation damage to personnel in the North Area. As the number of delivered protons increases, a reduction in the total beam losses is sought.

2 Modelling the TT20 transfer line

2.1 Overview of TT20

TT20 consists mostly of dipole and quadrupole magnets. There are two splitters that ensure that protons are delivered to three main targets. Splitter 1, which is the subject of this study, consists of a collimator upstream, called TCSC, and a magnetic septum, called MSSB. The TCSC face is about 610 m downstream from the start of TT20. By convention, x and y are chosen to be the horizontal and vertical directions, respectively, while s is the longitudinal directions.

2.2 Beam transport

In this report, beam loss reduction at Splitter 1 is considered. The initial beam distribution at the start of TT20 is transported downstream until it reaches the TCSC collimator. The beam is then tracked through both the TCSC and MSSB to study where particles are lost and how many of them are lost.

The initial distribution is taken from a simulation of slow extraction in the SPS [3]. The two distributions studied are outputs from a COSE, and a slow extraction with octupoles, denoted as the Octupole distribution.

The transport along TT20 is performed by inputting optical parameters into MADX and running the TWISS module. The Twiss parameters specified are α , β , D , D' and initial position and angle, in both the horizontal and vertical plane. In addition, the emittance in each plane is given. The original TT20 lattice written in MADX was copied from [4] and the operational optics is used. By running these files with the Twiss parameters given in those files, the Twiss parameters at the TCSC were obtained. These are considered as the nominal Twiss parameters at the TCSC. When the COSE and Octupole distribution parameters are inputted, the MATCHING module in MADX is used to find quadrupole strengths that match the Twiss parameters at TCSC back to the nominal Twiss parameters.

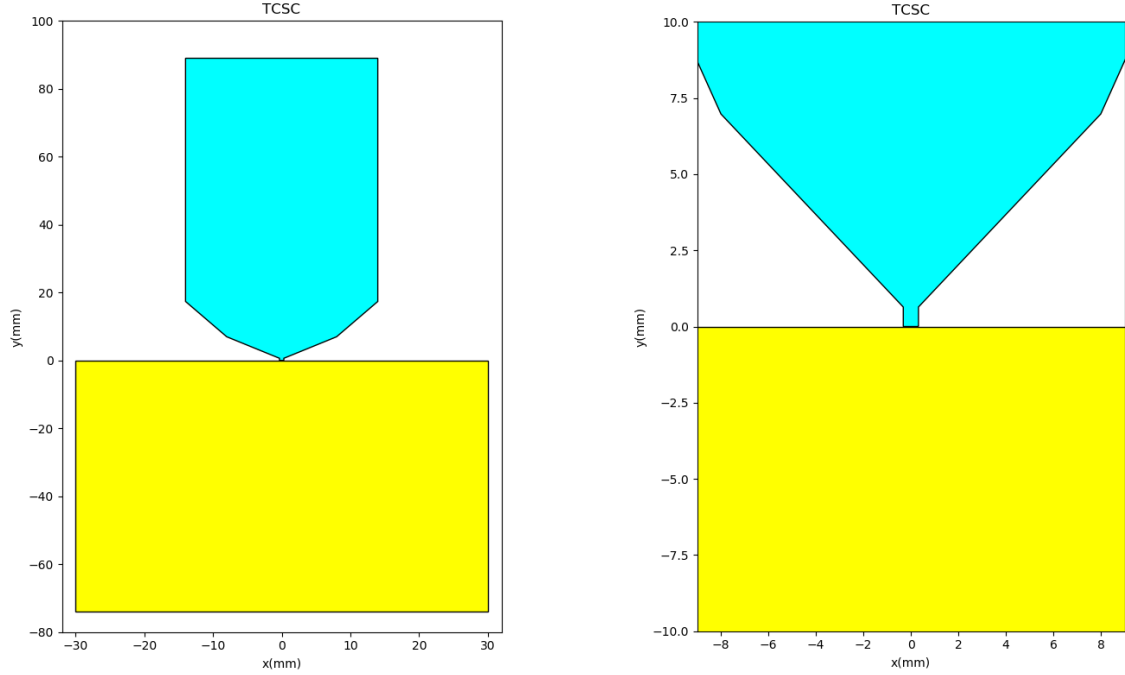


Figure 1: Model of the TCSC face used in the simulations. The MSSB face is almost identical.

2.3 Tracking through TCSC and MSSB

The MSSB is a Lambertson septum, which has a wedge shape. The upstream TCSC has a similar shape to protect the downstream septum. The transverse shape and dimensions of the TCSC and MSSB are taken from drawings on EDMS (Engineering & Equipment Data Management Service [5], [6]. The transverse face of the TCSC and MSSB are modelled in Python as geometric objects, as illustrated in Fig. 1.

In Fig. 1 the bottom region contains a magnetic field that deflects particles sideways. The top part contains the beam that remains undeflected.

From the MADX lattice, the TCSC has a length of 3.243 m, including the drift space between TCSC and MSSB. The MSSB consists of three parallel units with a small drift space between each. The total length of the MSSB including the drift spaces is 15.804 m. Tracking through the TCSC and MSSB is assumed to be a straight line propagation.

Using nominal parameters, the beam losses are 2.44% and 5.84% for the COSE and Octupole distributions, respectively, relative to the total number of particles at the start of TT20. Fig. 2 show the nominal distributions impacting the front face of the TCSC. On the right, the Octupole distribution has a larger horizontal size, and therefore impacts the white septum blade at higher vertical amplitudes. The losses for the Octupole distribution are therefore higher.

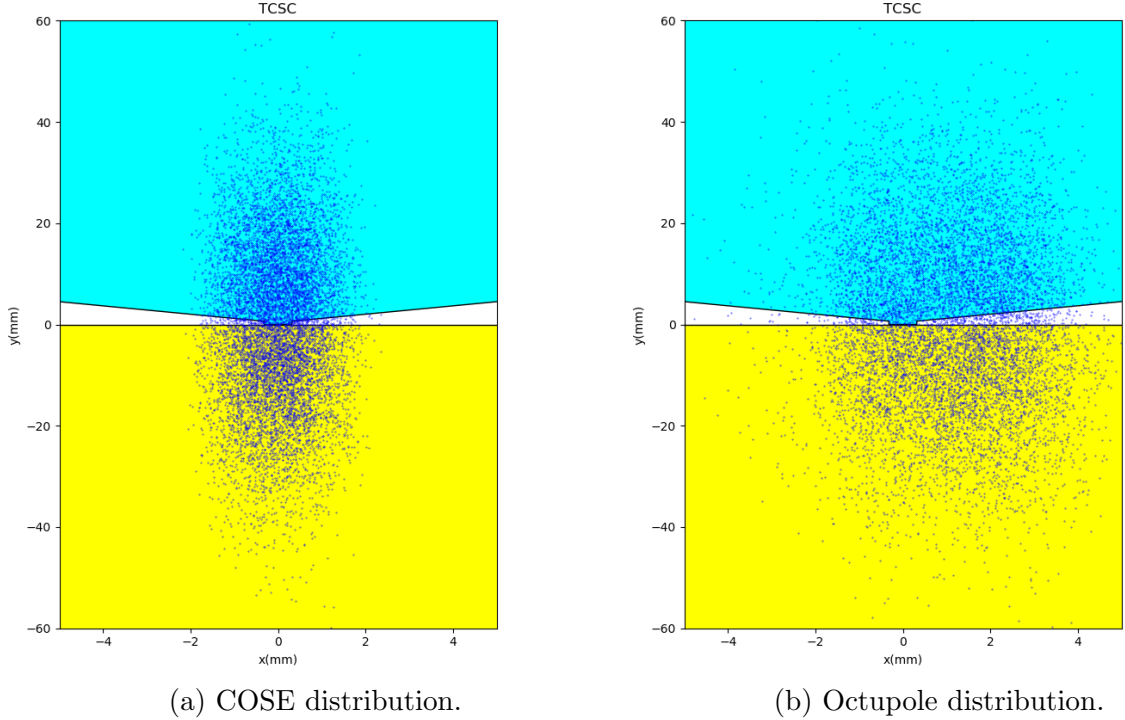


Figure 2: Illustration of particles that pass through the Splitter 1.

3 Passive scatterer

3.1 Model

Studies of beam losses at the slow extraction ZS in SPS have shown that placing an array of WRe wires upstream, with density 666.7 m^{-1} , can reduce beam losses at the ZS, even though there are losses at the diffuser. Overall, losses can be reduced by a factor 2.5 [7]. The performance of a similar passive scatterer has been simulated in TT20. The beam losses have been optimized by sweeping over three parameters: Length, width and position of the passive scatterer.

A proton that is incident on a thin block of material undergoes scattering. The three main types of scattering are Multiple Coulomb (MC) scattering [8], elastic nuclear scattering [9] with probability $p_e = 1 - \exp(-L/\lambda_e)$ and inelastic nuclear scattering with probability $p_i = 1 - \exp(-L/\lambda_i)$.

The passive scatterer, or diffuser, is modelled as a thin object with hard boundaries. The two transverse planes are treated independently, and probabilities and distributions are calculated using a random number generator. Furthermore, y' is assumed small and the diffuser is assumed short, so particles are assumed to only be incident on the front surface, and not the top or bottom along its length. Its horizontal extent is assumed much larger than the beam size, while the vertical size, the width, is a parameter.

3.2 Simulation and optimization of beam losses

A parameter sweep is performed over the diffuser length, width and position. Table 1 lists the sweep parameters for both the COSE and Octupole beams.

Table 1: Sweep parameters of diffuser.

Distribution	Parameter	Minimum	Maximum	Increment
COSE	Length (mm)	1	20	1
	Width (mm)	0.05	0.50	0.05
	Position	181	187	1
Octupole	Length (mm)	1	20	1
	Width (mm)	0.30	0.70	0.05
	Position	181	187	1

For the COSE distribution, the simulations give minimum beam loss is 1.61%. This is achieved with a diffuser length, width and position of 12 mm, 0.2 mm, and 184 respectively. Position 184 correspond to a position of $s = 581$ m. The Octupole distribution has a minimum beam loss of 3.78%, with diffuser length, width and position of 15 mm, 0.4 mm, and 183 respectively. Position 183 corresponds to a position of $s = 580$ m.

Both distributions show a similar behaviour for both distributions, with an optimum beam loss reduction factor of approximately 1.5.

4 Short Electrostatic Septum

4.1 Model

An Electrostatic Septum (ES) has the advantage of very small blade thickness. An ES is suitable for low energy beams. However, the effect of inserting an ES into the beamline, although small, could potentially reduce beam losses on the TCSC by opening a small gap in the beam that prevents particles from hitting the TCSC.

Particles are mainly deflected by the electric field in the ES. Scattering is also accounted for at the blade, which are WRe wires.

4.2 Simulation and optimization of beam losses

A parameter sweep is done to study the optimal ES parameters. Initially, the simulations showed there was no beam loss reduction because the kick from the ES was too small relative to the beam divergence at suitable locations along the transfer line. However, by inserting an extra quadrupole at $s = 90$ m, the beam divergence was reduced sufficiently to allow the ES to give an effective kick.

The results must be combined with costs and practicality, since the ideal ES has zero width and arbitrary field and length. The optimisation is identical for both the COSE and Octupole distributions. Table 2 show the ES sweep parameters.

Table 2: Sweep parameters of the ES.

Parameter	Minimum	Maximum	Increment
Length (m)	0.1	1.5	0.1
Width (mm)	0.1	1.0	0.1
Field (MV m^{-1})	0.5	5.0	0.5

For the COSE distribution, the minimum beam loss is achieved with a ES length, width and field of 0.8 m, 0.1 mm, and 5.0 MV m^{-1} respectively. For the Octupole distribution, there were several minima with similar lengths. The minimum with the shortest length has length, width and field of 1.0 m, 0.1 mm, and 5.0 MV m^{-1} . The beam losses are 0.43% and 0.32% for the COSE and Octupole beam, respectively.

In conclusion, the ES gives a factor 5.7 and 18.3 beam loss reduction for the COSE and Octupole distributions, respectively.

5 Bent Silicon Crystal

5.1 Model

In a bent crystal, a high energy particle will follow the direction of the bent atomic planes. This effect is called channeling [10] and gives a large deflection. It may undergo volume reflection [11], which is a smaller kick in the opposite direction. At CERN, the UA9 collaboration has measured these properties of Silicon crystals [12]. The effect of the crystal in the beamline is modelled using a PDF extracted from the data for the crystal installed in the ring during the 2018 crystal shadowing tests [3]. The crystal orientation is chosen such that particles are mostly kicked downwards and extracted at Splitter 1. This eliminates the need to pay attention to kicked particles downstream of Splitter 1. For this study, the crystal will operate in the volume reflection regime.

5.2 Simulation and optimization of beam losses

The crystal is modelled as an object with hard boundaries. Its geometrical shape is similar to the diffuser, but instead of WRe wires, the material is a silicon crystal. Its extent in the horizontal direction is much smaller than the beam size, while the vertical extent, the width, is a parameter. In the horizontal direction, it is assumed that elastic and inelastic scattering is negligible, while MC scattering is accounted for. In the vertical direction, scattering obeys the PDF.

A sweep over the number of crystals, crystal width and crystal position is performed. Table 3 shows the values of the parameters in the sweep.

The minimum beam loss was 0.44% and 2.71%. For the COSE distribution, this is achieved with 4 crystals, width of 0.6 mm and position $s = 580 \text{ m}$. For the Octupole distribution, there are 5 crystals, width of 0.4 mm and same position as for COSE.

For a crystal, there is a clear distinction in the behaviour of the COSE and Octupole beam. For the Octupole distribution, the loss reductions are only around a factor 2, while

Table 3: Sweep parameters of the Crystal.

Parameter	Minimum	Maximum	Increment
Number	1	5	1
Width (mm)	0.1	1.0	0.1
Position	181	188	1

for the COSE distribution the beam loss is reduced by more than a factor 5. This is because the Octupole distribution is larger in the horizontal plane, so the corresponding gap in the TCSC is larger due to the wedge-shaped septum blade and the resulting coupling between x and y directions in the TCSC gap. The crystal is unable to kick particles away from this larger gap.

6 Conclusion

The beam loss in the TT20 Splitter 1 has been studied for the COSE and Octupole beam distributions. To reduce the beam losses, the effect of a diffuser, electrostatic septum and bent silicon crystal on the beam loss has been simulated. The results are shown in Table 4.

Table 4: Table of beam losses with the different schemes, in addition to the nominal losses.

Beam losses	COSE	Octupole
Nominal	2.44%	5.84%
Diffuser	1.61%	3.78%
ES	0.43%	0.32%
Crystal	0.44%	2.71%

Clearly, for the COSE beam, the ES and crystal have similar performance, while the ES is efficient for the Octupole distribution. When taking into consideration cost and practicality, however, the diffuser is the simplest scheme. It involves putting a passive grid of wires with length in the order cm in an empty drift space. Therefore, if only small beam loss reduction is required, this is a cheap and simple solution.

For the ES, the whole scheme requires the insertion of an extra quadrupole, in addition to an ES with length on the order of a meter. There is certainly enough space in the transfer line because both components are placed far upstream, but they are relatively expensive components. The ES performance on the Octupole beam is by far superior to the diffuser and the crystal, so if a large beam loss reduction is required for the Octupole distribution this is the only efficient solution in this study.

The silicon crystal is probably the best trade-off between cost and performance. The main challenges are aligning more than 3 crystals, which this study found to be the minimum number of crystals necessary to get efficient loss reduction.

7 Acknowledgements

I would like to thank everyone in TE-ABT-BTP who has helped and supported me during my 13 weeks at CERN. In particular, I would like to thank Yann Dutheil for sharing his knowledge about beam dynamics and keeping me in occupied with interesting discussions, and many thanks to Matthew Fraser who always had an answer to all of my random questions. Furthermore, many thanks to everyone in the TE-ABT-BTP section for giving me an exciting and definitely memorable summer internship at CERN.

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