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AUTOMATISATION OF THE SPS ELECTROSTATIC SEPTA ALIGNMENT

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Abstract

An electrostatic septum (ZS) composed of 5 separate tanks is used to slow-extract the 400 GeV/c proton beam resonantly on the third-integer resonance from the CERN Super Proton Synchrotron (SPS). The septa are all mounted on a single support structure that can move the ensemble coherently. In addition, the internal anode and cathode of each tank can be moved independently. The septum is aligned to the beam by measuring and minimising the induced beam loss signals in the extraction region following an alignment procedure that is usually carried out at the beginning of each year. The large number of positional degrees of freedom complicates the procedure and until recently each tank was aligned one after the other semi-manually, typically requiring 8 h. It is not uncommon that the septum has to be re-aligned later in the run taking time away from the physics programme. To tackle this issue, a simplified beam dynamics and scattering simulation routine was developed to permit error studies with a large number of seeds to be carried out in a reasonable computation time. In this contribution, the simulation model will be described before the results of its exploitation to understand the efficacy of alignment procedures based on different optimisation algorithms is discussed and compared to the present operational procedure. The effort culminated with the implementation of an automated alignment procedure based on a Powell optimisation algorithm that reduced the time needed to align the septum by over an order of magnitude.

INTRODUCTION

The operational alignment of the septa in Long Straight Section (LSS) 2 of the SPS has improved iteratively over the last few years as the knowledge and experience of operating the system with high proton flux has been regained [1]. This is best illustrated by the improving end-of-year radioactivity levels along the extraction straight in LSS2, which have improved year-on-year and are now lying back on the historical trend as a function of total extracted flux [2]. The active length of the ZS stands at over 16 m and is composed of 5 separate units containing independent septa composed of wire-arrays strung on anode supports. The upstream and downstream ends of the anode supports and the girder supporting the ensemble can be moved independently, yielding a total of 12 degrees of freedom. By fixing the upstream ends of the girder and anode of the first tank, together with the extraction bump amplitude, the spiral step (transverse extracted beam size) is kept constant, reducing the dimensionality of the problem to 10 degrees of freedom. Misalignment between the wire-arrays in each tank leads to an increased effective septum thickness as seen by the beam; the probability of particles being scattered and lost increases and the extraction efficiency decreases. Obtaining and maintaining accurate alignment with the beam is crucial for minimising beam loss and the induced radioactivity of LSS2. Since the manual procedure is labour intensive, even with the aid of software applications to carry out the scans, automation of the procedure was investigated. These studies were motivated by the pressure for physics time that severely limits the time permitted to optimise the alignment.

THE SIMULATION FRAMEWORK

Particle tracking simulations were carried out to understand and investigate the efficacy of different alignment procedures. Simulation packages, such as FLUKA [3] or even multi-turn tracking simulations with MAD-X coupled to *pycollimate* [4], demand a level of detail that is computationally expensive. Given the relatively high dimensionality of the ZS alignment problem, a simplified model was established in order to cut down simulation time to reasonable values when running large batches of error seeds. To reduce the simulation time, a fixed particle distribution at the upstream end of the ZS was pre-computed by MAD-X and then sampled for every misalignment seed tested. Sampled particles are tracked along LSS2 taking into account misalignments of the individual wire arrays. Only the last three turns before extraction are simulated, giving a large speed-up in the simulation time. If a particle hits the wires, it is handed over to *pycollimate* to simulate the scattering and interaction process. Particles that are scattered back to the circulating side are then tracked around the ring until they are either extracted, absorbed by the ZS in an inelastic nuclear interaction or lost somewhere on an aperture restriction. 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 generating the initial distribution in MAD-X. The simulation code returns the extraction efficiency for a given seed and can be found on Gitlab [5]. It has been made in such a way that different custom or off-the-shelf optimisers can be easily plugged into the library.

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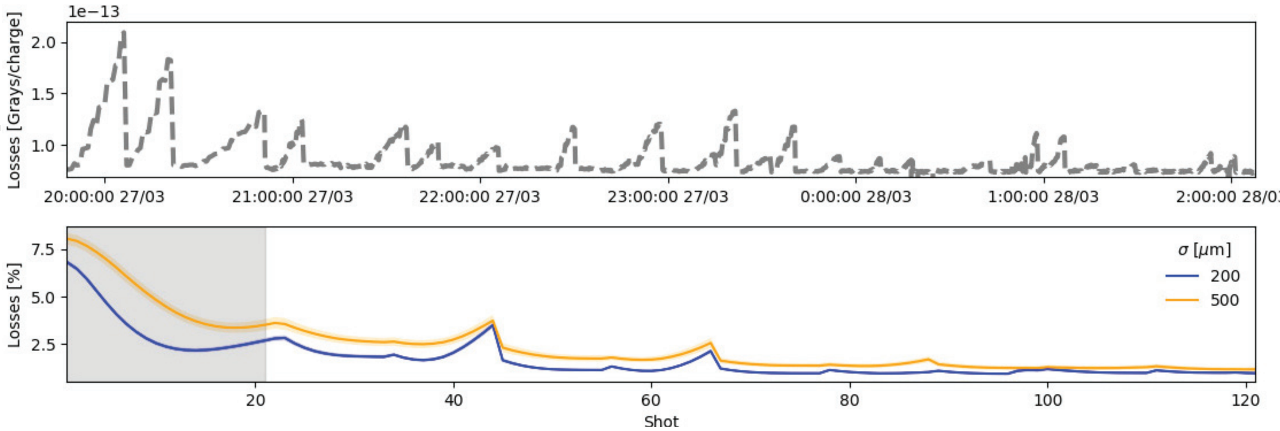

Figure 1: Top: Normalised BLM losses measured over 6 h for a single alignment session during 2018 re-commissioning. Overall improvement was 31 %. Bottom: 500 anode scan simulations with normally distributed initial misalignments. Average and 95 % confidence interval of the losses is shown. Shaded area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

MANUAL ALIGNMENT PROCEDURE

Currently, the ZS is aligned manually in a few shifts, each approximately 8 h in length, over the course of the commissioning period at the beginning of the operational year. Once the slow extraction process is 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 its upstream position constant. The position that yields the lowest losses, as measured by the LSS2 Beam Loss Monitors (BLMs), is chosen. Next, similar scans are repeated for all the anode motors one at a time, starting from the downstream end of ZS tank 1 and moving sequentially through the motors located downstream. The anode scans are then repeated until no improvement in beam loss is observed. The sum of the extraction losses in LSS2 during the alignment procedure over 6 h for a single iteration during the 2018 re-commissioning is shown in Fig. 1 and compared to a simulation of the procedure with two different assumptions for the tolerance on the initial misalignment of the anodes.

It was evident that an algorithm exploiting the global structure of the problem instead of locally optimising each degree of freedom would be of interest. Different optimisation and alignment algorithms capable of yielding similar performance with faster convergence were investigated [6].

COMPARISON WITH OTHER ALIGNMENT ALGORITHMS

The simulation tool was used to compare the current operational algorithm with a gradient descent algorithm. To simplify the comparison, the degree of freedom linked to the girder was removed from the simulation and only optimisation of the anodes considered. The gradient of the extraction efficiency was computed at each iteration in all 9 degrees of freedom by moving each anode motor one at a time, left and right, by a given step, with the upstream end of ZS tank 1 fixed [7]. After each iteration, taking 18 shots (9 degrees of freedom × 2 - left and right), the gradient of the extraction efficiency function was computed and all anodes moved in the direction of fastest descent. The algorithm was repeated with an exponentially shrinking step size. Figure 2 shows that the gradient descent algorithm greatly outperforms the operational procedure with a convergence that is statistically quicker and more repeatable, i.e. less sensitive to the initial misalignment seed. Interestingly, when errors on the precision of the anode motor control were implemented their impact was shown to depend strongly on the alignment procedure employed. The simulation tool was also able to confirm that the speed of convergence depends strongly on the number of degrees of freedom, as expected, i.e. fewer, higher voltage septa are easier to align.

First tests were also made implementing a Bayesian optimisation algorithm [8] into the simulation framework, but without significant improvement compared to gradient descent techniques.

ONLINE IMPLEMENTATION & TESTS OF AN AUTOMATED PROCEDURE

Beam tests using a modified version of an algorithm developed by Powell [9] were performed, which is presently used for different operational optimisation problems across the CERN injector complex. This algorithm is a derivative-free/zero-order algorithm, which makes it suitable for the ZS alignment case since the derivative is unknown a priori. Powell is based mainly on an estimation of the steepest descent after exploring the n-dimensional parameter space in n start directions employing a standard line search procedure, in this case Brent [10]. Afterward, a new direction is determined to replace the first start direction, while $n-1$ iterations follow the rest of the start directions. Within the next n iterations the second start direction is replaced in the same manner and so on until the convergence criteria are met. Since Powell's method is an unbounded optimisation method for convex problems, the algorithm was modified. The move-

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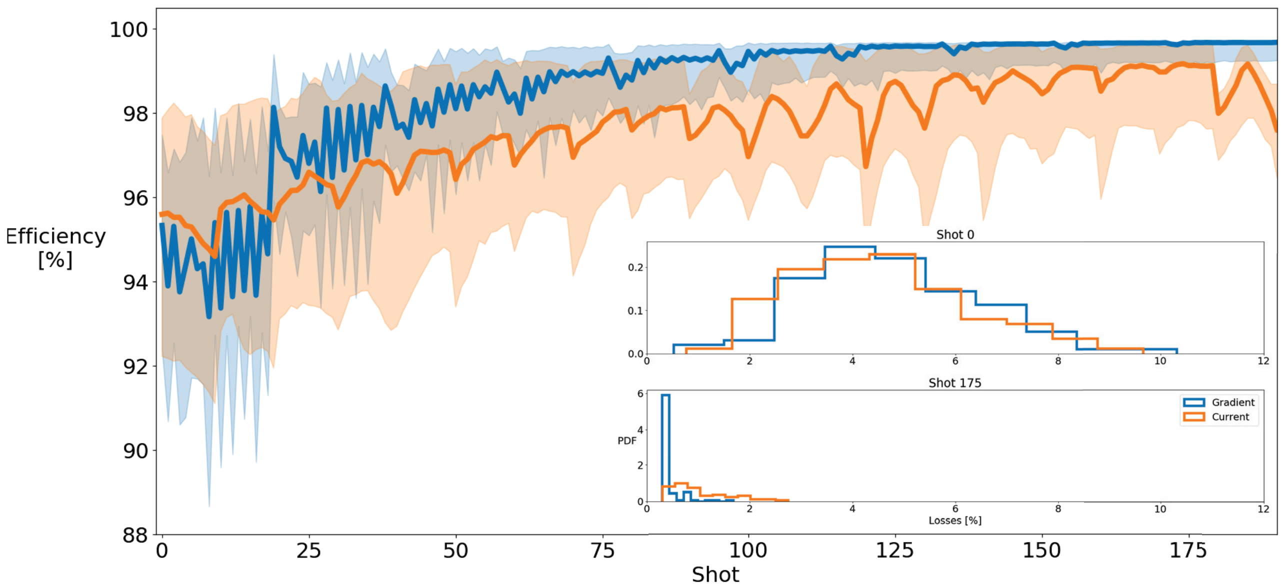

Figure 2: Simulations of the operational alignment procedure (orange) compared with a gradient descent algorithm (blue). The median and 90 % confidence interval are plotted from 200 error seeds randomly sampling initial anode positions from a Normal distribution with $\sigma = 500\,\mu\text{m}$. Inset: distribution of extraction efficiency at shots 0 and 175.

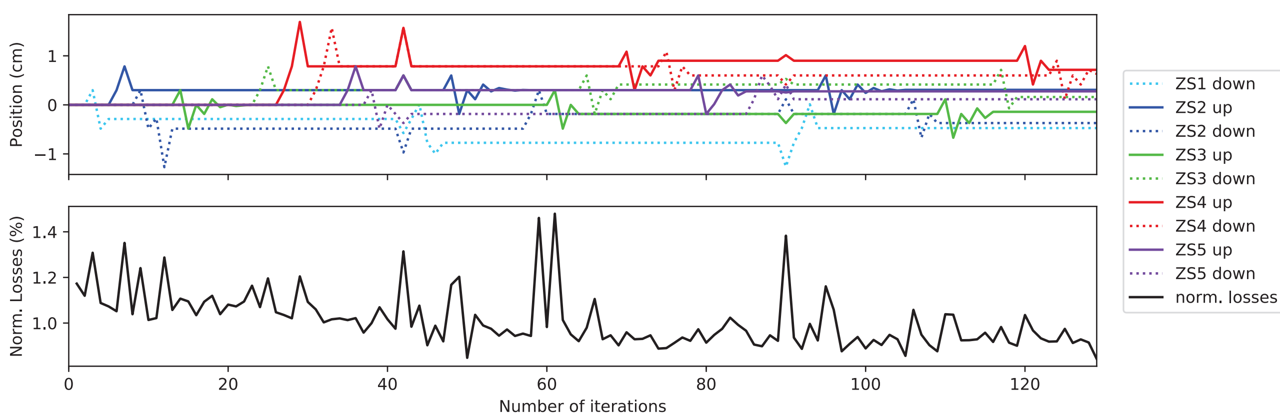

Figure 3: Beam test of automated alignment using Powell's method. The anodes were set to zero to simulate a restarting scenario. The algorithm was stopped after 129 iterations, where the losses were reduced by more than 28 %.

ment of the anodes was restricted by the software to respect the range available on the hardware, and, instead of sending the changes directly, the response was simulated with a penalty to steer the convergence. A similar modification was made to avoid very small changes in the anode positions being sent to hardware. The observable to minimise was the normalised sum of the extraction losses in LSS2. Several scenarios were tested online. An example of simulating the recommissioning after a long shutdown is shown in Fig. 3, where all anodes positions were initially misaligned by setting them to an arbitrary reference value of zero. The losses were reduced by 28 % by the algorithm, which was stopped after 129 iterations or approximately 40 min. This represents about a factor 10 in the improvement of the alignment time.

CONCLUSION AND OUTLOOK

A concerted effort has been made to understand the procedure presently used to align the SPS electrostatic septa, including its speed of convergence, reproducibility and impact on the extraction efficiency. An improved algorithm based on gradient descent demonstrated promising performance in simulation. As a first step and with the limited time available, dedicated beam tests successfully demonstrated a significant speed-up using a modified Powell optimiser used for optimisation problems elsewhere at CERN. The next steps will include an operational implementation of the Powell optimiser to automate and speed-up the alignment procedure. Beam dynamics error studies of the Powell optimiser would be beneficial as would beam tests with the gradient descent algorithm.

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