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EFFECTS OF ELECTROSTATIC SEPTUM ALIGNMENT ON PARTICLE LOSS DURING SLOW EXTRACTION AT CERN SPS

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Abstract

Slow extraction is an intrinsically lossy process that splits the beam with an electrostatic septum (ES), employing a thin-wire array to delimit the high electric field region that deflects the beam into the extraction channel. At CERN's Super Proton Synchrotron (SPS) the ES is over 16 m long and composed of 5 separate units containing separate wire-arrays that can be moved independently. The tanks are all mounted on a single support structure that can move the ensemble coherently. As a result, the large number of positional degrees of freedom complicates the alignment procedure in operation. Obtaining and maintaining accurate alignment of the ES with the beam is therefore crucial for minimising beam loss. In this paper, we investigate the alignment procedure for different operational scenarios using particle tracking simulations to understand the beam loss along the extraction straight as a function of the relative positions of each of the 5 separate ES units. An important aspect of the study was to understand the required alignment tolerance to achieve optimum extraction efficiency for a given configuration of wire-array thicknesses.

INTRODUCTION

The SPS provides a 400 GeV/c slow-extracted proton beam to CERN's North Area (NA). The extraction scheme is a 1/3-integer sextupole-driven extraction with non-zero chromaticity. This scheme involves increasing the beam's amplitude in the horizontal plane until it jumps into the high field region of an electrostatic septum (ES), which kicks it into the transfer line. By the very nature of this process, some particles will inevitably hit the septum wires and be lost either by inelastic nuclear interaction or after being scattered. Future proposed facilities to be hosted at CERN's NA, such as the Beam Dump Facility (BDF), will require an unprecedented number of 4×10^{19} Protons On Target (POT)/year. In order to attain this figure, the extraction efficiency would need to be improved dramatically, since simply increasing the beam's intensity would make radioactivation and cool-down times of Long Straight Section 2 (LSS2) of the SPS prohibitively high.

The ES in LSS2 consists of five tanks mounted on a moveable girder. The tanks are 3.13 m long, with 78 cm gaps between them. Each tank contains an anode made up of an array of 2080 W-Re wires and a cathode, separated by a ~20 mm gap. The anode wires are between 60 (tanks 1 and 2) and 100 microns (tanks 3-5) thick. The upstream and downstream ends of the anodes and the girder can be moved independently, yielding a total of 12 degrees of freedom. The cathode moves with the anode position to maintain the requested gap spacing and therefore electric field. However, the upstream end of the girder and of the first tank are nominally kept constant at 68 mm throughout the alignment procedure, since this position, combined with the extraction bump amplitude, determines the spiral step. This reduces the dimensionality of the problem to 10 degrees of freedom. Random misalignments between the tanks mean the effective thickness of the anode wires is higher than nominal. Therefore, the probability of particles being scattered and lost increases with misalignment.

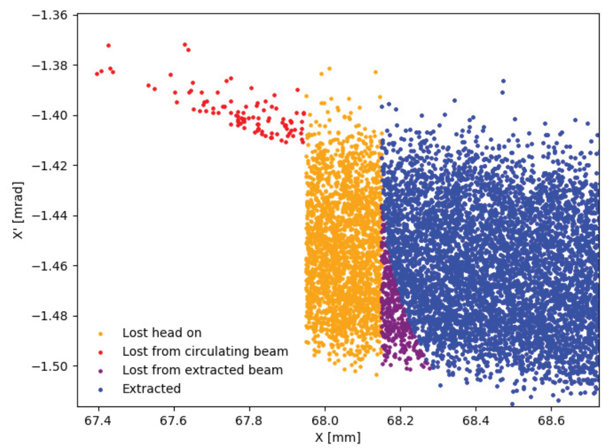

Figure 1: Horizontal phase space distribution in the vicinity of the first ES wire. Particles lost or extracted are shown for the nominal alignment with simplified ES geometry (effective thickness 200 μm, no gaps between tanks) in the black absorber approximation. Most particles are lost due to non-zero wire thickness at the ES upstream (orange). The remaining losses stem from the angular spread of the beam, which occur downstream, both from the inside (purple) and outside (red) of the ES.

A typical loss profile with a simplified model of the ES geometry is shown in Fig. 1. In this model, the five anodes are one single block of material, with no gaps between tanks. Tank misalignments are accounted for by imposing a bigger effective wire thickness of 200 μm. The density of the wires is scaled accordingly so that the total amount of material seen by the beam is kept constant. Furthermore, the wires are modelled as black absorbers, thus disregarding scattering. The extraction inefficiency, defined as

$$1 - \epsilon = \frac{N_{\text{lost}}}{N_{\text{lost}} + N_{\text{extracted}}} \tag{1}$$

is 2.9% for this model. Most particles are lost at the ES upstream because they arrive with an X coordinate between

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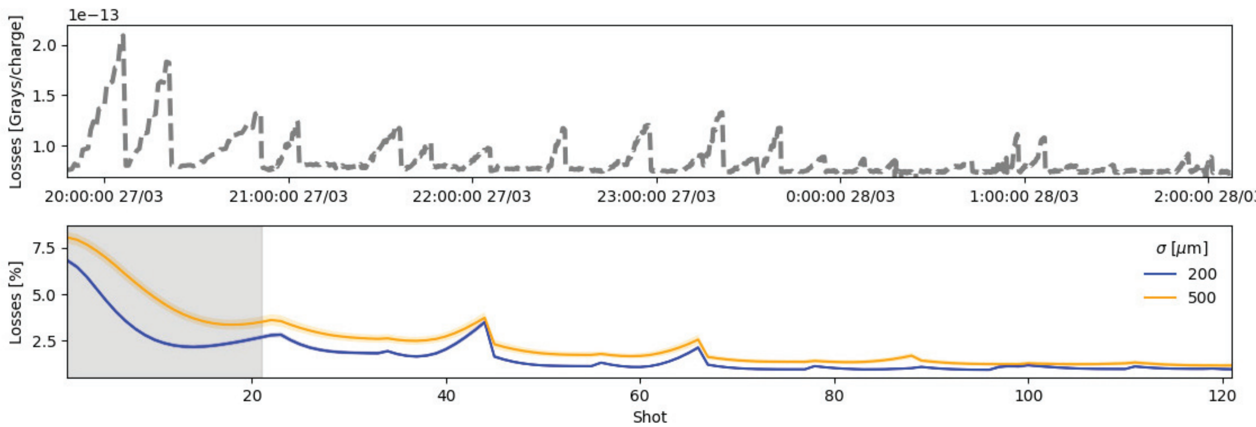

Figure 2: Top: Normalised BLM losses measured during the last alignment procedure over 6 hours for a single iteration of alignment during 2018 re-commissioning. Overall improvement was 31%. Bottom: 500 anode scan simulations with normally distributed initial misalignments. Average and 95% CI losses shown. Shaded area indicates girder scan with subsequent scans following ES tank anodes 1 to 5.

the inner and outer edges of the anode, striking the first wire. The rest are lost due to angular spread, and impinge on the anodes further downstream, either from the circulating (zero-field) or the extracted side (high-field).

In this paper, a simulation tool combining tracking and scattering routines along with the detailed geometry of the ES anodes and the electric field is presented. The tool allows the effect on extraction efficiency of individual tank misalignments to be studied, thus improving upon the aforementioned model. The tool is then exploited to implement and test the current alignment procedure. The model will be extended to test different alignment procedures and automated optimisation algorithms in the future.

SIMULATION MODEL

The standard tool presently used at CERN for assessing the efficiency of a slow extraction scheme is a combination of particle tracking in MAD-X with scattering implemented in `pycollimate` [1]. Simulations with an even more accurate model of the interaction of the beam with the ES wires have been carried out with FLUKA, for which a complete model of the LSS2 geometry has recently been developed [2, 3]. However, simulations with such a level of detail are computationally very expensive and a complete description of multi-turn effects has yet to be implemented. Given the relatively high dimensionality of our problem, simplified models are necessary in order to cut down simulation time to reasonable values.

To reduce the simulation time, a fixed particle distribution at the upstream end of the ES was pre-computed by MAD-X and then sampled for every alignment error seed tested. Sampled particles are then tracked along the ES taking into account wire misalignments. The geometry of the ES is fully implemented, with the first two wire arrays being 60 μm thick and the next three 100 μm thick. If a particle hits the wires, it is handed over to `pycollimate` to simulate the scattering process. Particles that are scattered back to the circulating side are then tracked around the ring until they are either extracted, absorbed by the ES in an inelastic nuclear interaction or lost somewhere on an aperture restriction. No particles are left in the ring at the end of the routine. This means that extraction efficiency and beam loss add up to one, so either of them can be taken as figure of merit. The tracking around the ring is done with a simplified lattice containing only linear elements and non-linear thin lens extraction sextupoles. This scheme allows us to reduce the number of turns the particles are tracked by a factor of $\sim 10^4$, since the bulk of the work only has to be done once in MAD-X. Future extensions of the model should include the cathode as well.

ALIGNMENT PROCEDURE

Currently, the ES tanks are aligned manually in a few 8 hour shifts over the course of the commissioning period at the beginning of the operational year. In 2017, once the alignment was adjusted and losses acceptable for high intensity operation the ES could be kept in the same position through the rest of the year's operation. The procedure is as follows: once the slow extraction has been correctly set-up with the orbit flattened in LSS2, and the extraction bump and sextupoles correctly scaled, the angle of the girder is scanned, whilst holding the upstream position constant. The position that yields the lowest losses, as measured by the LSS2 Beam Loss Monitors (BLMs), is chosen. FLUKA simulations are being carried out to demonstrate that the loss signal is indeed proportional to the total number of protons lost with the specific locations of BLM's in LSS2 [4]. The alignment set-up of the ES is carried out at low intensity to minimise risk of damaging the septum and to minimise the induced radio-activation. Investigations are presently on-going to ensure machine reproducibility at the different

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intensity levels used for alignment compared to high intensity operation.

Next, similar scans are repeated for all the anode motors, starting from the downstream end of ES1, before moving onto the upstream end of ES2 and moving downstream sequentially. The anode scans are then repeated until no improvement in beam loss is observed.

Since the procedure is labour intensive, requiring several dedicated sessions of about 8 hours each, and the loss profiles for each scan are reproducible, there is hope that it could be soon automated. On the other hand, even with an automated implementation of the current procedure, high pressure for physics time severely limits the number of iterations that could be carried out. This calls for the exploration of different strategies capable of yielding similar performance with faster convergence. For example, an algorithm that exploits the global structure of the problem instead of locally optimising each degree of freedom could be of interest.

ERROR STUDIES

The performance of the operational alignment procedure was tested by imposing initial random misalignments on the up and downstream positions of the anodes of each tank. For the present study, the maximum number of iterations was set to one, i.e., each degree of freedom was scanned just once. The misalignments were drawn from a normal distribution centred on the axis of the girder and with σ = 200 or 500 μm. A total of 500 simulations were carried out, each one having a different set of initial misalignments. The results are shown in Fig. 2, compared to BLM data representing a sum of the response on relevant BLM's in LSS2 that was obtained during the last alignment session in March 2018.

First, we proceeded with a girder scan. The optimal positions of the simulated girder scans appear to be biased towards the extracted beam with respect to the nominal case. The reasons behind this are unclear, although part of the effect may be explained by the fact that sensitivity to losses is greater towards the ring [5].

After fixing the girder downstream end at the position yielding the highest extraction efficiency, anode scans were carried out sequentially as described in the previous section. Figure 2 compares actual data from the last alignment session to the our model. In the machine, losses were reduced by 31% this year. The average improvement for our simulations was 49% for σ = 200 μm (and 54% for σ = 500 μm), but the improvement varied significantly between trials, with an Inter-Quartile Ranges (IQR) = 29% and 23%, respectively. Our implementation of the procedure is able to reproduce the fact that losses are less sensitive to misalignment in the downstream tanks. Most of the improvement happens when scanning ES1 and ES2. By the time the scan of ES5 is performed, the algorithm has already converged. This is true even when the final efficiency obtained is quite poor, i.e. it seems that for certain initial misalignments the algorithm gets stuck in a local minimum. Further studies are needed in order to verify if this behaviour persists when the procedure is iterated several times and whether the results for the downstream tanks are dominated by numerical noise in the simulation.

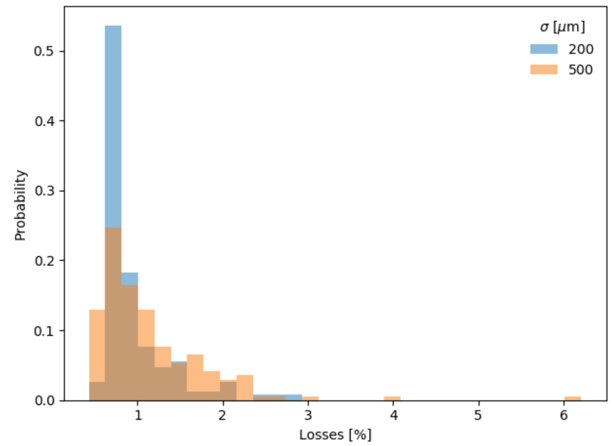

Figure 3: Distribution of losses after one iteration of the alignment procedure with 500 randomly sampled initial misalignment error seeds. Higher initial misalignments translate into more beam loss and greater variance.

A histogram of the extraction inefficiency after one iteration is shown in Fig. 3. The median value was 0.77% for 200 μm and 0.94% for 500 μm, with an IQR of 0.33% and 0.71%, respectively. These are to be compared with the 0.83% losses for the case of straight-line alignment. The code is currently being benchmarked against MAD-X, pycollimate and FLUKA, and the origin of the mismatch should be accounted for in the near future.

CONCLUSIONS AND OUTLOOK

In this paper we presented a model for studying the effect of septum tank misalignments on slow extraction efficiency at the SPS. Due to the existence of ten positional degrees of freedom, our main goal was to develop a fast simulation tool that would allow us to test a large number of wire arrangements in reasonable time. This was achieved by offloading the bulk of the tracking to MAD-X and sampling from the same particle distribution for all tank arrangements, whilst implementing tracking of only the last few turns in a simplified model including scattering. Furthermore, we have implemented and started testing the current manual alignment procedure. Future studies implementing multiple iterations of the procedure as well as uncertainties in the tanks positions will help us assess whether upgrading the anode motors to increase their precision will be cost effective in terms of loss reduction. Benchmarking of the code with other standard tools is on-going to understand the absolute extraction efficiency and the reduction in losses observed with respect to the straight-line case that has only been simulated to date. Finally, we hope to use the same model to test other automated algorithms in the future.

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